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NCAR Annual Report 2011

A Message from the Director
Supporting Science's Future
NCAR Community Science In the Field
Tools to Support Community Research
Research Serving Society
Metrics

2009-2014 Strategic Plan »

2011 Annual Report

A Message from the Director

Roger Wakimoto

This is the time of year where things slow down momentarily, giving me a chance to take a look back at the previous year's work, even as efforts for Fiscal Year 2012 move ahead. Both the community and NCAR continue making notable scientific achievements.

Critical to NCAR's efforts to serve the university community are our leaders. In 2011 two of our labs – the Earth Observing Laboratory (EOL) and the NCAR Earth System Laboratory (NESL) – both gained new directors, Vanda Grubišić and Jim Hurrell, respectively. In addition, Michael Thompson became the High Altitude Observatory's director in July 2010. After 23 years, Rick Anthes has stepped down from his role as president of the University Corporation for Atmospheric Research (UCAR). While Rick will continue in his scientific endeavors, I'd like to thank him for his years of effort on behalf of NCAR, UCAR, the National Science Foundation, and the university community. I would also like to welcome Tom Bogdan, who begins as UCAR president in early January 2012. I look forward to the years to come working with these new team members.

Other exciting news includes finalization of the NCAR-Wyoming Supercomputing Center (NWSC) construction and commissioning, completed in October 2011, on schedule and within the planned budget for the project. At the start of operations in 2012, NWSC will house one of the world's fastest supercomputers for scientific research, as well as a premier data archival facility that will preserve valuable research data including extensive climate history records. With the last two missions flown this summer, the HIAPER Pole-to-Pole experiment comes to an end. This multi-university, multi-institution, multi-agency effort led by Harvard, generated an extraordinarily detailed mapping of the global distribution of greenhouse gases, black carbon and related chemical species in the atmosphere. Congratulations to all involved on the effort to create this rich set of observations.

Congratulations are also due to the EOL team led by Terry Hock, which received recognition from John Hickenlooper, Colorado's Governor, for innovative dropsonde technology created and refined over the past five years. The 2011 Colorado Governor's Award for High-Impact Research recognizes outstanding research that will change the quality of life for people here and all over the world. Also of note is work done by the Research Applications Laboratory's wind energy team, which worked with the National Renewable Energy Laboratory and Xcel Energy to provide highly detailed, localized weather forecasts to help Xcel's wind energy production. The forecasts enabled the utility to better integrate electricity generated from wind into the power grid, in particular by helping plant operators decide when to power down traditional coal and natural gas plants and rely on wind energy instead, in the process saving rate payers millions of dollars.

Continuing our focus on helping educate the next generation of scientists, the Integrated Science Program (ISP) ran a 2-week colloquium on African weather and climate. The colloquium brought together students and researchers working on climate and weather issues in Africa, with a focus on learning how to use remote sensing, numerical simulation and prediction, statistical data analysis, and visualization tools to address scientific questions. The Advanced Study Program's (ASP) *Statistical Assessment of Extreme Weather Phenomena under Climate Change* included 100 participants – including students, lecturers, and researchers – visited NCAR over a three-week period. Expanded from two weeks, the extra week allowed students more time to work on hands-on projects, and added a topical Research Colloquium during the middle week, in which researchers had a rare opportunity to engage in five days of discussion with other experts in the field of extreme value theory. The ASP also ran a student workshop that coincided with the Denver-based World Climate Research Programme's open science conference, which brought together for the first time ever its entire research community.

In addition to the news above, NCAR and our community participated in many other notable scientific efforts. Please take time to read the suite of stories that comprise the 2010 NCAR Annual Report for details on these projects and many other exciting research efforts occurring in 2010. I encourage you to see the annual reports created by each of our Laboratories, Programs and our Observatory. These provide a further variety and breadth of details on 2011 work.

With best wishes for 2012 and sincere thanks for your ongoing support, and the hard work of the past year,

Roger

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Log in

National Center for Atmospheric Research | NCAR 2011 Annual Report

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NCAR Annual Report 2011

A Message from the Director
Supporting Science's Future
NCAR Community Science In the Field
Up, Up, and Away: Concordiasi Driftsonde takes to Antarctica's Skies
New Wind Profiler Design Adds Research-Design Flexibility
Web 2.0 at NCAR
PREDICTing Hurricane Formation in the Atlantic Basin
Tools to Support Community Research
Research Serving Society
Metrics

2009-2014 Strategic Plan »

NCAR Community Science In the Field

Observations of natural phenomenon are critical to developing understanding of science. Obtaining such observations is the stuff of field programs and campaigns. Featured in the following pages are some of the projects that NCAR supported and ran in 2011. Highlights run the gamut from gathering detailed atmospheric data over Antarctica to predicting hurricane formation in the Atlantic Basin. Also featured is a new, modular wind profiler that has the flexibility to meet a broad range of research needs, and a look at NCAR's Web 2.0 capabilities that keep our various audiences - the public, scientists, funders, etc. - up to date on the latest efforts going on within NCAR and the community.

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Log in

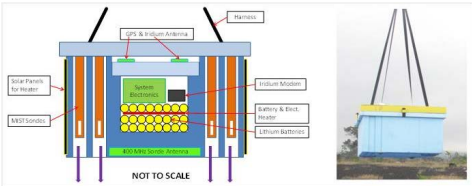
NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
  - Up, Up, and Away: Concordiasi Driftsonde takes to Antarctica's Skies
  - New Wind Profiler Design Adds Research-Design Flexibility
  - Web 2.0 at NCAR
  - PREDICTing Hurricane Formation in the Atlantic Basin
- Tools to Support Community Research
- Research Serving Society
- Metrics

2009-2014 Strategic Plan »

Up, Up, and Away: Concordiasi Driftsonde takes to Antarctica's Skies

Like salt in soup, research tools often go relatively unnoticed unless missing or malfunctioning. Lacking the right tools may result in scientific outcomes or understanding that is less impactful, and potentially more difficult to achieve. When tools work well, greater possibility exists for discovery, and in some cases the right tool may offer new or unlooked-for results. In the recent Concordiasi Project launched from McMurdo research station in Antarctica, Driftsonde technology provided the equivalent of not just the salt but the vegetables, protein and broth for the Météo-France-, National Science Foundation-funded field campaign.



This schematic shows the balloon-based Driftsonde concept. The Driftsonde releases dropsondes, which measure and relay information on wind, temperature, humidity and other meteorological characteristics as they descend through the atmosphere. These data get sent back to the Driftsonde. In turn, the Driftsonde transmits the data to satellites, such as the IRIDIUM Leo satellite, which provides critical information used in near-real time weather forecasting.

The Driftsonde System, developed by a team of mechanical, electrical and software engineers in NCAR's Earth Observing Laboratory (EOL) to provide a low-cost way of taking instant measurements along a vertical profile of atmosphere, looks something like a giant weather balloon – a weather balloon that offers oversized observing capabilities. Launched from the ground and able to stay aloft for up to several months, Driftsonde systems provide Concordiasi researchers with a sophisticated suite of tools.

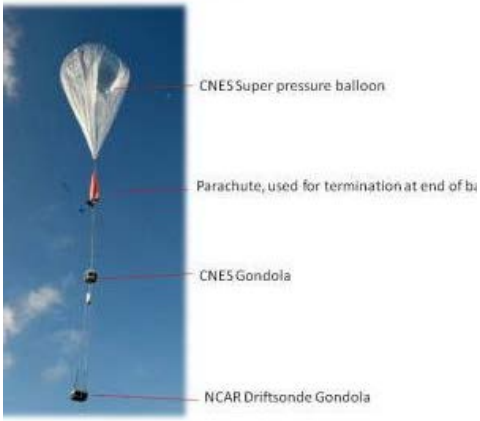
Fitted with dropsonde instrumentation, once launched Driftsondes collect the detailed atmospheric information transmitted back from dropsonde sensors to the Driftsonde gondola. Measurements include observed atmospheric characteristics such as wind, temperature, humidity, and pressure.

Operated remotely using a web-based interface, this design allowed dropsonde control and monitoring to occur from anywhere in the world with an internet connection. This proved helpful during Concordiasi's 24/7 operations, when Boulder- and France-based operators transitioned operations at the respective day's beginning and end in each country.

These capabilities also allowed dropsonde release to occur at desired points along the Driftsonde flight path. Points of interest included remote geographic areas and significant weather events, for example. Also, a main focus for Concordiasi scientists, the EOL team worked closely with Météo-France to ensure that some dropsonde releases coincided with satellite overpasses to facilitate validation of these remotely sensed data, says Steve Cohn, manager of EOL's In-situ Sensing Facility (ISF).

"We also kept an eye on areas that atmospheric models indicated were sensitive to new data, so if something particularly interesting was taking place or about to happen, atmospherically, a dropsonde could be launched," Cohn says. "The team worked closely with Antarctic modelers and forecasters to identify such events."

The Concordiasi Driftsondes were built and deployed by NCAR and flown on France's space agency (Centre National d'Etudes Spaciales) super pressure balloons and included as part of an International Polar Year research effort. With launches occurring in September and October 2010, some of the Driftsondes remained aloft into December.



Flight train of Concordiasi balloon just after launch in Antarctica.

Météo-France initiated and led the Concordiasi project, which is named after France's Concordia research station located on the Antarctic Plateau and the IASI (Infrared Atmospheric Sounding Interferometer) satellite instrument; IASI is a key element of the METOP series of European meteorological polar-orbiting satellites. The campaign included researchers from around the world who looked to the Driftsonde observing systems to validate satellite data and obtain detailed information on the atmosphere in data-sensitive areas – areas where models indicated need for more information for validation, or very remote areas where data are rarely if ever collected. Other Concordiasi measurements focused on understanding the microphysics of polar stratospheric clouds.

Driftsonde Systems Help Validate Radiance Data and Offer Views on Cloud Microphysics

Polar-orbiting satellites over Antarctica collect radiance data. These snapshots of upwelling radiation coming from the surface or lower atmosphere can be translated into temperature data, providing insights on surface-level and atmospheric processes. Satellite-sensor precision varies, however, which can affect output from weather and climate models using the satellite-derived temperature data. Consequently, data validation becomes imperative. Dropsonde measurements of temperature will help achieve this end.

Equally important to Concoridasi scientists was broadening the depth of knowledge related to stratospheric clouds and small-scale physical processes. At the best of times, cloud formation and dispersal and the atmospheric characteristics affecting cloud dynamics are nuanced, but at such high altitude (18 km) and in one of the planet's most remote areas, this becomes even more of an issue. Importantly, the data collected during Concordiasi will increase **understanding of processes driving ozone-hole formation each** spring in the Southern Hemisphere.

Toward these ends, the fall 2010 Concordiasi program flew 13 Driftsondes from McMurdo, the main U.S. research base on Antarctica. Fitted with as many as 52 miniature dropsondes, the Driftsondes transmitted detailed atmospheric information via satellite to a ground-based station in real time. While such a capability may seem conventional, reliable real-time satellite data transfer has only recently become viable globally. Although the Driftsonde System was developed for the African Monsoon Multidisciplinary Analyses (AMMA) in 2006, Concordiasi offered an opportunity to enhance remote operations, real-time data download capabilities and quick-turn upload functionality that feeds operational weather models. The team also improved Driftsonde technology to allow the systems to function aloft over the span of several months.

During Concordiasi, operators on the ground vetted atmospheric data soon after Driftsonde transmittal, running the data through quality-control procedures before uploading it to the Global Telecommunications System (GTS); a World Meteorological Organization effort, the GTS facilitates *collection, exchange and distribution of weather observations and data*. Once in this system, Concoridasi data were used by operational models at research centers around the world responsible for creating near-real-time weather forecasts.

The 639 dropsonde profiles collected during Concoridiasi provide an unprecedented spatial data set over Antarctica. They offer valuable data for future atmospheric research in this region of the world.

In addition to providing new insights on Antarctic atmospheric characteristics, several spin-off developments have benefitted from this work. Among these is perfecting technology created by EOL engineers for a dropsonde system on NASA's Global Hawk, an unmanned aerial vehicle that, like the Driftsonde, flies at stratospheric altitudes, collecting data that would otherwise not be accessible to researchers. This technology also allows real-time dropsonde release and download of data from a ground station – Driftsonde technology development led to this capability. Additionally, EOL developed the Mini dropsonde specifically for the Driftsondes; these smaller dropsondes will prove useful for future research campaigns on manned aircraft. And, up next, a new dropsonde system is under development for use on the NSF/NCAR Gulfstream V (GV) research airplane. The new system will automate GV dropsonde launches; currently an operator manually launches the dropsondes.

"This upgrade is a huge step forward," explains Cohn. "Today, safety demands that during excessive turbulence operators remain in their seats on the GV – this means the sondes don't launch. Automating launch gives scientists and staff who operate the system greater control over dropsondes."

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Log in

NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
  - Up, Up, and Away: Concordiasi Driftsonde takes to Antarctica's Skies
  - New Wind Profiler Design Adds Research-Design Flexibility
  - Web 2.0 at NCAR
  - PREDICTing Hurricane Formation in the Atlantic Basin
- Tools to Support Community Research
- Research Serving Society
- Metrics

2009-2014 Strategic Plan »

New Wind Profiler Design Adds Research-Design Flexibility

One size fits all research equipment has advantages: scientists know what they're dealing with, this approach saves on costs, and can serve more than one project. But, despite the advantages, one-size-fits-all sometimes leaves a desire for something more tailored to meet research needs.

During T-REX (the Terrain-Induced Rotor Experiment), scientists studied atmospheric dynamics occurring leeward of mountain-ridge crests. Run in 2006 in California's Owens Valley, deployable, upward-looking 915 megahertz (MHz) wind profilers assisted with observations of the atmosphere. These Doppler radar provided details on atmospheric characteristics such as winds, turbulence, clouds, and precipitation. The wind profilers can measure winds upward to three kilometers at a resolution as high as 60 meters, with temperatures measurable up to about one kilometer. While glad to have the upward-looking, mobile radars, the scientists would have benefited from additional atmospheric detail.

The prototype hexagonal antenna modules of EOL's new 449 MHz wind profiler radar undergoing testing at NCAR Foothills Lab in Boulder.

"One size fits all doesn't offer much flexibility at times – it's like using one hammer to hit all kinds of nails," says William Brown, a project scientist at the National Center for Atmospheric Research's (NCAR) Earth Observing Laboratory (EOL), and leader for the lab's atmospheric profiling group. "For T-REX, we wanted to see the wide range of atmospheric dynamics, but only had enough wind profilers to set up at a few locations and didn't have flexibility, for example, to vary how deep we could look into the atmosphere."

Having talked about alternatives to the 915 MHz profiler during a number of projects, including renting or borrowing equipment, T-REX eventually led EOL's In-situ Facility (ISF) team to explore the option of building one themselves. Their engineering skills combined with EOL's Computing Data and Software (CDS) facility, made this entirely possible. They wanted a wind profiler that both better met researchers' needs and increased the equipment manageability factor – quick and easy to set up and lighter weight.

The team envisioned a modular design that would allow the option of lining a series of wind profilers along the expanse of a research site or combining a number of individual radars to create a single, more powerful wind profiler able to see beyond the 3-km atmospheric boundary layer. The other issue facing them: such a wind profiler would have to work within the narrow radio frequency range allocated by the U.S. federal government for scientific use. Many of the frequencies within the radio frequency spectrum are reserved for use by cell phones, and television and radio broadcasting.

Taking all of these needs and desires into consideration, ISF took the idea of creating a modular 449 MHz wind profiler for future research to EOL management, which funded the initial development effort in 2008.

The resulting modular 449 MHz wind profiler, as the IFS team envisioned it, offered an exciting advance in weather data collection, by providing a network of upward-looking radar, able to "see" a minimum of 4 km into the atmosphere at a range resolution of 50 meters and time resolution of a few minutes. Such a system would be able to provide detailed observations on the characteristics of the atmospheric boundary layer between the Earth's surface and the top of the troposphere where much of the weather that society experiences occurs.

The development is proceeding in stages. So far a prototype, three-module system has been built, and additional funding received from the NCAR directorate is enabling more modules to be constructed. Being modular and deployable, the system can be loaded onto a trailer and sited wherever research needs require. Once in the field, the 449's network of radar antenna modules can be assembled as a single-antenna unit, or multiple units that build on the cumulative capacity to look higher into the atmosphere. And, while weather balloons are equally mobile, it is expensive to deploy balloons in large numbers and they cannot provide the same level of continuous detailed focus on a selected

area of study.

A field campaign, the Persistent Cold Air Pool Study (PCAPS), run by the University of Utah, Michigan State University and NCAR offered a first-test opportunity for the 449 MHz wind profiler in 2010. Many cities surrounded by mountains have issues with inversions in which overlying warm air traps cooler – often polluted – air in the underlying basin or valley, PCAPS observations will help with understanding weather conditions that contribute to these inversions. The study required continuous weather monitoring, which included launch of more than 150 weather balloons, as well as use of NCAR's 915 and 449 MHz wind-profiler radars to capture details of wind, temperature, precipitation and humidity along vertical columns of atmosphere above Salt Lake City.

"PCAPS offered a chance for side-by-side testing of the 915 and 449 MHz wind profilers, as well as the opportunity to fiddle with and fine-tune the 449's 3-antenna prototype – with good results," says Steve Cohn, manager of EOL's In-situ Sensing Facility.

PCAPS relied on the three-module wind profiler, however future visions include stringing together multiple antenna modules to suit the required research need – whether looking at the mid- or upper troposphere, or as far as the lower stratosphere. A 7-module network configuration is now being built that will allow the radar to look at the mid-troposphere; this configuration will be tested in summer 2012.

Further down the road, scientists and engineers in EOL hope to make observations of the lower stratosphere by stringing together 19 antenna modules that will provide information on the atmosphere's characteristics spanning from 300 meters to 15 kilometers from the Earth's surface, at a resolution as fine as 100 meters.

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Log in

National Center for Atmospheric Research | NCAR 2011 Annual Report

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NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
  - Up, Up, and Away: Concordiasi Driftsonde takes to Antarctica's Skies
  - New Wind Profiler Design Adds Research-Design Flexibility
  - Web 2.0 at NCAR
  - PREDICTing Hurricane Formation in the Atlantic Basin
- Tools to Support Community Research
- Research Serving Society
- Metrics

2009-2014 Strategic Plan »

Web 2.0 at NCAR

Communications teams within the National Center for Atmospheric Research (NCAR) have fully embraced social networking technology. The HIPPO (HIAPER Pole-to-Pole) flights in 2009 set the stage for the initial introduction of Web 2.0 into NCAR. At the start of this study to collect observations within the global troposphere to better understand the global carbon cycle, interested viewers could watch the progress of the National Science Foundation/NCAR Gulfstream V (GV) as it flew across the globe, from pole to pole, using the Google Earth tracking tool. In recent years, EOL broadened its capabilities in this area by hiring a public education and outreach coordinator, Alison Rockwell, to help publicize its many field campaigns and field-research-support efforts. In doing so, new functionality including video, Facebook, and Twitter got added to the mix.

EOL has provided a site that breaks the variety of project foci up for easier viewing; among these are severe weather, climate processes, atmospheric patterns, ocean processes, and air chemistry, **www.eol.ucar.edu/field_projects/project-categories/ocean-systems**. Here, readers can find links with user-friendly, digestible views on the details of EOL projects under way or recently completed.

A view of NCAR-Wyoming Super Computing Center visitors' center while under construction and upon completion.

For example, under the Ocean Dynamics section, DYNAMO (run in 2011), HIPPO (run from 2009-2011), and VOCALS (run in 2008; VAMOS (Variability of the American Monsoon Season) Ocean-Cloud-Atmosphere-Land Study) are among the featured research projects. Project pages contain YouTube videos, as well as the series of Twitter and Facebook feeds created during the project lifetime.

"The beauty of this system is that after creating a Facebook entry, the entry gets fed to Twitter automatically, so a single notice of events is generated simultaneously onto different sites looked at by different audiences," says Rockwell.

In addition, YouTube is a highly utilized feature at EOL, with videos taken during campaign preparation, while the campaign is in action, and post-flight to fully capture a "day in the life" for those who haven't experienced a typical day in the field.

EOL is not alone in its social media efforts. The Computational and Information Systems Laboratory (CISL) has targeted the NCAR-Wyoming Supercomputing Center (NWSC) as the path to leaping into the Web 2.0 foray, covering development of the building that will soon house NCAR's supercomputers, as well as providing project background, and other details on the effort. A construction web-cam set up at the site lets virtual visitors see the latest developments in the NWSC structural build, nwsc.ucar.edu/. For those having missed earlier building phases, a time-lapse video shows the facility's construction from the ground up, with glimpses provided of the changes in weather and seasons throughout the effort an added viewing bonus.

Not to be left behind in the realm of Facebook and Twitter, the NWSC team maintains updates to both sites that give notice of project milestones, a heads up on talks going on at conferences and meetings, and other relevant information. Images from weekly reports written to keep NCAR and Wyoming project managers and NWSC personnel updated are multi-purposed, with relevant images and captions uploaded to Facebook and Twitter, in addition to a variety of photos that document project progress.

The High Altitude Observatory also has a Facebook page – perhaps no surprise given the number of graduate students

and postdocs associated with the Observatory, says HAO's Associate Director, Michael Thompson.

"Our Facebook pages helps connect existing postdocs and graduate students with former students – so far, we've got 260 followers, which seems pretty good given that we only recently made the site available," continues Thompson.

In addition to NCAR's efforts, the University Corporation for Atmospheric Research (UCAR), NCAR's managing body, provides a variety of Web 2.0 capabilities, http://www2.ucar.edu/news/social-networking-ncar-ucar. These include Facebook and Twitter, as well as a number of blogs and YouTube channels highlighting NCAR and UCAR research, and Flickr, which features images from a digital image library and COMET, a science-education program.

For more information see: **www.nwsc.ucar.edu** and **https://www.eol.ucar.edu/field_projects**

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Log in

NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
  - Up, Up, and Away: Concordiasi Driftsonde takes to Antarctica's Skies
  - New Wind Profiler Design Adds Research-Design Flexibility
  - Web 2.0 at NCAR
  - PREDICTing Hurricane Formation in the Atlantic Basin
- Tools to Support Community Research
- Research Serving Society
- Metrics

2009-2014 Strategic Plan »

PREDICTing Hurricane Formation in the Atlantic Basin

Some tropical weather systems originating over Africa end up forming hurricanes upon reaching the central or western Atlantic ocean. Forecasts of the movement of hurricanes, once formed, have improved markedly during the past three decades, however a major challenge remains to predict the formation of hurricanes. By understanding the formation stages of hurricanes, scientists hope to improve numerical forecasts and provide additional forecast guidance tools so that accurate forecasts can be made farther in advance. They anticipate improving hurricane forecasts out to as much as seven days – today, fairly accurate hurricane forecasts can be achieved three to five days in advance of storms. This longer lead time may further reduce societal and infrastructure losses.

Thus far, observations of hurricane formation – tropical cyclogenesis – have been limited because hurricane development typically happens over vast expanses of ocean. Typically the only observations are made by satellites, and while vital to forecasting, satellite measurements can't observe everything needed to make accurate forecasts. Using the NSF/NCAR Gulfstream V (GV) aircraft in the Atlantic basin as part of the PRE-Depression Investigation of Cloud-systems in the Tropics (PREDICT) field experiment, scientists gained a wealth of new observations captured during flights over the basin during hurricane season. In particular, they wanted to observe wave-like disturbances whose characteristics are theorized to provide clues about the likelihood of hurricane formation.

PREDICT Research Flight number 4, August 21, 2010.

"During PREDICT, we located storm systems early, and followed them over several days before they developed," explains Chris Davis, one of the project's principle investigators. "Having double crews allowed us to follow storms, gaining detailed information on formation processes."

Two of three well-sampled storms became tropical storms, says Davis, one did not. All three provided insights of hurricane genesis, as well as on factors contributing to lack of development.

"Because the project focused on tropical cyclogenesis, we looked at weak, early stage storms forming in the tropics. Having an opportunity to see a system *not* turn into a tropical storm is as important as seeing storm formation," Davis says.

One of the desired project outcomes was to gain a set of cyclogenesis-prediction conditions that could help determine whether something would or would not happen, hurricane-wise, with the goal of taking some of the element of surprise out of the forecasting mix. As a result, perhaps the most exciting outcome of the effort was in finding that consistency exists between real-life storm formation and theories of what might happen. This, says Davis, offered a case of theoretical analysis matching up with real-life dynamics. PREDICT provided an opportunity to observe and document such outcomes.

Operating during the 2010 hurricane season from August through September, the National Science Foundation-sponsored PREDICT team was not alone in its efforts to study hurricanes in the Caribbean. NOAA and NASA also ran programs during this timeframe. The fortuitous timing led to collaborations when aircraft from each agency could observe the same weather system. Data and analysis outcomes will be shared between the three agency teams.

Together, the teams have gathered a wealth of data, and expect much to be gained upon further study. Basic data analysis is underway, which includes identifying areas that would benefit from further, future investigation. PREDICT has also resulted in advances from a practical research perspective. These include real-time monitoring and mission refinements. Since PREDICT's end, subsequent research missions using the GV have benefitted from the ability developed during PREDICT to stream information in real time about the best locations to send the plane to gather required or desired information. Moreover, PREDICT efforts have assisted in refining data archival and retrieval techniques via the web, which speeds analysis capabilities. Data archived at EOL in the field catalog are more readily

retrievable, and the ability to look at data has improved. All of this, in combination, says Davis, leads to improved future campaigns and has enhanced PREDICT's contribution to the research community.

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NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
- Tools to Support Community Research
  - Forecasting Tool Optimizes Integration of Wind Energy into the Electricity Grid
  - New Coronagraph Assists in Detecting and Tracking Solar Activity
  - Earth System Grid (ESG)
  - Cyberinfrastructure for data-enabled science
- Research Serving Society
- Metrics

2009-2014 Strategic Plan »

Forecasting Tool Optimizes Integration of Wind Energy into the Electricity Grid

Many in our research community rely on NCAR for providing research tools that are critical to helping find answers to scientific and societally relevant questions. Among these tools and capabilities are the Earth System Grid, which assists with efficient delivery of scientific data to new and existing users, a new coronagraph that facilitates detecting and tracking solar activity, and forecasting capabilities that improve integration of wind-generated electricity into the utility grid.

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Log in

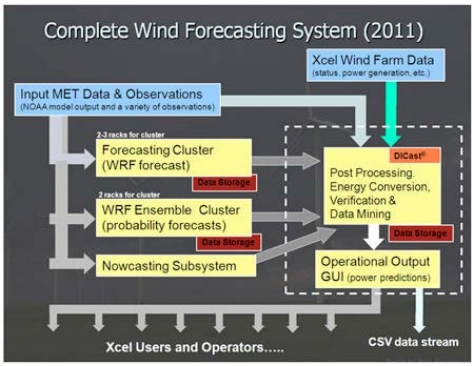
NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
- Tools to Support Community Research
  - Forecasting Tool Optimizes Integration of Wind Energy into the Electricity Grid
  - New Coronagraph Assists in Detecting and Tracking Solar Activity
  - Earth System Grid (ESG)
  - Cyberinfrastructure for data-enabled science
- Research Serving Society
- Metrics

2009-2014 Strategic Plan »

Forecasting Tool Optimizes Integration of Wind Energy into the Electricity Grid

Wind as an energy source has captured the attention of energy and utility industries. However, when it comes to wind-energy generation, accurate forecasts are crucial for efficient planning and resource management. Knowing when the wind will blow and when it won't has been a major impediment to ensuring wind power meets its full potential. But as wind forecasts improve this may become less of an issue. The Research Applications Laboratory (RAL) at the National Center for Atmospheric Research (NCAR) is contributing to this greater level of reliability. Working with Xcel Energy, the nation's leading utility in wind energy, and the National Renewable Energy Laboratory (NREL), scientists and engineers have developed and deployed an advanced wind power prediction system – the NCAR/RAL Wind Power Forecasting System.



Conceptual diagram of the wind energy prediction technology components that will be incorporated into the final configuration.

With 3.4 million electric customers, Xcel Energy is the fifth largest combined electric and gas utility in the United States. It boasts the largest wind energy capacity in the continental U.S. with more than 50 wind farms, 2972 turbines, and 4062 MW of wind power. The company knew that to expand their renewable capacity from 10% to 30% to meet the State of Colorado's renewable energy requirement, they needed a significant improvement in wind prediction. In addition, accurate wind forecasts and uncertainty information are necessary both for day-ahead trading and real-time decision making regarding power levels of back-up energy generation units and transmission. Until recently, the commercial marketplace lacked access to wind-power forecasting capabilities that provided the needed level of accuracy.

As the wind capacity of a utility grows, it becomes more difficult to effectively integrate this variable resource into the power mix. Accurate wind power forecasts significantly improve integration by reducing uncertainty of wind generation, and in doing so lead to cost reductions as reliability of output improves. In addition, reliable day-ahead forecasts enable more efficient energy trading between utilities that lead to more economic power dispatch.

RAL's wind power forecasting system substantially advances the state-of-the-science of wind power forecasting through integrating advanced modeling capabilities, real-time data assimilation, nowcasting, and statistical post-processing technologies. The system utilizes both publically available model data and weather observations and wind forecasts produced from a customized NCAR-developed wind forecasting model that also incorporates real-time data (e.g., wind speed, power, availability, etc.) from 2972 wind turbines. The observations and model forecast data are combined using NCAR's Dynamic, Integrated, Forecast System (DICast) technology, which automatically calibrates and adjusts the predictions based on real-time feedback from the wind generators.

The forecasting system enables utilities to integrate large amounts of wind energy into the power grid by providing comprehensive forecasts of wind-power generation on both short-term time scales of 15 minutes to three hours, and at scales that allow longer term planning – on an hourly basis up to 168 hours (7 days) in advance. Implementation of the system has resulted in a 40% reduction in wind energy prediction error, which has improved integration of wind power into the electric grid. In 2010 alone, the increased accuracy saved Xcel Energy rate payers $6 million.

This wind energy forecasting system is widely considered, nationally and internationally, to be the most advanced system of its kind with the details of the system configuration and component technologies freely shared with the meteorological and energy communities, says William Mahoney, the NCAR scientist who conceived the project and provided project oversight.

"Never has so much real-time [meteorological and power system] data been leveraged in an operational wind energy

forecasting system. This was truly ground-breaking work," says Eric Pierce, Xcel Energy's Managing Director of Energy Trading and Commercial Operations. "Xcel as seen return of investment through cost reductions due to greater operational efficiencies."

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Log in

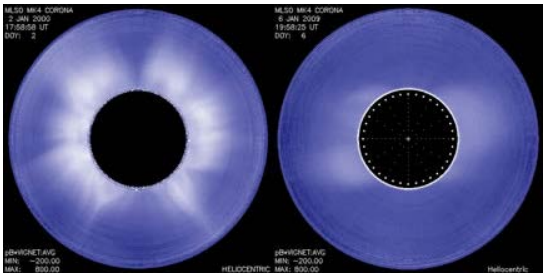
NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
- Tools to Support Community Research
  - Forecasting Tool Optimizes Integration of Wind Energy into the Electricity Grid
  - New Coronagraph Assists in Detecting and Tracking Solar Activity
  - Earth System Grid (ESG)
  - Cyberinfrastructure for data-enabled science
- Research Serving Society
- Metrics

2009-2014 Strategic Plan »

New Coronagraph Assists in Detecting and Tracking Solar Activity

Streams of charged ions, radiation, and other matter are routinely ejected from the Sun's atmosphere outward into the solar system. When directed Earthward and depending on their strength, effects of these mass ejections from the solar corona can increase radiation levels in the Earth's upper atmosphere, posing hazards to astronauts, and to a lesser extent for high altitude airplane flights particularly over the north and south poles. In addition, generation of strong electrical currents from these storms may affect functioning of electrical transmission lines and the dependent power grids, and interfere with radio and satellite signals, which can affect air transportation and day-to-day activity of society. Helping to provide a better view and warning of such space weather phenomena, scientists rely on a variety of instruments including coronagraphs. These telescopes are designed with disks that block – occult – the bright light of the Sun's surface to provide a view on the fainter outer solar atmosphere known as the corona. Scientists study this region because the most energetic forms of solar activity, such as coronal mass ejections (CMEs) and flares, originate in the corona.



Comparison of coronal brightness between solar activity maximum (left) and activity minimum (right). Images were acquired with the MK4 Mauna Loa K-coronameter on Jan 2, 2000 during solar maximum and on Jan 6, 2009 during solar minimum. Brighter regions are locations where the Sun's magnetic field contains the plasma creating high density regions; dark regions are where the magnetic field is open, allowing the plasma and embedded magnetic field to escape to form the solar wind. Images have the same scaling and color table to illustrate solar cycle variations.

NCAR's new K-coronagraph will soon be deployed to the Mauna Loa observatory in Hawaii, replacing the existing MK4 coronagraph. Like the MK4, the new coronagraph will measure the polarized white light emitted from the corona. Like all coronagraphs, the K-coronagraph effectively replicates a solar eclipse artificially. An occulting disk located inside the telescope blocks the bright light emitted from the Sun's surface, overpowering the corona, which is a million times dimmer. Using the K-coronagraph, scientists expect to be able to observe CME dynamics at early formation stages, which will allow researchers to better understand how they form and providing time to prepare for resulting space weather effects.

CMEs form enormous, magnetically charged loops of coronal material, with larger CMEs propelling billions of tons of material toward Earth at roughly 1.5 million kilometers per hour (~900,000 miles per hour) with the fastest ones traveling more than 10 million kilometers per hour (seven million miles per hour). The number of CMEs that form varies with the sunspot cycle. During solar minimum, when solar activity is low, one CME may be generated each week. During the other extreme of the Sun's cycle, the solar maximum when solar activity is much higher, several CMEs may be generated daily. CMEs, explains Joan Burkepile a project scientist in NCAR's High Altitude Observatory, may also play an important role in reversing the direction of the Sun's magnetic field that happens each sunspot cycle.

"HAO scientist B.C. Low has theorized that CMEs may play a critical role in removing twisted coronal magnetic flux. The cumulative effects of many CMEs over the sunspot cycle removes the old cycle magnetic flux from the corona, enabling the reversal of the Sun's magnetic field, and making way for the next sunspot cycle," says Burkepile.

Large Angle and Spectrometric Coronagraph (LASCO) halo coronal mass ejection (CME) of February 17, 2000. The portion of the halo directly over the south pole was recorded by the MK4. This is one of the brighter halos recorded by LASCO.

The K-coronagraph will assist in detecting and tracking CME activities, aiding prediction of geomagnetic storms. Among its capabilities is a low signal-to-noise ratio, which means it has the capacity

to provide research with extremely high quality images of the very low corona in white light. The K-coronagraph will acquire images every 15 seconds across a field of view that ranges from 1.05 to 3 solar radii – approximately 20,000 to 800,000 miles above the solar surface. While enormous from the perspective of a view on Earth, the resulting relatively narrow, detailed images allow scientists to more readily identify CME speeds and acceleration rates over time; such perspective is critical for understanding processes related to CME generation and dynamics. Currently, a variety of theories exist about the details of CME formation. Improved observations will assist in refining these ideas.

Like its predecessors, the K-coronagraph will also be used in conjunction with space-based coronagraph observations. Ground-based versions complement satellite sensors by providing coronal views that are lower, or closer, to the coronal regions located nearest to the Sun's surface. Ground-based coronagraphs – and the K-coronagraph in particular – have advantages over satellite coronagraphs in that they are more accessible in the event of modifications or upgrades being needed. Also, data transmission costs are less, and facilities are more easily maintained over sustained periods of time. Ideally, the K-coronagraph will become part of an international network of similar telescopes, useful for supporting solar research as well as cultivating future generations of instrumentation scientists.

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Log in

NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
- Tools to Support Community Research
  - Forecasting Tool Optimizes Integration of Wind Energy into the Electricity Grid
  - New Coronagraph Assists in Detecting and Tracking Solar Activity
  - Earth System Grid (ESG)
  - Cyberinfrastructure for data-enabled science
- Research Serving Society
- Metrics

2009-2014 Strategic Plan »

A History of the Earth System Grid and Gateways

Approximately every five years, the Intergovernmental Panel on Climate Change (IPCC) issues a report providing the world with an updated assessment of the risks of human-induced climate change. This report relies on information produced by physical and social scientists from around the globe based on research done in the years leading up to publication. For the climate model runs alone, significant amounts of data have to be delivered from researchers to a data clearing house where it is stored and served on-demand to meet user requests for the information. According to the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory, which hosted all of the climate model data for the IPCC Fourth Assessment Report (AR4), more than 35 terabytes (TB) of climate model output from 17 modeling centers worldwide were made available to the science community. Twelve hundred registered users had downloaded more than 337 TB of data as of January 2007, the month before AR4 publication. As of late 2011, nearly 600 peer-reviewed publications had been written that used the IPCC AR4 model output archived at PCMDI.

The IPCC assessment offers only one example of the need for data center staff and tools capable of providing large volumes of data seamlessly. Adding to this challenge is the increasing number of scientific endeavors that demand raw data to begin the research process and the related increase in data users, many of whom have limited experience working with large computing systems to access the available information. The open availability of such large volumes of data to the global user community, comprised not just of research scientists but also the general public, students, policymakers, economists, urban planners, and other analysts, requires specialized resources and staff. The skills of computer scientists and software engineers, and data managers and data scientists, plus the computing hardware and software needed, are all necessary to enable easy access to these data.

"As demand for data increases from users with varied computing expertise, the scientific community and NCAR needed to find a means of delivering data in a more streamlined fashion," explains Gary Strand, a software engineer at the National Center for Atmospheric Research (NCAR) who specializes in climate model data management.

NCAR – and Strand – has long served climate model data to its user community. But as user numbers grew, they recognized a need for improved protocols for serving these data to new and existing users. In the late 1990s, says Strand, the U.S. Department of Energy (DOE) began a project called "the Earth System Grid" (ESG) as a means of transferring large volumes (10 TB or more) of data between the DOE laboratories distributed across the United States.

"DOE funded the Earth System Grid to find a way to efficiently move data between Argonne National Laboratory in Illinois and Lawrence Livermore National Laboratory in California, and other DOE labs," explains Strand. "The ESG project success led Warren Washington, an NCAR senior scientist, to consider the resulting approach as useful for delivery of NCAR climate data, both from the perspective of NCAR data users and for those on the data delivery side."

NCAR become involved in the Earth System Grid (ESG) in the early 2000s. NCAR was the first "gateway" of the ESG, using the new technology to deliver the DOE-funded Parallel Computer Model (PCM) climate data to the wider user community.

Working with the DOE labs and PCMDI, NCAR researchers and their DOE colleagues met weekly to discuss hardware and software needs for the system, as well as figuring out a way to distribute data via the Web in response to the growing variety of users and user needs. By 2004, the group had a solid prototype for Web-based data delivery that allowed both experienced and less expert users broader data access, and streamlined the work required behind the scenes. Between 2004 and 2006, Strand says that just for NCAR, the number of users requesting and being served PCM data grew from dozens to hundreds. Around this same time, the newly developed Community Climate System Model version 3 (CCSM3) working groups also sought to use the ESG Gateway to deliver CCSM3 data.

"ESG has been incredibly successful. In 2005, PCMDI become that second ESG Gateway for the AR4 data – and these data are still actively mined by users. With the IPCC Fifth Assessment Report now under way, ESG data distribution gateways have expanded to centers around the world, and this redundancy of data availability and delivery benefits all, and indicates buy-in for the ESG by the global scientific community," Strand says.

Side Bar: Updates on the Community Earth System Model

In June 2010, NCAR researchers delivered climate data from the Community Earth System Model (CESM) to the global

climate community. Completion of CESM 1.03 earlier this year includes the capability for modelers to run Coupled Model Intercomparison Project 5 (CMIP5) and Representative Concentration Path (RCP) simulations. In addition, CESM has a new Scientific Steering Committee Chairperson and Project Lead in Marika Holland.

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Log in

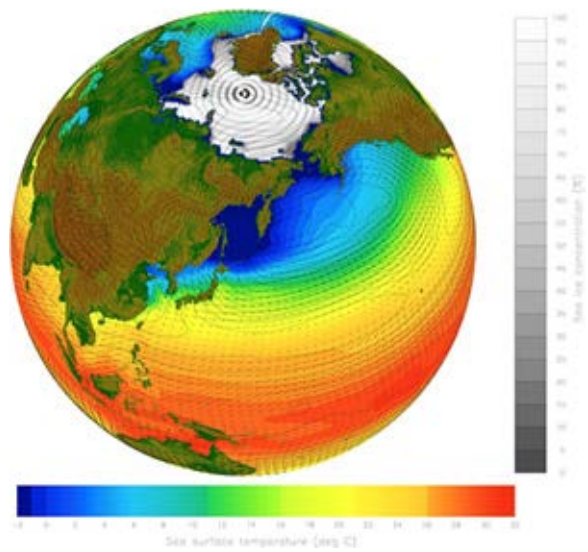
NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
- Tools to Support Community Research
  - Forecasting Tool Optimizes Integration of Wind Energy into the Electricity Grid
  - New Coronagraph Assists in Detecting and Tracking Solar Activity
  - Earth System Grid (ESG)
  - Cyberinfrastructure for data-enabled science
- Research Serving Society
- Metrics

2009-2014 Strategic Plan »

Cyberinfrastructure for data-enabled science

In FY2011 climate scientists using CCSM and CESM intensified their program of extremely ambitious climate change simulations for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). This work follows the experimental design of the Fifth Coupled Model Intercomparison Project (CMIP5). CMIP5 describes a set of coordinated climate model experiments designed to address questions about climate change that arose from the IPCC's previous assessment report (AR4). CMIP5 is a five-year experimental design, but the new data infrastructure developed in NCAR's Computational and Information Systems Laboratory (CISL) improved the efficiency of the workflows for these critical simulations and reduced their time to completion. Further, algorithms developed in CISL were used to assimilate the observed global temperature and ocean salinity as initial conditions for the IPCC's ensemble decadal predictions. Developing this capability with the Data Assimilation Research Testbed (DART) required use of CISL's Climate Simulation Lab (CSL) resources to complete the long-term simulations in time for AR5.



The figure depicts a single month from a simulation of the 20th century from the Community Earth System Model (CESM), a coupled model that integrates atmosphere, ocean, land, and ice components. The figure shows wind vectors (arrows) from the lowest atmosphere layer and contours of sea level pressure. The ocean model surface temperatures are shown in orange to blue colors (see color key at bottom), and sea ice is shown in grayscale (see key at right).

NCAR's CISL recently deployed the Globally Accessible Data Environment (GLADE) that makes data workflows more efficient and simplifies data access and usage. Researchers can now structure their workflows to use stored data directly without first needing to copy it to and from systems for supercomputing and data analysis and visualization (DAV). GLADE's centralized high-performance file systems span supercomputing, data post-processing, DAV, and HPC-based data transfer services. This data architecture increases the efficiency of modeling workflows and significantly improves the speed at which researchers can run, analyze, and visualize their simulations. CISL's data infrastructure improved the productivity of CMIP5 climate modeling experiments and helped them be completed in time for inclusion in IPCC AR5.

IPCC simulations rely on data delivered via the Earth System Grid (ESG), a science gateway to climate data collections that are hosted at eight sites around the globe including NCAR. This federated system serves thousands of IPCC AR5 researchers and forms the primary data access facility for the challenging petascale CMIP5 activity. The Earth System Grid Center for Enabling Technologies (ESG-CET) is a long-term initiative that develops a globally distributed petascale data management environment for CMIP5/IPCC-AR5 and U.S. climate science. CISL leads this gateway development effort and focused FY2011 ESG development on data management priorities for the CMIP5 IPCC work. To expand ESG support for CMIP5 metadata, CISL's ESG developers delivered enhanced security, federation, data versioning, and replication capabilities, along with more sophisticated and scalable services for data analysis and data products.

In FY2011, CMIP5 experiments created more than 1 PB of data. In addition to making CISL's HPSS archival system available to store this data, CISL dedicated 500 TB of GLADE disk to ESG, and 400 TB of that was consumed by CMIP5 efforts. As this data was created and stored at NCAR, the GLADE architecture expedited its archival, analysis, visualization, and distribution around the world via ESG. CISL continues its community leadership role to develop data

services that can address the future challenges of data growth, preservation, and management. CISL's disk and tape storage systems provide an efficient, safe, reliable environment for hosting datasets, and CISL's data services continue to be further streamlined, improved, and expanded through the new data-centric design facilitated by GLADE.

Only a small number of institutions, such as NCAR, have the resources necessary to conduct high-end climate research, model development, and campaigns such as the IPCC assessments. The technical requirements of scientific applications such as climate system models are highly specialized: a discipline-specific approach to supercomputing allows CISL to tailor system design and services for these requirements. It also ensures that model development and research in Earth System processes can occur in a controlled yet responsive environment where researchers can prepare complex models and perform the computationally demanding tests required to validate them. To refine predictions of future climate change, CISL prepares for more sophisticated coupled atmosphere-ocean-ice-land models by developing and operating science gateways and other Grid-based technologies that handle massive data flows. Science gateways provide a specific community with some level of integrated, web-based data and knowledge management, secure data access, simulation capability, plus the ability to perform data analysis and visualization. CISL develops and operates science gateways to improve scientific communities' access to shared resources.

CISL's 11 science gateway projects and initiatives share cyberinfrastructure and span climate science, regional climate change, Arctic science, solar science, digital preservation, and international efforts to develop knowledge infrastructure. Many of these efforts are tied to major interagency, national, and international initiatives, including, for example, the World Meteorological Organization (WMO), the Intergovernmental Panel on Climate Change (IPCC), the World Climate Research Program (WCRP), the International Polar Year (IPY), and the Library of Congress' National Digital Information and Infrastructure Preservation Program (NDIIPP). Most of these projects use open source, web portal infrastructure called the Science Gateway Framework (SGF).

CISL develops the SGF as shared cyberinfrastructure to support a wide range of community activities. The SGF serves as a foundation for the Earth System Grid (ESG) and many other national and international science efforts including the WCRP Coupled Model Intercomparison Project (CMIP), the IPCC Fifth Assessment Report (AR5), the Community Earth System Model (CESM), and many more. The SGF-based ESG is currently running at NCAR, several Department of Energy facilities including Lawrence Livermore National Laboratory/Program for Climate Model Diagnosis and Intercomparison (PCMDI), Oak Ridge National Laboratory, Lawrence Berkeley National Laboratories/ National Energy Research Scientific Computing Center (NERSC), as well as at NASA's Jet Propulsion Laboratory, the British Atmospheric Data Centre, the German Climate Computing Center, and Australia's National Computational Infrastructure; all support CMIP5 activity and other projects. The ESG is a complex software package with many stakeholders and is easily deployable at sites anywhere in the world. This petascale system is a critical community resource for CCSM, CESM, and CMIP5/IPCC.

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National Center for Atmospheric Research | NCAR 2011 Annual Report

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A Message from the Director
Supporting Science's Future
NCAR Community Science In the Field
Tools to Support Community Research
Research Serving Society
NCAR's New Leadership Line-up
Developing the Model for Prediction Across Scales
Exploring "Chemical Weather" Forecasting and Analysis
Sun's Convection Zone Sheds New Light on Solar Cycle
Finding the Missing Energy in the Global Energy Budget
Metrics

2009-2014 Strategic Plan »

Research Serving Society

A driving National Science Foundation and NCAR mission is for society to benefit from the science community's research efforts. Among the featured stories for 2011 is a look at new insights on the solar cycle, an update on climate and weather model capabilities that allow scientists to more easily model across varying scales of interest, finding the "missing energy" in the global energy budget, an exploration of chemical weather issues affecting society and ways of managing these issues through science, as well as an introduction to a several new NCAR leaders.

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NCAR Annual Report 2011

- A Message from the Director
- Supporting Science’s Future
- NCAR Community Science In the Field
- Tools to Support Community Research
- Research Serving Society
  - NCAR’s New Leadership Line-up
  - Developing the Model for Prediction Across Scales
  - Exploring “Chemical Weather” Forecasting and Analysis
  - Sun’s Convection Zone Sheds New Light on Solar Cycle
  - Finding the Missing Energy in the Global Energy Budget
- Metrics

2009-2014 Strategic Plan »

NCAR’s New Leadership Line-up

Jim Hurrell, associate director of the NCAR Earth System Laboratory (NESL), Michael Thompson, associate director of the High Altitude Observatory (HAO), and Vanda Grubišić, associate director of the Earth Observing Laboratory (EOL).

Three new leaders have recently taken the helm at the National Center for Atmospheric Research (NCAR). The center has also gained a new president at the University Corporation for Atmospheric Science (UCAR), NCAR's managing body. All are well known to NCAR and its scientific community. They are Michael Thompson, associate director of the High Altitude Observatory (HAO), Vanda Grubišić, associate director of the Earth Observing Laboratory (EOL), Jim Hurrell of the NCAR Earth System Laboratory (NESL), and Thomas Bogdan who becomes UCAR president in January 2012.

While the details of NCAR's leaders' agendas differ, Michael, Vanda and Jim all have research and program plans aimed at better serving the scientific community and pushing forward research being done in their respective organization's area of expertise.

Of the three, Michael is, relatively speaking, a veteran director at this point. Taking up the baton on July 1, 2010, Michael has visited Boulder annually since completing a postdoctoral visiting-scientist appointment with HAO in 1988-89; he became an NCAR affiliate scientist in 2003. Michael comes to NCAR from the University of Sheffield in England where he had a dual role as the head of the School of Mathematics and Statistics and professor of applied math and solar physics. His research there focused on helioseismology, asteroseismology, solar physics, and inverse problems. With luck and some juggling, he intends to continue his research along with his duties as HAO Director. Michael takes over from Michael Knölker, who held the director position since 1994.

Vanda comes to NCAR from the University of Vienna. There, she was hired as the first female full professor of any geoscience discipline in the University's 640-year history to lead the Chair of Theoretical Meteorology, the position once held by Felix Maria Exner. Vanda first visited NCAR in 1991 as a Yale graduate student, then returned as an ASP post-doc in 1995-1997, becoming head of EOL on July 11, 2011. Also, like Michael, she spent time at NCAR after her postdoc, working closely with scientists in NESL's Mesoscale and Microscale Meteorology (MMM) division studying mesoscale atmospheric dynamics, before leaving NCAR for the Desert Research Institute for 10 years; she became NCAR affiliate scientist in 2008. Her research has always included strong observational and modeling components. Vanda succeeds Roger Wakimoto, who took on the role of NCAR Director.

Newest laboratory head of the three, Jim took the reins of NESL on September 1, 2011, taking over from Greg Holland who acted as interim head, filling in the gap between former AD Guy Brasseur's departure from the position and identification of Jim as NESL's new leader. Working in the Climate and Global Dynamics division (CGD) since graduating with his doctorate degree in atmospheric science from Purdue, Jim arrived at NCAR to work with Warren Washington in the Climate Analysis Section of CGD. A post-doc for nine months, Jim was hired as a ladder-track scientist in 1991 when an opening occurred. His career includes leadership of CGD, and Chief Scientist of the Community Climate Projects, among other roles; he is currently Co-Chair of the World Climate Research Programme on Climate Variability and Predictability (CLIVAR).

Michael Thompson

Both his experience at NCAR and HAO's international reputation were draws for Michael to the director position.

"HAO has reputation of being one of the greatest solar physics institutes in the world, it measures far above its budgetary weight in terms of new research output and instrumentation," says Michael. "Observatory research capabilities and focus recently have been extended to include Earth's magnetosphere – so HAO expertise ranges from

the Earth's upper atmosphere to the solar core."

HAO has one of the strongest visitor programs at NCAR; programs range from postdoc positions that extend for up to two years to visiting graduate students who have co-advisors at HAO to affiliate scientists, as well as short- and long-term visitors. The student-based and postdoctoral programs, Michael explains, give HAO greater access to graduate students, who provide a source of new ideas and growth for HAO, and let HAO offer the community a service in terms of training future researchers in solar-terrestrial physics. Since Michael's arrival, focus on affiliate scientists has increased, with greater visibility of these visitors to HAO, NCAR, and the scientific and solar physics community. Among the methods to achieve this end is a dedicated section on HAO's web site introducing each of these scientists.

Both HAO and visitors benefit, says Michael, from the intellectual ties and technical skills, opportunities to work one-on-one on a given research problem, and sharing insights and expertise on HAO's community models and data sets. Strategically speaking, visitors' know-how has an added benefit in that it can help deliver on the Imperatives and new Frontiers in HAO's plan cost effectively.

COSMO – the Coronal Solar Magnetism Observatory – features as a big part of Michael's vision for HAO, with plans for COSMO to be built, and three cutting-edge instruments to be housed at the Mauna Loa Solar Observatory (MLSO) in Hawaii. Among the instruments will be a new K-coronagraph, a white light telescope that detects the evolution of white light reflected from the solar corona, and a chromosphere and prominence magnetometer that will be used to take disk and limb measurements of magnetic fields in the chromosphere and solar prominences, which can be precursors to coronal mass ejections. COSMO's centerpiece will be a large coronagraph, comprising a 1.5-meter lens feeding light to a larger, more light-sensitive version of the Coronal Multi-channel Polarimeter (CoMP); this will provide information on magnetic fields and oscillations (Alfvén waves) in the Sun's corona. Each of these instruments will provide new insights on solar coronal dynamics, which can affect space weather that, in turn, affects the Earth.

Vanda Grubišić

Vanda's affiliation with NCAR and EOL extends back to her graduate-school days at Yale when as a first-year student she worked on the Hawaiian Rainband Experiment (HARP) project, which focused on investigating formation and dynamical and microphysical structure of rainbands offshore of Hawaii's Big Island. Flying on the NSF/NCAR Electra offered a rocky introduction to airborne atmospheric research. Summed up as a five-hour encounter with virtually non-stop boundary-layer turbulence, Vanda describes it as one of the most miserable flights ever.

"Everyone on board was green. The late Joachim Kuettner, a veteran field project manager and researcher who was a science observer on the same mission, leaned over to assure me the flight would be over soon," Vanda recalls.

Not remaining on terra firma for long, Vanda hopped back on the research plane at the earliest possible moment, and thus a career of field campaigns and research commenced.

One among many reasons for her return to NCAR is a passion for EOL's mission. EOL provides end-to-end support for observational science that is unmatched elsewhere, says Vanda. Lab staff designs and builds new sensors and instruments, integrates them onto existing and new platforms, offers support in field mission design, on-the-ground mission support and coordination, data collection, data quality control, as well as data tools and services.

The service EOL provides has given a considerable boost and sustained support to observational science for the NSF-funded atmospheric science university community we primarily serve, explains Vanda.

"All services benefit through being informed by the science done at NCAR and EOL, and by EOL scientists working closely with the members of the community. The science is complex, and a lot is done by EOL staff behind the scenes that is easy to miss even by the experienced user – I have always had a great appreciation of EOL staff and all of EOL's efforts and accomplishments," she explains.

Vanda notes that EOL closely watches the direction in which the science evolves given that the lab has to be able to anticipate where the new frontiers will be in order to provide service in the future. In the process, EOL scientists and engineers reflect on how the science will be done and how new observations and related tools might help these efforts. Since becoming EOL's director, Vanda says she has gained new appreciation of the lab – especially on the development side. As a university user, she has been aware of EOL's deployment and data capabilities and expertise. Since taking on her new role, she has immersed herself in learning first-hand the full extent of the development activities and how they interplay with the rest of the activities within the lab.

As an observationalist and a modeler, her knowledge and skills bring new perspective to EOL. She sees her job as bridging the two research approaches, assisting with ensuring communications and closer interactions between the modeling and observational communities. For science to advance, a close interplay between these two areas is needed – Vanda says that EOL is and will increasingly be more engaged in this realm. In the process, strengthening the collaboration with NCAR's other labs will continue to be a focus.

Her vision for EOL is to start from its existing position of strength – advanced observational science and technology. This includes a suite of ground-based and airborne instruments and platforms suitable for physical process studies. Historically the focus for EOL has been on mesoscale and microscale phenomena. Given the current direction of science focused on climate and Earth system science, as well as the new capabilities provided by the long-range high-altitude NSF/NCAR Gulfstream V (HIAPER) aircraft and its state-of-the art instrumentation, Vanda sees EOL's challenge in extending observational science support to climate-related process studies. Part of that challenge lies in strengthening the ties to the climate community, in particular the climate-modeling community, both within and outside of NCAR. On bringing these two traditionally disparate communities together within NCAR, Vanda plans to work with Jim Hurrell to

ensure the needs and talents of both groups are met and the science frontier moved forward.

Jim Hurrell

Skilled at sports, but considering odds slim of either making the Major League baseball cuts or earning a living in the U.S. Professional Golfers' Association, Jim looked to other career options in college. Synoptic meteorology proved hard to ignore, having grown up with Indiana's tornadoes and a father fascinated by the daily weather forecasts; his dad regularly tuned in to NOAA's National Weather Service (NWS) forecasts, and flipped through all three local news channels' forecasts every evening.

His father's influence and interest in meteorology followed Jim to college where, as a freshman, he signed up for the same introductory atmospheric science class his dad had taken at the University of Indianapolis several years earlier for fun. His atmospheric science professor – who also taught Jim's dad – had ties to the local NWS station in Indianapolis, where he helped Jim get a job as an announcer, reporting on the weather to help pay for college. This added fuel to the academic fire because here Jim had a chance to learn meteorology from veterans working in the field. Then, as a graduate student at Purdue, Jim's interest shifted to climate as a way to understand the dynamics driving synoptic weather patterns, and ultimately led him to NCAR as a postdoc to work with Warren, and soon after to the Climate Analysis section, where he took on a ladder-track scientist position.

Jim's research focuses on regional climate change, global warming, atmospheric patterns such as the North Atlantic Oscillation (NAO), and computer modeling of climate. He is particularly interested in understanding the interaction between human-induced global warming and natural climate patterns such as El Niño and the NAO.

His 20-year tenure at NCAR and leadership roles within the climate community have led to strong relationships across NESL's divisions, NCAR and the wider research community. This history and experience also feeds his vision for NESL. His knowledge of NESL scientists' deep expertise in the realm of weather, climate and chemistry, combined with the tools and technologies (models, instruments, observing platforms) developed with community input, offers synergistic opportunities for researchers, both at NCAR and within the broader community, to gain further understanding of fundamental Earth processes. This knowledge will be critical for informing society and decision makers about environmental issues that humans will have to manage now and into the future.

"Supporting the cross-pollination of scientific expertise across fields is an ongoing increase in computing power," Jim says. "Together, the potential exists for NESL and the community to develop the predictive capability needed to answer pressing societal questions related to extreme weather and climate, among other questions, on national, regional and local scales."

At this point, he explains, climate change is unavoidable, however the magnitude depends on what society decides to do about the problem. This reality is driving a need for local and regional information, attribution and prediction with lead times of hours, days, and years into the future. This is where Jim sees NESL stepping in. Bringing together and integrating expertise from across the laboratory will be critical to understanding future climate regimes and extreme weather.

Thomas Bogdan

Tom takes over the leadership of UCAR early next year. Currently, he is the director of the National Oceanic and Atmospheric Administration's Space Weather Prediction Center (SWPC). Prior to joining the SWPC in 2006, Tom was a senior scientist at NCAR, where he began work as a postdoctoral scientist in 1983, researching solar magnetic activity. Richard Anthes, who has led UCAR since 1988, and was previous to that NCAR's director, will hand the baton on to Tom on January 9, 2012.

Tom earned his Ph.D. (1984) and master's degree (1981) in physics at the University of Chicago and his bachelor's in mathematics and physics from the University at Buffalo, the State University of New York, in 1979. He has authored or co-authored more than 100 papers in solar-terrestrial research. He is a fellow of the American Meteorological Society and serves on its Council of the Members. Tom also works closely with the World Meteorological Organization as the U.S. point of contact for space weather issues. He has chaired and served on numerous National Science Foundation, NASA, and National Research Council committees and panels that provide advice to federal agencies and policymakers, and serves on the Advisory Council for the College of Arts and Sciences at the University at Buffalo.

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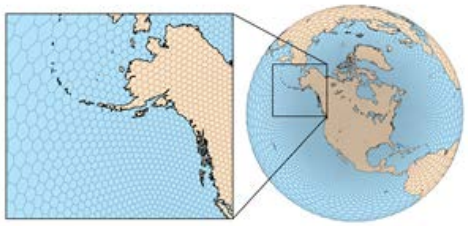
NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
- Tools to Support Community Research
- Research Serving Society
  - NCAR's New Leadership Line-up
  - Developing the Model for Prediction Across Scales
  - Exploring "Chemical Weather" Forecasting and Analysis
  - Sun's Convection Zone Sheds New Light on Solar Cycle
  - Finding the Missing Energy in the Global Energy Budget
- Metrics

2009-2014 Strategic Plan »

Developing the Model for Prediction Across Scales

Meteorological centers providing real-time forecasts to society rely heavily on computer models for these predictions. All the computer models have algorithms responsible for solving the basic equations representing how the atmosphere and other geophysical components evolve. Most models use a latitude-longitude (lat-lon) mesh to decompose the Earth into discrete cells. This mesh wraps around the modeled globe; in polar regions, the narrow lat-lon cells require special mathematical filtering techniques to stabilize the computer models. Because these polar filters make computations more complex, processing speeds slow. If using machines capable of massively parallel processing – that is, supercomputers that have the ability to run at peta-flops speeds (1015 operations per second) – the need for filters slows down computational speeds and greatly constrains the ability to run the increasingly complex models that scientists require to understand and predict complex Earth-system processes.



The Voronoi-tessallation grid, shown above, uses nominally hexagonal cells to cover the Earth to form the basis for the algorithms used in the computer model. The grid above shows an 8-times grid magnification over Alaska and western Canada - note how the mesh varies smoothly from the coarse to fine region. This hexagonal mesh offers advantages over latitude-longitude mesh because each cell is of similar size and shape to the ones next to it, no matter the global location; the cells look the same anywhere on the globe, and this uniformity simplifies and speeds processors' calculations.

As a result, since the late 2000s, scientists in the Mesoscale and Microscale Meteorology (MMM) division of the National Center for Atmospheric Research (NCAR) have looked for model-solver constructions that would eliminate the need for the polar filters. Working with a number of partners, including scientists at Los Alamos National Laboratory, Exeter University, Florida State University, and University of South Carolina, the team considered a variety of options before selecting a Voronoi-tessallation, which uses nominally hexagonal cells to cover the Earth, to form the basis for the algorithms used in the computer model. The hexagonal mesh offers advantages over latitude-longitude mesh because each cell is of similar size and shape to the ones next to it, no matter the global location; the cells look the same anywhere on the globe, and this uniformity simplifies and speeds processors' calculations.

"We turned to collaborators both within and outside of NCAR who had expertise in global weather and climate modeling, as well as familiarity with hexagonal meshes, to create the Model for Prediction Across Scales (MPAS)," says Bill Skamarock, a senior scientist in MMM.

Finding a good uniform mesh for the globe is only the first step of the process. Scientists also wanted the capability to maintain a global view but, as needed, have the ability to zoom in and get a better, more refined view over select regions, while not slowing down the processing by making the entire mesh fine-scale. For instance, over mountainous areas, higher resolution assists in more accurately replicating the details of atmospheric dynamics over complex terrain. At lower resolution, these nuances are frequently muddied and often lost. The Voronoi mesh can be varied between high and low resolution in a smooth and continuous manner. The variable resolution mesh, however, looks like a uniform mesh to the processors hence the same solution algorithm developed by the NCAR scientists and their collaborators are used on both uniform and variable resolution meshes and computational speed is maintained.

For the atmospheric component of MPAS, the NCAR team worked on combining the methods used on the Voronoi mesh with those used on NCAR's Weather and Research Forecasting (WRF) model. This allows the sharing of much software between the two models, and the models are similarly robust. The WRF model provides users with a well-tested weather and research forecasting standard that many in the scientific community have come to depend upon. MPAS is envisioned as the WRF next-generation model for global forecasting and regional climate applications, and by making the capabilities of the two models uniform to the greatest degree possible, the eventual model transition will become more seamless.

This initial work has focused on solving equations for cloud-permitting resolutions. Accurately modeling clouds (which vary on scales of millimeters to kilometers), and cloud processes related to formation, and dissipation, have long been the stumbling block for comparison with real-world observations and model projections of climate and weather effects on Earth. Gaining the ability to model cloud dynamics accurately is one of the driving forces for modern climate modeling, and a lynchpin in moving model outputs closer to matching observations. WRF represents the state-of-the-art in cloud permitting weather and regional climate simulation. MPAS is as accurate as WRF, but it does not suffer from the polar filtering issues of WRF and similar models, and it incorporates local refinement seamlessly in contrast to the abrupt change in refinement associated with the traditional grid nesting used in WRF. Thus MPAS is a major advancement in our simulation technology that, in concert with the introduction of the latest petaflop supercomputers, will allow scientists both inside and outside NCAR to address critical problems in numerical weather prediction, climate and regional climate.

In addition, MPAS outputs will be a critical part of NCAR's regional climate research program, which Greg Holland leads out of the NCAR Earth System Laboratory. MPAS analytical tools will be developed to allow scientists to consider more easily facets of climate change that have direct public impacts.

"Statistical and analytical tools will be developed that facilitate addressing questions society is interested in," says Holland. "For example, MPAS will enable improved application of a hurricane damage index that can be used to predict damage both in current and future storms in current dollars – information critical to the insurance and reinsurance industries, as well as other businesses, but that will also benefit decision makers and the interested public."

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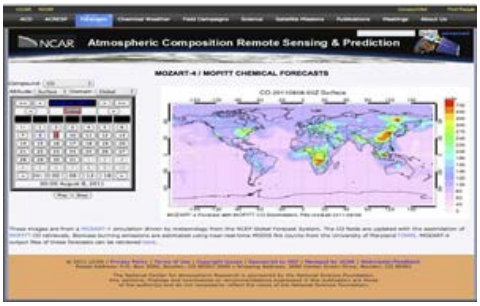
NCAR Annual Report 2011

- A Message from the Director
- Supporting Science’s Future
- NCAR Community Science In the Field
- Tools to Support Community Research
- Research Serving Society
  - NCAR’s New Leadership Line-up
  - Developing the Model for Prediction Across Scales
  - Exploring “Chemical Weather” Forecasting and Analysis
  - Sun’s Convection Zone Sheds New Light on Solar Cycle
  - Finding the Missing Energy in the Global Energy Budget
- Metrics

2009-2014 Strategic Plan »

Exploring “Chemical Weather” Forecasting and Analysis



Marrying observations from satellites and on-the-ground observations and air-chemistry model output has direct benefits to human health and well being, in addition to honing scientific understanding of atmospheric processes. Specifically focusing on this area are members of the National Center for Atmospheric Research’s (NCAR) Atmospheric Composition Remote Sensing & Prediction (ACRESP) program in the Atmospheric Chemistry Division who meld modeling and chemical observations to form air quality analyses and forecasts across different spatial and temporal scales. The large-scale, long-term satellite observations of chemical composition are of special importance in this regard since they complement very detailed, but highly localized, information about “chemical weather” provided by ground networks.

“Satellite observations help us identify regional gaseous and particle pollution from human activity and other chemical compounds that occur naturally in the atmosphere, as well as those that drift in the atmosphere after special events such as dust storms or fires. These observations allow us to analyze the physical and chemical processes taking place that might lead to smog events or reduce visibility, and they also assist with identifying and forecasting changes in air quality,” says David Edwards, a senior scientist and ACRESP head.

ACRESP efforts support one of NCAR’s five strategic Frontiers: to develop community tools for integrating Earth and Sun system measurements with models. NCAR’s strategic frontiers are areas where opportunity exists to build on existing programs and accelerate scientific progress to address societal needs. Each of the ACRESP research programs described below achieves this end.

A major focus wrapped into each of its efforts is data assimilation of observations into models to assess how well model data matches real-world observations of atmospheric chemistry and chemical weather (air quality). Leveraging NCAR’s Data Assimilation Research Testbed (DART), ACRESP researchers assess model output from the chemistry perspective – with a bias toward using satellite observations, says Edwards – and refine it so that it better replicates observed atmospheric characteristics and phenomena.

ACRESP Research Efforts
The team uses Measurements of Pollution in the Troposphere (MOPITT) data to identify paths of atmospheric pollution, which is a critical component of air quality analysis and forecasting. MOPITT, a long-lived instrument found on NASA’s TERRA satellite, monitors carbon monoxide pollution in the Earth’s lower atmosphere, and these measurements, when included in the chemistry versions of the Community Atmospheric Model (CAM-Chem) and Weather Research and Forecasting (WRF-Chem) model, assist with air quality forecasts, and can provide essential information to those interested in the trajectory of pollutants such as ground-level ozone or fine particles such as soot.

Gabriele Pfister, who is part of the ARCRESP group, is working with air quality agencies looking at local air quality. For example, agencies want to know the degree to which city residents in Los Angeles are impacted by pollution moving over the Pacific Ocean from Asia. Or, in another example, they want to understand how down-wind states might be affected by pollution plumes from California wildfires.

“MOPITT data assisted in answering these questions,” Edwards says.

ACRESP provides a key service to field campaign efforts targeted at developing better understanding of pollution transport by forecasting pollution-plume trajectories and resulting chemical weather. Using MOPITT data, the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4) and the Community Atmosphere Model (CAM-Chem),

Louisa Emmons and others from the team, assisted with flight planning for NASA's Arctic Research of the Composition of the Troposphere from Aircraft and Satellites aircraft experiment (ARCTAS). They predicted the track of chemical emissions and pollutants from forest fires in boreal Eurasia and North America. The focus of ARCTAS was to understand regional responses in the Arctic to global change including atmospheric composition; such responses range from melting of ice sheets and permafrost to decreased snow albedo and changes in halogen chemistry from sea salt aerosols deposited on the ice.

Another notable effort, involves an effort to run chemical weather instruments placed on commercial geostationary satellites, which Edwards leads.

“We are proposing to rent space on satellites owned by companies providing satellite television coverage – they’ve got room on the satellites, and see sharing the satellite both as a way of defraying cost and doing their bit for furthering scientific understanding,” says Edwards. “Along with HBO being beamed down into millions of living rooms, chemical weather observations that provide detailed information on regional pollution and atmospheric chemistry would be beamed down to research centers.”

For NCAR and its research partners, not having to build a platform on which to place the instruments or paying for satellite launch would save many millions of dollars and provide a valuable service to society.

“The key part of each of these ACRESP efforts is understanding how well our chemical forecasts measure against reality,” explains Edwards. “If they don’t match well, we try to understand why and identify ways in which to use models and measurements together so the forecasts more accurately reflect what really happened.”

For additional information see:

http://www.acd.ucar.edu/acresp/
http://www.acd.ucar.edu/mopitt/
http://www.acd.ucar.edu/gctm/

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Log in

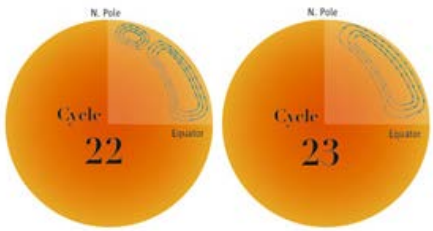
NCAR Annual Report 2011

- A Message from the Director
- Supporting Science’s Future
- NCAR Community Science In the Field
- Tools to Support Community Research
- Research Serving Society
  - NCAR’s New Leadership Line-up
  - Developing the Model for Prediction Across Scales
  - Exploring “Chemical Weather” Forecasting and Analysis
  - Sun’s Convection Zone Sheds New Light on Solar Cycle
  - Finding the Missing Energy in the Global Energy Budget
- Metrics

2009-2014 Strategic Plan »

Sun’s Convection Zone Sheds New Light on Solar Cycle

Human knowledge typically builds on first-hand understanding learned from our own experiences. Basics include consideration of the physical characteristics of an object or phenomenon. For instance, knowing the typical velocity or density of a thing, or having an idea of the timing for a particular event’s occurrence, can feed our understanding of both the entity being considered and similar objects, and may add to the existing body of scientific knowledge. When studying the Sun, this proves true; leaning on what we know and are learning about our own planet is critical for gaining understanding of the lesser known solar environment.

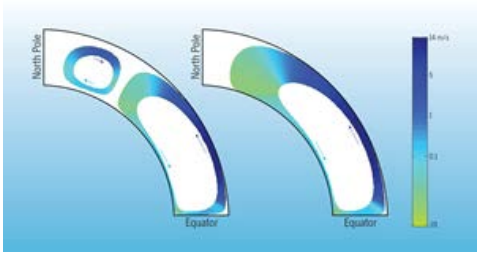


The meridional flow of solar plasma, from the sun's equator to its pole at the surface and then back to the equator at depth, carries magnetic flux in a circulation pattern analogous to a conveyor belt. Recent research has shown that in the last solar cycle (number 23), the meridional flow reached higher latitudes than in previous cycles—a phenomenon speculatively associated with the unexpected length of that cycle (12.5 years), which ended in 2009. Now, a flux-transport dynamo model by Dikpati et al. suggests that the combination of a long meridional flow, extending all the way to the pole, and a reduction in return flow speed may indeed have caused the unusually long duration of the last solar cycle and thereby delayed the onset of the current cycle. Long-term data from the Mount Wilson Observatory indicate that in previous cycles (such as number 22)—all with durations close to 10.5 years—the meridional flow only reached latitudes of 60° or 70°. The model predicts cycle durations consistent with those observed. Thus, it may be possible to determine the length of the solar cycle by measuring the latitudinal extent and speed of the meridional flow (Image courtesy of Mausumi Dikpati, edited, recolored and published in Science 329(5990):371).

With a limited number of instruments available to assist in studying our planet’s star, most aspects of solar cycle understanding have been deduced from observations obtained using satellites and telescopes located at Earth-based observatories, as well as from theoretical hypotheses that rely on modeling solar phenomenon using the basic laws of physics. One relatively well studied region of the Sun, the solar convective zone, occupies the outer 30% of the solar interior. This convective zone is critical to studying and understanding solar cycles as it is from this region that sunspots appear at the solar surface. The activity and characteristics of sunspots allow scientists to identify the beginnings and ends of solar cycles as well as gain insights into how the solar 'dynamo' – the physical process generating the Sun’s magnetic field – works. The Sun's convection zone operates in some ways like the Earth's oceans. The Sun’s magnetized plasma – hot, ionized gas – circulates throughout this convection zone. Plasma flows from the equator, poleward, in a fashion similar to the Earth’s global ocean circulation. Like the oceans, which transport heat toward the Earth’s poles, solar plasma acts as a conveyor belt, transporting magnetic flux poleward. At or near the poles, the plasma sinks and at depth flows back toward the equator. The latitude at which this sinking occurs turns out to be very important, according to findings from a recent study by NCAR’s Mausumi Dikpati, Peter Gilman, Giuliana de Toma, and UCLA’s Roger Ulrich. A modulation in this latitude, as well as a change in speed of the flow, postulated the research team, might explain why the recently ended Solar Cycle 23 had a longer phase than previous cycles.

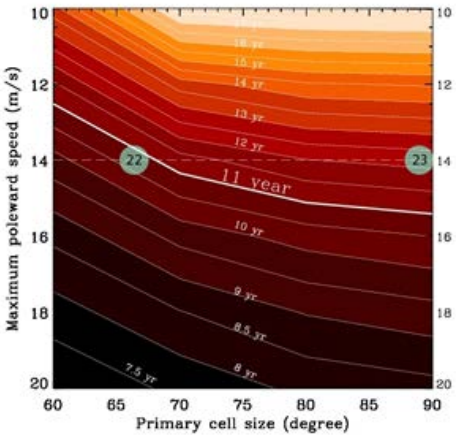
“Cycles 19, 20, 21 and 22 each lasted about 10.5 years,” says Dikpati. “Cycle 23 lasted notably longer – 12.6 years.”

Dikpati and the other researchers began by looking at solar observations obtained by Ulrich from Mount Wilson Observatory (MWO), an observatory affiliated with UCLA, to see if the speed of the meridional



An NCAR model of magnetic flux below the Sun's surface, developed by Mausumi Dikpati and colleagues, shows the extended reach of flux transport during the solar cycle that ended in 2008 (right), compared to the previous cycle (left). The larger loop is believed to be related to the extended duration of the cycle.

plasma flow within the Sun's convective zone changed between cycles 22 and 23. They also looked to see how close to the solar poles the poleward flow reached. MWO observations and data from the Global Oscillation Network Group (GONG), a six-station network of solar velocity imagers, and the SOlar Heliospheric Observatory (SOHO), a joint European Space Agency-NASA satellite, now provide observations that reach to 80-degrees latitude; historically such data were not considered reliable poleward of 50-60 degrees. For the Earth, this would be equivalent to terminating observations at Canada's most southern points, the northern-most regions of Mongolia or France, or the southern borders of Argentina. In other words, important areas of the solar orb were insufficiently observed.



A two dimensional map of dynamo cycle-period, obtained from the simulations of a flux-transport dynamo, as function of latitude-extent of primary meridional flow-cell and maximum poleward surface-flow speed. The thick, continuous white line denotes the contour of an 11-year-cycle period. Thin white lines denote contours of other periods in half-year intervals. The horizontal broken line marks the maximum surface-flow speed of 14-meters-per-sec. The positions of cycles 22 and 23 in this map are shown by semi-transparent gray patches

Geographically expanded observations became relatively easy to obtain with the launch of SOHO and establishment of the GONG stations. For MWO, improved instrumentation, resolution and calibration, and higher latitude-reach of data collected developed after 1985 greatly aided comparisons between Cycle 22 and 23, including, particularly, the meridional circulation of the plasma. MWO, GONG and SOHO data indicate that the peak rate of plasma flow toward the pole was unchanged from cycle 22 to cycle 23. In cycles 20 to 22, the poleward flow reached about 60 degrees. In cycle 23, however, it apparently reached all the way to the pole. Could this difference be responsible for the change in cycle duration for cycle 23 compared to cycle 22? To find an answer, the scientists dug deeper into the mystery, considering the lower two-thirds of the convective zone, which cannot be seen using observations alone. To enhance their understanding of unseen circulation, the scientists turned to a model – the Predictive Flux-transport Dynamo model – to approximate the dynamics of the system as a whole. This dynamo model simulates the evolution of magnetic fields in the outer third of the Sun's interior and provides a physical basis for projecting the nature of upcoming solar cycles from the properties of previous cycles, including changes in cycle period from one cycle to the next. Dikpati and collaborators showed that with the same peak flow speed at the surface, but with the greater latitudinal extent of the poleward flow, the return flow toward the equator at the bottom of the convection zone would be smaller. Incorporating this insight into the dynamo model revealed that cycle 23 would be about two years longer than the previous cycle, cycle 22, in agreement with the observations, says Dikpati. Having discovered a likely link between solar conveyor belt length and solar cycle length, Dikpati and colleagues are now turning to understanding the frequency of such occurrences. It is notable that in the early phases of cycle 24, the present cycle, the poleward meridional flow is again stopping around 60 degrees latitude, suggesting cycle 24 may return to a period of 10-11 years. But we must wait until the end of the current cycle to find out.

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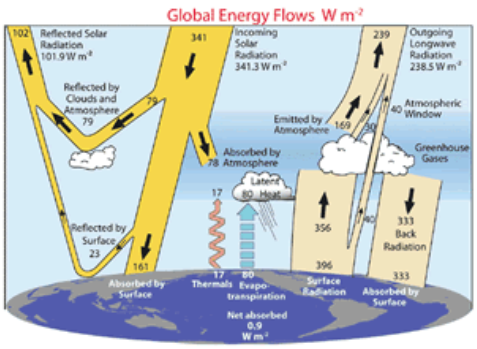
Log in

NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
- Tools to Support Community Research
- Research Serving Society
  - NCAR's New Leadership Line-up
  - Developing the Model for Prediction Across Scales
  - Exploring "Chemical Weather" Forecasting and Analysis
  - Sun's Convection Zone Sheds New Light on Solar Cycle
  - Finding the Missing Energy in the Global Energy Budget
- Metrics

2009-2014 Strategic Plan »

Finding the Missing Energy in the Global Energy Budget



The global annual mean Earth's energy budget for the March 2000 to May 2004 period in W m-2. The broad arrows indicate the schematic flow of energy in proportion to their importance. From Trenberth, K.E., J.T. Fasullo, and J. Kiehl, 2009: Earth's global energy budget. Bull. Amer. Meteor. Soc., 13 pages.

In an unchanging climate, the amount of energy coming into the Earth should match the amount of energy going out of the system. However in the real world with increasing greenhouse gases in the atmosphere, there is an energy imbalance and "global warming" that Kevin Trenberth, John Fasullo and Jeff Kiehl, researchers at the National Center for Atmospheric Research (NCAR) found was 0.9 Watts per square meter. Moreover, in a subsequent paper published in Science, Trenberth and Fasullo found that this value increased between 2007 and 2009 in association with a La Niña event. El Niño Southern Oscillation (ENSO) events occur regularly, exhibiting notable climate conditions that can be easily tracked. But during this period, tracking where the energy had gone by carrying out an inventory indicated a substantial shortfall, or "missing energy."

"During La Niña events, the cooler ocean water in the equatorial Pacific and cooler atmospheric temperatures mean less radiation lost to space, and the fewer clouds mean more solar radiation absorbed," explains Trenberth. "So despite extra heat coming into the system as part of the natural energy balance, environmental conditions are colder. It is this heat, sequestered in the ocean, which then often leads to El Niño events, in which the surface equatorial waters and atmospheric temperatures warm."

Trenberth and Fasullo built on global energy balance work done earlier. With improvements in both top-of-the atmosphere satellite instrumentation, as well as ocean instruments that collect temperature, pressure, salinity and other critical data, the scientists wanted to use the improved observations and reassess the earlier radiative energy budget calculations; the enhanced observations led to identification of the missing radiative energy of order 1 Watt per square meter (W/m2) from 2008 through 2009.

Because of the importance of the question as it relates to climate change and attribution of areas of concern and need for more study, Trenberth and Fasullo presented their results ahead of paper publication in meetings with their peers. Spurred on by the mystery, response from oceanographers looking at ocean heat content and atmospheric scientists looking at radiation measurements in pursuit of an answer to the location of the missing energy reduced the amount missing by about 50 percent, Trenberth says.

Scientists suggested that some of the energy might be found in the ocean, which is an enormous repository for the world's energy. The oceans have long accounted for about 90 percent of the energy added to the climate system, storing some of this energy in its deepest waters. Some of the energy, says Trenberth, also likely went toward melting of sea ice and glaciers, however the energy requirements for this would be minimal as compared to the missing 1 Watt/m2.

Trenberth and Fasullo's work has also suggested that there may be other trouble spots in knowing the global energy balance at the surface of the earth. New estimates of downwelling radiation from the greenhouse effect by the NASA Langley group are much larger than Trenberth, Fasullo and Kiehl suggested but if correct would imply that the global precipitation estimates are too low by 20 percent. Because the same calculations are performed in climate models, the possibility exists that there is an incorrect energy accounting by global climate models.

"It might be that the climate models are wrong," says Trenberth. "The models may be overestimating radiative energy

transfers within the atmosphere most likely associated with the properties and distribution of clouds and aerosols - however, the Langley group used the latest CloudSat data. Nevertheless, the complex three-dimensional shape of clouds are approximated in models, which appreciably affect the amount of energy scattered and absorbed, and thus the long-wave energy re-radiated back to the surface."

Trenberth concludes saying that more and better observations will be required to validate climate model output. In addition to assisting in generating more realistic distributions and properties of clouds and aerosols, using observations to validate climate models will enhance understanding of effects of aerosols and clouds, as well as providing better estimates of energy transfer into and away from Earth. This is a vital task if we are to confidently predict future climate change.

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NCAR Annual Report 2011

- A Message from the Director
- Supporting Science's Future
- NCAR Community Science In the Field
- Tools to Support Community Research
- Research Serving Society
- Metrics

2009-2014 Strategic Plan »

Metrics

The metrics featured below offer qualitative and quantitative measurements and assessments of the productivity, quality, and impacts that NCAR programs and activitieshave on our research community, our sponsors, and society in general.

Field Programs

Collecting field data is a scientist's stock in trade. Direct observations shed insights on weather, climate, and related Earth-system phenomena. Ranging from a few weeks to several months, field programs (field-based observing campaigns or experiments) ensure successful data collection.

NCAR led or participated in 37 field campaigns in 10 countries and the United States. Locales ranged from the Atlantic Basin in the heart of hurricane season to Antarctica, and included more than 1,772 participants.

Editorships

NCAR staff also serve as publication editors. These positions recognize the appointee's leadership in the field and serve a critical role in developing a given field's future focus.

Forty-one NCAR staff served in 56 different editorial roles on 46 different publications or journals. Publications included top-tier journals such as the *Bulletin of the American Meteorological Society* and *Weather, Climate, and Society*.

External Committee Service

NCAR staff are called upon to participate in and often lead external scientific, technical, policy, and educational committees. These committees are instrumental in advancing and promoting the work of the scientific and technical community.

This year, 144 NCAR staff served in a multitude of roles on 412 external committees for national and international scientific, education, and governmental organizations, including entities such as the Governor's Office of Information Technology, the U.S. Decadal Strategy for Solar and Space Physics, and the World Climate Research Programme. Positions ranged from Co-organizer to Panel Member. More than 65% served on more than one committee.

Presentations

NCAR Staff give presentations about data, models, theories, hypotheses, reviews, and results around the world to audiences ranging from scientists and engineers to the general public.

More than 86,000 people were in the audience when 291 NCAR staff made more than 1,300 presentations across the country and around world, from Granada, Spain to Taipei, Taiwan. Examples range from Alan Burn's (HAO) presentation on "Composition Changes in the Lower Thermosphere" in San Francisco, California to Melissa Bukovsky's (CISL/IMAGe) presentation on "Uncertainties of Climate Change" in Copenhagen, Denmark.

Posters

NCAR Staff present posters about their research at conferences and workshops

More than 83,000 people were in the audience when 88 NCAR staff made more than 120 presentations across the country and around world, from Squaw Valley, California to Toulouse, France. Examples range from Laura Landrum's (NESL/CGD) poster on "Last Millennium Experiment: NCAR's CESM1 and Preliminary Results" at the Paleoclimate Modelling Intercomparison Project Phase III Conference in Kyoto Japan to Jared Lee's (RAL) poster on "Down-selection of NWP Ensemble Configurations" at the American Meteorological Society meeting in Seattle, Washington.

Colloquia & Symposia

Smaller, often unilateral events, colloquia, symposia, and tutorials focus primarily on education or training. This metric measures entire events that NCAR hosted alone, or co-hosted with other institutions or agencies.

NCAR sponsored 42 colloquia, symposia, and tutorials in Boulder and abroad. Participants per session averaged out to more than 37, for a total audience of more than 1,500 peers and students. Some of the co-hosts include the World Climate Research Program, Air Force Weather Agency, and the Army Test and Evaluation Command.

Workshops and Conferences

NCAR-hosted or -co-hosted workshops and conferences are generally larger, bilateral events convened for the purpose of discussion, consultation and exchange of views and information.

NCAR sponsored 72 workshops and conferences in nine countries and eight U.S. states. We partnered with sponsors from the university community, such as Stanford University, Seoul National University, and the University of Wyoming, and with government agencies including the Department of Energy, FAA, and the Environmental Protection Agency, as well as with non-profit partners like the University Consortium for Geographic Information Science and the American Statistical Association. In total, these workshops and conferences reached just over 3,700 participants around the world.

Teaching Appointments

NCAR staff make important contributions through teaching appointments at institutions of higher education in positions ranging from Faculty Affiliate to Professor.

Teaching appointments at institutions of higher education currently number 37. Thirteen percent of these appointments occur in five countries around the world; 87% took place in eight U.S. states, including the University of North Dakota. The longest term is 35 years and counting and the current cumulative commitment adds up to more than 202 years of service.

Graduate Advisors

NCAR staff serve as research advisors for graduate students around the world.

Of the 85 graduate students that have NCAR staff serving as graduate advisors, 27% hail from Colorado institutions; 47% attend schools in 19 other states. The remaining 26% study at schools in 13 countries around the world, including five students from the University of Eastern Finland who are advised by James Smith.

Thesis committees

NCAR staff serve as dissertation or thesis committee members for internal and external graduate students.

Eight Masters students and 83 PhD candidates work with 59 NCAR staff as they pursue their degrees from universities in 23 U.S. states; this includes 34 students from Colorado institutions. Fourteen students come from nine countries, with Austrian students leading the international count at three.

NCAR Student Appointments

Students also enjoy NCAR-based appointments.

In FY11, there were 28 Graduate Student, 12 Graduate Research Assistant and 26 undergraduate Student Assistant appointments. There were also 18 student internships coordinated through the **Summer Internships in Parallel Computational Science (SIParCS) program**, and the **EOL Undergraduate Engineering Internship program**. These students hail from home institutions ranging from Metropolitan State College of Denver to Cornell University. NCAR also awards postdoctoral fellowships to talented staff through the **Advanced Study Program** and **other laboratory visitor programs**.

Special Appointments

NCAR Affiliate Scientists: Select university and research-community scientists are invited to carry out long-term, highly interactive, collaborative work with UCAR scientists and are appointed as Affiliate Scientists with three-year terms. This appointment is particularly suitable for parties who desire an extended, close-working relationship on scientific problems of mutual interest. Currently, 33 hold appointments including Dr. Ruby L. Leung of Pacific Northwest National Labs. She is collaborating with NCAR scientists on an effort to develop a next-generation regional climate model based on the Weather Research and Forecasting (WRF) model for upscaling and downscaling; Dr. Leung collaborates with CGD and MMM in NCAR Earth Systems Laboratory.

Emeritus/Emerita: Scientific and Research Engineering staff who have made significant contributions to NCAR through long and distinguished service in senior positions in research may be granted emeritus or emerita status. This designation confers a life-long honorary distinction. Approval of the President and the Board of Trustees is required. Currently the ranks of Emeritus/Emerita number 15 with the recent appointment of eminent NESL/MMM scientist Don Lenschow who is continuing his research on both the clear and cloud-capped planetary boundary layer.

K-12 Outreach

Staff across NCAR work directly with classes and groups of K-12 students by developing or delivering lectures, conducting tours, and leading or participating in field trips and other educational activities.

Forty NCAR Staff worked with K-12 students from 45 schools. Activities included mentoring, lectures, tours and field trips reaching 17 different communities. Examples range from supporting Wild Earth Saturday, to speaking at the Expanding Your Horizons workshop, to participating in annual Girl Scouts and NCAR activities.

Among the highlights: Astrid Maute (HAO) served as a roaming judge at a Regional Science Fair at the University of Colorado; David Schneider (EOL) provided a presentation to as well as individualized guidance for high school teachers participating in the RETI (Research Experience for Teachers Institute) program; and Doug Nychka (CISL/IMAGe) gave a presentation to a visiting math camp from the Denver Montclaire International School.

Awards

Each year a number of NCAR Staff are honored for their work and contributions to the Atmospheric and related sciences.

Nineteen staff received special recognition for their work in FY11. Joan Kleypas (NESL/CGD) received the Heinz Award in the Environment. This award honors individuals who have confronted environmental concerns with a spirit of innovation and who demonstrate action and creativity in approaching the protection of our environment.

Hugh Morrison (NESL/MMM) was awarded the American Meteorological Society (AMS) Carl-Gustaf Rossby Research Medal. This medal is the highest award for atmospheric science of the AMS. It is presented to individual scientists, who receive a medal.

Maura Hagan (NCARDIR) was elected as an American Geophysical Union (AGU) Fellow. To be elected a Fellow of AGU is a special tribute for those who have made exceptional scientific contributions. Nominated Fellows must have attained acknowledged eminence in the Earth and space sciences. Primary criteria for evaluation in scientific eminence are major breakthrough/discovery and paradigm shift.

Fellowships

A fellowship is typically a special appointment granting support for a term in order to support advanced research or study.

Five NCAR staff received fellowships in 2011. Paul Winkler was awarded an Erwin-Schroedinger Fellowship which is for young and especially highly qualified scientists. The goal of the fellowship is facilitation of access to new scientific areas, methods, procedures, and techniques. His project will employ mass spectrometric techniques to analyze the chemical composition of nanoparticles as small as 10 nm, providing direct insights into the mechanisms and species that control the initial stages of nanoparticle growth.

Scientific and Technical Visitor Appointments

Each year students, scientists, engineers, weather forecasters, and other professionals from around the country and world receive special visitor appointments from labs and programs across NCAR to collaborate with scientific, educational, or technical staff; conduct independent research; or participate in and/or oversee a professional project. Many receive financial support for their visits and some visitors temporarily join the NCAR staff.

This year, NCAR's 768 Visitors hailed from 324 institutions, located in 42 different U.S. states and 40 different countries.

Visit Length - Number of Scientific and Technical Visitors in FY11

1 day to 1 week – 189
8 days to 2 weeks -78
2 weeks to 2 months – 173
>2 months to 6 months – 162
> 6 months to 1 year+ - 166
Total 768

Scientific and Technical Visitor Types - Headcount in FY11

Visitors on Payroll - 59
NCAR-funded Visitors - 303
Externally funded Visitors - 406
Total 768

Publications in the UCAR Open Sky Institutional Repository

NCAR's publication records are curated in the **UCAR Open Sky Institutional Repository**. OpenSky is the open access institutional repository supporting UCAR, NCAR, and UCP, extending free and open access to our scholarship for the benefit of research and education.

OpenSky is operated by the NCAR Library, with the goal of providing free and open access to the scholarship of UCAR, NCAR, and UCP. Founded on the principle that public access to the scholarly record is essential to the advancement of science and society, the vision of OpenSky is to support the broad mission of UCAR to foster science, support its community, and facilitate the transfer of knowledge.

In support of this vision, OpenSky will provide long-term storage, preservation, access to scholarly works and the products of scientific research created by UCAR, NCAR, and UCP authors.

A publication is an academic or technical work of writing containing original research results, reviews of existing results, or scholarship. "Refereed" publications undergo an editorial "blind" or anonymous process of peer review by one or more referees (who are experts in the same field) in order to check that the content of the paper is suitable for publication in the journal. A paper may undergo a series of reviews, edits and re-submissions before finally being accepted or rejected for publication. "Non-refereed" articles have been reviewed by editors or boards before being accepted for publication but have not gone through a formal blind review. Attached are **NCAR's refereed lists for the period October 1, 2010 to September 30, 2011**. Search for recent NCAR publications by author, date, keyword or status please go to the **NCAR Publications database**.

For excellent library resources please go the **NCAR Library Web site**.

623 Total Publications (**download PDF bibliography**)

Refereed: 623
UCAR and Other: 99
UCAR and University: 176
UCAR only: 74
UCAR, University and Other: 274

UCAR Outstanding Publication award for FY11:

Tom Warner (RAL) posthumously received the FY11 UCAR Outstanding Publication Award for his book “Numerical Weather and Climate Prediction.” The book provides an exceptionally well-written account of the practical and cutting-edge aspects of numerical predictions, with a particular emphasis on understanding model processes, as well as their limitations and how errors affect solutions. It includes clear descriptions of best practices, predictability, operational forecasting, and a wide range of special applications of numerical models not found in previous textbooks. This volume is a comprehensive reflection of the author’s far-reaching experience gained through 30 years of teaching courses on numerical weather and climate prediction as well as mentoring a long line of graduate students and young professionals. Each chapter includes useful exercises and suggests further reading material. This textbook has already reached Cambridge University Press’s top 10 bestselling titles in atmospheric science and meteorology, despite its very recent publication.

For a full list of each metrics topic, contact Helen Moshak, **moshak@ucar.edu**.

Attachment	Size
FY11OpenSkyRefPubs.pdf	317.71 KB

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Advanced Study Program | ASP
2011 Annual Report

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

ASP Director's Message

The Advanced Study Program (ASP) helps NCAR and the scientific communities that it serves to prepare for the future by engaging in human, institutional and broad intellectual capacity building. ASP entrains a broad community of scholars, encourages the exchange of information and the development of new perspectives, and provides unique hands-on educational experiences and many opportunities for students, advisors, and early career scientists to collaborate with a wide variety of NCAR scientists and engineers engaged in research, modeling, and observational activities.

The two-year ASP Postdoctoral Fellowships encourage the development of early career scientists in the field of atmospheric and related sciences and direct attention to timely cutting-edge scientific areas. Approximately 10 new appointments are made annually for positions across NCAR. Fellows' research advances are reported separately in the NCAR Laboratory Annual Reports.

Through its remaining components, the Graduate Visitor Program (GVP) and Faculty Fellowship Program (FFP), ASP promotes research activities, fosters graduate education, and develops partnerships between NCAR scientists and their colleagues in universities and other institutions.

Accomplishments

The ASP awarded 11 new postdoctoral fellowships in spring 2011. These new fellows have already begun to arrive and to participate in ASP activities, providing a boost to the ongoing program. Between the FFP and the GVP, the ASP supported 140 months of long-term visits to NCAR in FY10. Four faculty members came to NCAR as part of the 2011 Faculty Fellowship Program while 25 GVP awards were given as a result of the 2010 GVP search. Most of the GVP awards also include an advisor visit.

The ASP continued its ongoing efforts to better serve diverse communities in FY2011 through the continuation of the collaboration with North Carolina Agricultural and Technical University.

More on all of these programs can be found in this report.

FY2012 Plans

ASP will continue to engage and develop the scientific workforce of the future through its core visitor and fellowship program elements that engage all graduate students and postdoctoral fellows in residence at NCAR, including monthly seminars, monthly informational socials, the annual ASP retreat and ongoing mentoring opportunities. Through the highly successful Thompson Lecture Series, ASP will bring two prominent scientists to NCAR for extended interactions with this cohort. Shadia Habbal, a professor at the University of Hawaii, will be visiting November.

The annual ASP Colloquium series will focus on the topic of Subseasonal Variability and its Impact at the Weather-Climate Intersection. As in 2011, the colloquium will expand to three weeks from two to accommodate a revival of an NCAR tradition: the ASP Research Colloquium. The new format will include a one-week colloquium geared toward researchers engaged in the colloquium topic. Students will stay for three weeks to participate in lectures and hands-on activities.

ASP will support the NCAR Software Engineering Assembly's first ever conference and also provide organizational support for the Technology Innovation Forum and the activities of the Early Career Scientists Assembly (ECSA).

ASP will continue to promote diversity in the atmospheric sciences by supporting travel of NCAR scientists to give seminars at historically black colleges and universities (HBCUs), supporting teaching opportunities of NCAR postdocs at HBCUs and encouraging participation in ASP programs of individuals from underrepresented groups. ASP's Jia Yue will teach for a semester at Hampton University, an HBCU in Virginia.

Additional details along with other ASP plans are included in this report.

ASP Postdoctoral Fellows, Graduate Visitor Program visitors, and Faculty Fellowship Program visitors, June 2011.

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Log in

Advanced Study Program | ASP
2011 Annual Report

sponsored by

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

ASP Postdoctoral Fellowships

ASP serves as a catalyst for burgeoning research that spans NCAR activities. The most important ASP component is the Postdoctoral Fellowship Program, which has been a part of NCAR for forty-five years and has sponsored over 450 postdoctoral scientists' research. The ASP appoints approximately 10 new postdoctoral scientists each year. During their two-year NCAR appointments, fellows benefit from the opportunity to work with NCAR scientists, from exposure to the breadth of science at NCAR, and from the independence they are encouraged to develop. Many former fellows now occupy prominent positions at UCAR universities or at NCAR, and many of the present collaborations between NCAR and university scientists derive from associations that developed in the postdoctoral program.

In FY11, the ASP appointed 11 new fellows (from over 110 applications) in a diversity of disciplines spanning the NCAR activities. In addition to the diversity of disciplines, the new fellows represent a diversity of population including gender and ethnicity. Also in FY2011, the ASP regular "socials" and other activities that often included an education or career development aspect. These activities not only brought members of ASP together, but also included any postdoctoral fellow or graduate student within the organization who wished to attend. The ASP aims to create a meaningful experience not only for ASP fellows, but for all fellows at NCAR. As part of this plan, NCAR/ASP is a sustaining member of the National Postdoctoral Association and we celebrated National Postdoc Day with a family picnic.

In FY2012, ASP plans to continue the core elements of the program, including monthly seminars, bi-weekly research reviews, regular socials, and the Thompson Lecture Series along with the annual research planning sessions and on-going mentoring that ASP postdocs receive.

ASP Postdoctoral Fellows with Thompson Lecture Series guest lecturer, Bjorn Stevens, Max Planck Institute for Meteorology.

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Log in

Advanced Study Program | ASP
2011 Annual Report

sponsored by

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

Building Partnerships with University Faculty

The ASP established the Faculty Fellowship (FFP) program in 2005 with the goal of funding medium-to long-term collaborative visits between the NCAR scientific staff and the university community. The program provides opportunities for university faculty to spend three to 12 months at NCAR, and for NCAR scientific staff to spend three to 12 months at a U.S. university. University faculty may also bring graduate students with them to NCAR. The FFP provides support for travel costs, temporary living per diem, and graduate student expenses.

In FY11, applicants submitted proposals and budgets for 3- to 12-month visits that occurred between 1 June 2011 and 31 May 2013. ASP received five viable applications. All five applicants were extended offers for visits that either occurred in FY11 or will take place in FY12. All five of those faculty visitors will bring at least one graduate student with them for a total of a total of six graduate students.

The program gives university faculty an opportunity to take advantage of their National Center in a meaningful and productive way, while providing unique research opportunities for the accompanying graduate students.

Faculty Fellowship Program visitors Danielle Draper and Juliane Fry from Reed College at the Bio-hydro-atmosphere interactions of Energy, Aerosols, Carbon, H2O, Organics & Nitrogen (BEACHON) field campaign site, August 2011.

From some 2011 participants:

Aside from the inspiring setting in the flatirons, NCAR provided us with an invaluable opportunity to meet with other

scientists and get a feel for what a truly collaborative and engaging atmosphere NCAR fosters. We met many other scientists (such as Peter Gent and Veronika Eyring) during lunches and other casual encounters in the lab, and we also made a few longer lasting relationships with people such as Simone Tilmes and Mike Barlage, both of whom were very generous in spending extensive time with us in discussing project ideas...Overall, we both feel that this visit to NCAR will play a pivotal role for us in our graduate careers. Interacting on a daily basis with such a diverse and helpful crowd of people boosted our spirits every day and made us excited to come into work the next morning.

Mira Losic and Lili Xia

(Rutgers University, NJ)

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Log in

Advanced Study Program | ASP
2011 Annual Report

sponsored by

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

Providing University Students Access to the Resources of NCAR

The Advanced Study Program provides university graduate students and their advisors with access to NCAR resources through the Graduate Visitor Program (GVP). The program, now in its sixth year, was created in response to multiple requests from NCAR scientific staff for graduate student support. It was also developed in response to university community requests for access to NCAR resources and facilities that are not available at a university. ASP recognized the need to establish a program that would sponsor a significant number of meaningful visits and collaborations with graduate students and their advisors. The GVP responds to that need.

The Graduate Visitor Program provides NCAR scientific staff with opportunities to bring graduate students to NCAR for three- to 12-month collaborative visits. These visits are undertaken with the endorsement and complementary support of the graduate students' thesis advisors. While residing at NCAR, the students conduct research in pursuit of their thesis requirements. The students receive support to cover their travel and living expenses in Boulder. Funding is also provided to allow the students' advisors to visit NCAR for a period of up to two weeks. The students' home institutions continue to pay the students' salary, benefit, and tuition expenses while they are in residence at NCAR.

As a result of the 2011 GVP search, 25 GVP awards were given to students and most of those included a visit by the student's advisor.

The Graduate Visitor Program is becoming more popular every year. The ASP recognizes that students and their advisors are the bridge builders between NCAR and the university community. The ASP contends that the Graduate Visitor Program will seed significant and long-term collaborations. This program helps to extend NCAR capabilities by bringing students on-site to work on research of mutual interest and by providing NCAR scientific staff with the opportunities to participate in graduate student research and education. Through this program, NCAR increases its contribution to the education of the next generation of scientists, researchers, and faculty. In turn, the graduate students help invigorate NCAR and their home institutions. Finally, the Graduate Visitor Program provides opportunities to partner with universities and engage Ph.D. students from underrepresented groups in NCAR research activities. The ASP anticipates that the program will help diversify the future workforce at NCAR and in the geosciences professoriate and research communities.

Here's what the students have to say about the program:

If someone asks me about how is to be part of the ASP-Graduate Visitor Program my answer will be: GREAT! For:

Gathering new knowledge with the crème de la crème in atmospheric sciences,

Reinventing yourself with new ideas,

Experiencing the world through the international people,

Advancing to a new level in our career as young professionals and the perfect

Training to become a good scientist.

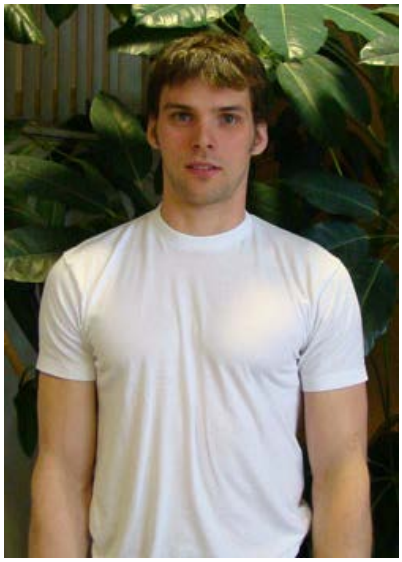
In other words, NCAR is the Disney Land for young researchers in this field. It is the perfect school to jump to the real world, and it is definitely the place to be. The GVP gives you not only the necessary tools to improve in your academic level, but it also helps you to understand the importance of making interdisciplinary and collaborative work, and to explore new cultures and ideas that speak the same language of science.
-Yaítza Luna-Cruz,Howard University

The graduate visitor program is an extraordinary opportunity for graduate students to work with NCAR scientists on projects mutually beneficial to both parties. For myself, this has involved accelerating my Ph. D. research dealing with assimilation of radar data for the prediction of convective storms. The interactions with my mentors and other NCAR scientists will surely extend beyond the dates of my visit when I return to my home institution, providing me with an invaluable set of resources and collaborators as I continue through my career.
-Ryan Sobash, University of Oklahoma

Visiting NCAR through the ASP Graduate Visitor Program has been invaluable to both my research and career. My favorite part of the program has to be that I have been able to meet and discuss science with so many who share an infinite curiosity about atmospheric sciences and whose doors are always open for any questions I might have. The connections I have made and conversations I have had will last with me throughout my career. I suggest applying for this program to any graduate student interested in expanding the breadth and depth of their research.
-Catrin Mills, University of Illilnois at Urbana Champaign

The thing I like most about GVP is that it gives an opportunity to meet and work with influential leaders in my field, which will benefit my career a lot.
-Yanshi Huang, University of Texas, Arlington

I have had the unique experience of seeing first-hand what goes on at a climate modeling center. The view into the model development process has given me a greater appreciation for the efforts undertaken at places at NCAR and has made me a much more informed scientist and will no doubt influence my future research directions and efforts.
-Benjamin Hillman, University of Washington



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Log in

Advanced Study Program | ASP
2011 Annual Report

sponsored by

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

ASP Summer Colloquium

For several decades, the ASP has hosted at least one 2-week colloquium every summer on an emerging science topic of interest to the NCAR community. The colloquia are designed for graduate students in new or rapidly developing areas of research for which good course materials may not yet be available. In recent years, the colloquia have had both a lecture component and a hands-on tutorial component. NCAR Scientific staff members in partnership with one or more university collaborators write proposals for colloquia topics, and in the event that their proposal is selected, organize the colloquium curriculum with logistical support provided by the ASP.

In FY11, the summer colloquium was expanded to three weeks. This expansion served two purposes: 1.) it allowed the students more time to work on hands-on projects, and 2.) it allowed for the addition of a Research Colloquium (RC) on the same topic during the middle week. The RC is the realization of the Faculty-Scientist Colloquium that was proposed in the Program Plan. This year's colloquium was entitled Statistical Assessment of Extreme Weather Phenomena under Climate Change and was attended by 100 participants over the three weeks including students, lecturers, and researchers.

This year's organizers included Eric Gilleland, Greg Holland, Rick Katz (NCAR), Arun Kumar (NOAA), Mike Patterson (US CLIVAR), Balaji Rajagopalan (CU Boulder). The US CLIVAR program provided generous support for many participants of the Research Colloquium.

The objective of the colloquium was to provide training in use of extreme value analysis to assess how frequency, duration, and intensity of extreme weather events could shift as part of global climate change.

The colloquium included tutorials, lectures by guest speakers, and group research projects. According to the organizers, the event was attended by top graduate students. The group projects, consisting of multidisciplinary teams, were also quite successful and in some cases, conference presentations and/or journal articles are planned as follow-ups.

In FY2011, the book that resulted from the 2008 ASP Summer Colloquium was published:

Lauritzen, P.H., Jablonowski, C., Tauylor, M.A., and Nair, R.D. Editors2011: *Numerical Techniques for Global Atmospheric Models*. Springer-Verlag, 556 pp.

2011 ASP Summer Colloquium Students

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Log in

Advanced Study Program | ASP
2011 Annual Report

sponsored by

ASP Annual Report 2011

ASP Director's Message
Table of Contents
ASP Postdoctoral Fellowships
Building Partnerships with University Faculty
Providing University Students Access to the Resources of NCAR
ASP Summer Colloquium
Profiles in Science
Sebastien Blaise
Jasper Kok
Matthew Long
Marielle Saunois
Julie Theriault
Hui Tian
Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

Profiles in Science

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Log in

Advanced Study Program | ASP
2011 Annual Report

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
  - Sebastien Blaise
  - Jasper Kok
  - Matthew Long
  - Marielle Saunois
  - Julie Theriault
  - Hui Tian
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

Sebastien Blaise

Geophysical simulations with dynamic adaptivity

My work as an ASP postdoc is to participate to the development of a new generation of models for the simulation of oceanic and atmospheric flows. The goal is to develop a set of numerical techniques and demonstrate their potential for solving multiscale geophysical flows in an efficient manner.

I currently focus on the Shallow Water Equations that are discretized using the Discontinuous Galerkin method. This method takes advantage of the potential of unstructured meshes to increase the resolution exactly when and where it is needed, giving rise to multi-scale/physics numerical simulations. With this approach, a wider range of space- and time-scales of motion can be represented without having recourse to the brute-force approach consisting in enhancing the resolution homogeneously.

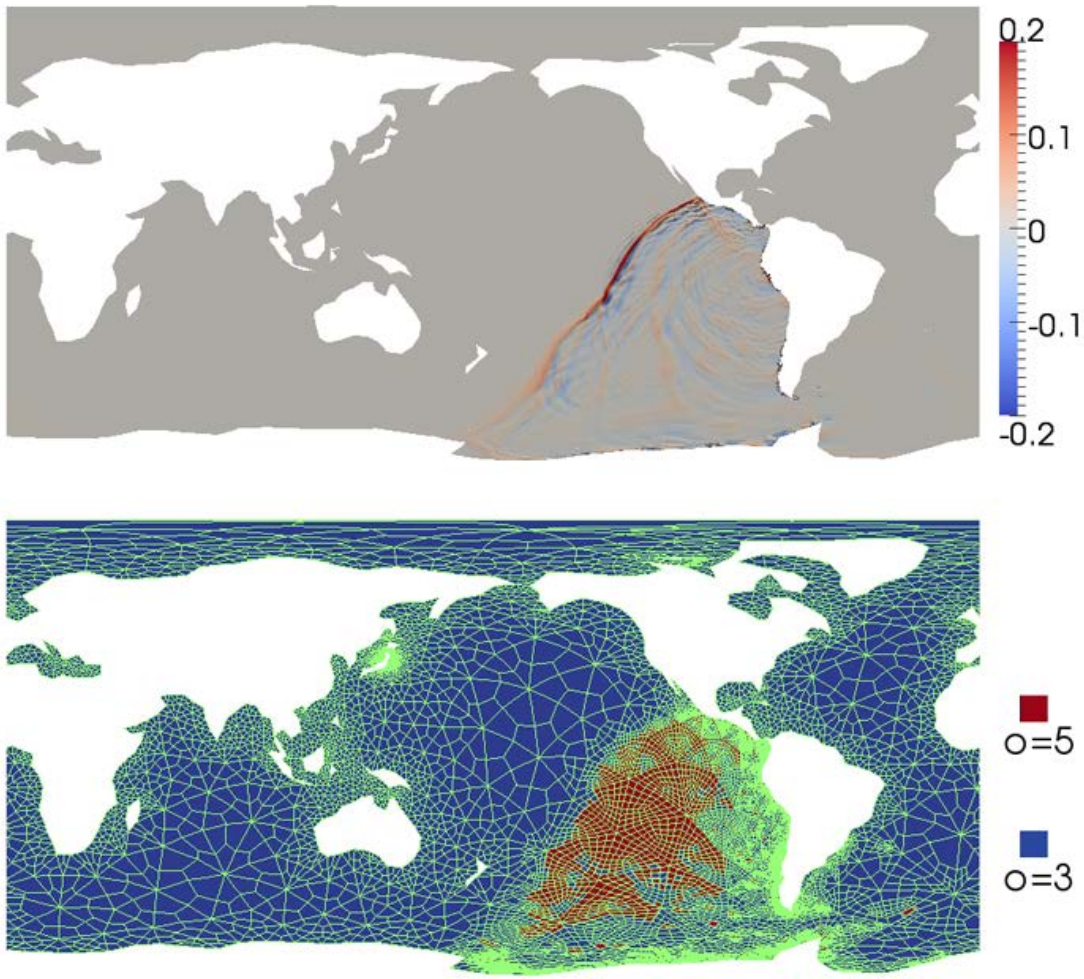
The other key aspect of the model is dynamic adaptation: the mesh and the order of interpolation are adapted dynamically during runtime to minimize the discretization error and capture the key aspects of the flows. The mesh is refined using the Adaptive Mesh Refinement (AMR) technique: it is modified by splitting elements recursively into finer sub-meshes, until the desired level of refinement is reached. A local conservative projection of the data is performed when the order of interpolation changes or when the mesh is adapted to transfer the solution form the old representation to the new adapted representation.

In order to take advantage of parallel computing, the mesh is partitioned into sub-domains attributed to each processors. The high level of locality of the method (few communications between elements lying on different processors) makes it very efficient on large parallel computers. Load balancing is performed to equilibrate the work of each processor that can be modified by adaptation steps.

Application to a global tsunami

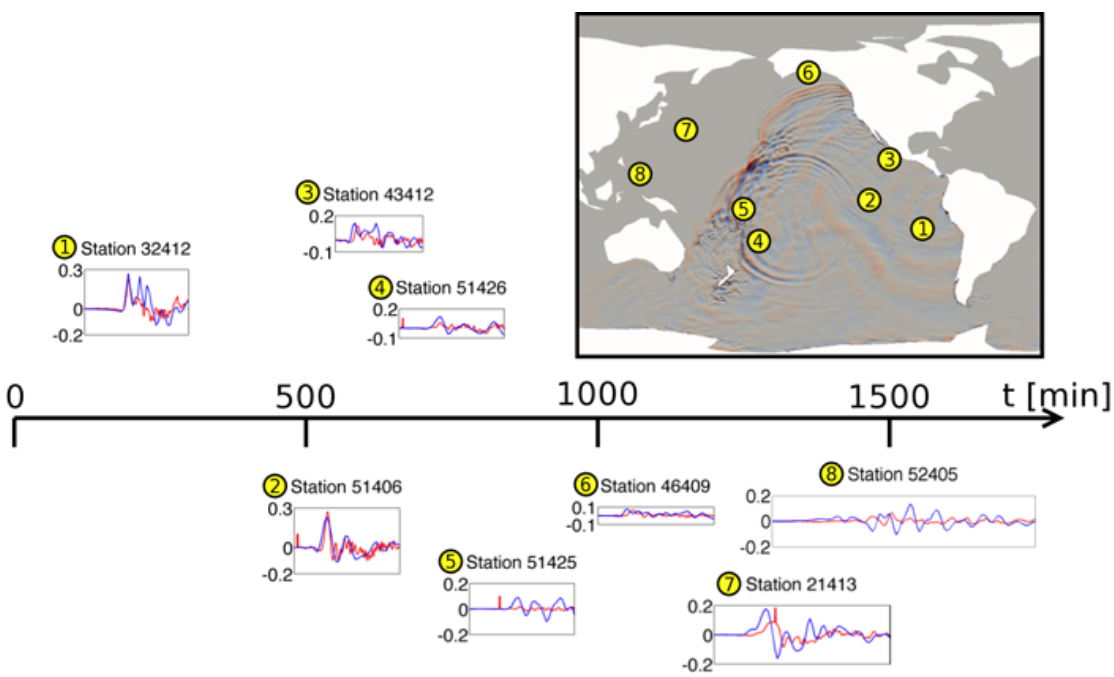
The model has been applied to compute the propagation of the 2010 Chilean tsunami through the global ocean. The bottom topography of the sea is very steep, and the water depth can vary from 9000 m to 0 m in a single element. This application is then a good testcase to check the stability of the model when applied to tough realistic configurations.

As long as the tsunami propagates through the Pacific Ocean, the order of interpolation and the mesh are adapted to track the wave. The computational power is used effectively by concentrating the load where it is needed (front of the wave). The resolution remains however high in the shallow areas along the earthquake initial uplift, where the propagation of the wave is slow due to the very low depth.



Propagation of the wave. UP: Free-surface elevation [m]. DOWN: State of the mesh with order of interpolation.

The elevation of the free-surface has been compared with the DART data from the NOAA Center for Tsunami Research at eight different stations. It is seen that the model estimates accurately the time at which the tsunami reaches the different stations. The amplitude of the waves is also well predicted, except for the stations 5 and 8. Those stations being located in very shallow areas with an irregular an bathymetry and several small islands, the resolution of the model is probably not sufficient to reproduce accurately the height of the waves.



Free-surface elevation: model data (blue) and DART data (red). The different plot boxes are aligned with the timeline to indicate the time at which the tsunami reaches the different stations (t=0 at the moment of the initial earthquake).

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Log in

Advanced Study Program | ASP
2011 Annual Report

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
  - Sebastien Blaise
  - Jasper Kok
  - Matthew Long
  - Marielle Saunois
  - Julie Theriault
  - Hui Tian
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

Jasper Kok

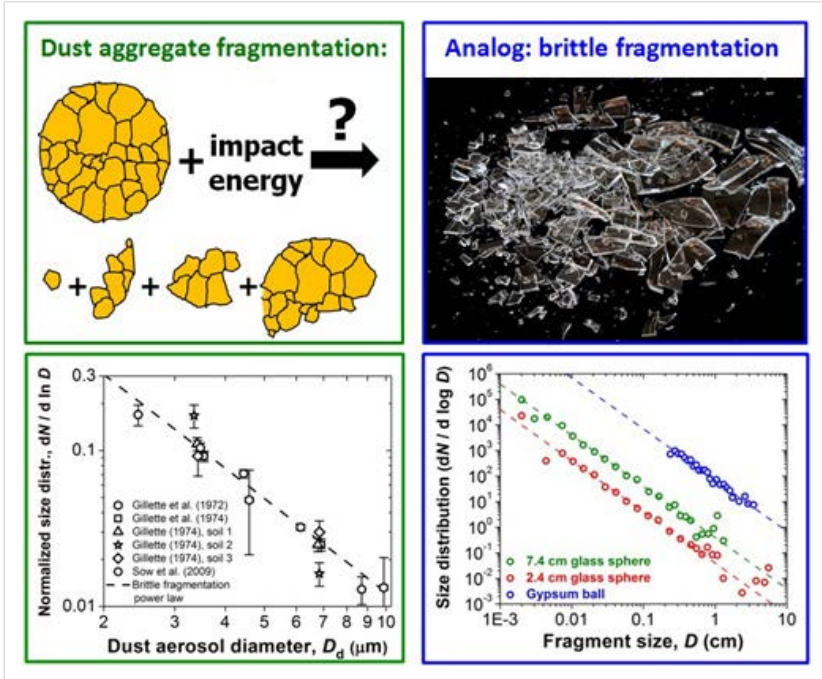
Researching broken glass for clues to the climate forcing of mineral dust aerosols

Particles suspended in the atmosphere, such as soot and desert dust, affect the Earth's energy balance by scattering and absorbing both solar (shortwave) and terrestrial (longwave) radiation. In addition, these particles, called 'aerosols,' affect cloud properties such as reflectivity and lifetime by seeding clouds. The total effect of aerosols on climate is one of the largest uncertainties in attributing past and forecasting future climate changes.

One of the most abundant types of aerosol is the "mineral dust" aerosol. These dust aerosols are emitted from desert soils through a process called "saltation," in which sand-sized particles (~ 200 µm diameter) are picked up by wind and bounce along the ground. The impact of these sand particles on the soil ejects the much smaller dust aerosols by fragmenting aggregates of dust particles in soils. Although the processes leading to dust emission are thus qualitatively understood, a detailed quantitative understanding of dust emission is still missing. As a consequence, the fraction of emitted dust aerosols in the clay size range (< 2 µm diameter), which both interact most efficiently with shortwave (solar) radiation and have the longest lifetime, differs by up to a factor of 4 between climate models.

To provide climate models with a better way of parameterizing the size distribution of emitted dust aerosols, I developed a theory of dust emission based on the physics of brittle material fragmentation, such as glass breaking. The fragmentation of glass and other such brittle materials shows a beautiful behavior called "scale invariance" (Figure 1). That is, despite the enormously complex physics that occurs when a piece of glass is shattered, the resulting distribution of fragment sizes follows a simple power law. From soil science, we know that aggregates of dust particle in soils fail as brittle materials when stressed such that we would expect the brittle material fragmentation power law to also occur for dust emission. And this, indeed, is the case for the limited size range of 2 – 10 µm (Figure 1). Particles larger than this range are produced less than expected from the power law because the spacing between cracks created in the fragmented dust aggregates is too small. Similarly, particles smaller than this range are produced less because the discrete particles in the soil aggregates have a finite size, preventing the creation of smaller fragments.

Figure 1: *The fragmentation of brittle materials such as glass is "scale invariant," meaning that the number size distribution follows a simple power law (lower right). Soil dust aggregates fail as brittle materials when stressed, with cracks propagating along the surfaces of the constituent dust particles (upper left). The fact that the emitted dust size distribution is well-described by the brittle fragmentation power law in a limited size range (lower left) thus indicates that dust emission is analogous to the fragmentation of brittle materials like glass.*



These insights into the physics of how dust aerosols are created allowed me to derive a simple expression for the size distribution of emitted dust aerosols that is in excellent agreement with measurements. Most climate models, on the other hand, tend to overestimate the fraction of emitted clay aerosols (< 2 μm diameter) by a factor of ~2–8 (Figure 2). Since climate models are generally tuned to the shortwave radiative effect of dust aerosols, which is dominated by clay, these findings suggest that climate models have substantially underestimated the emission of larger silt (> 2 μm diameter) aerosols, which tend to have more of a warming effect. This has potentially important implications for the simulated effect of dust on weather and climate, as well as the fertilization of ocean ecosystems by the deposition of mineral dust. Work is in progress to implement these findings into weather and climate models.

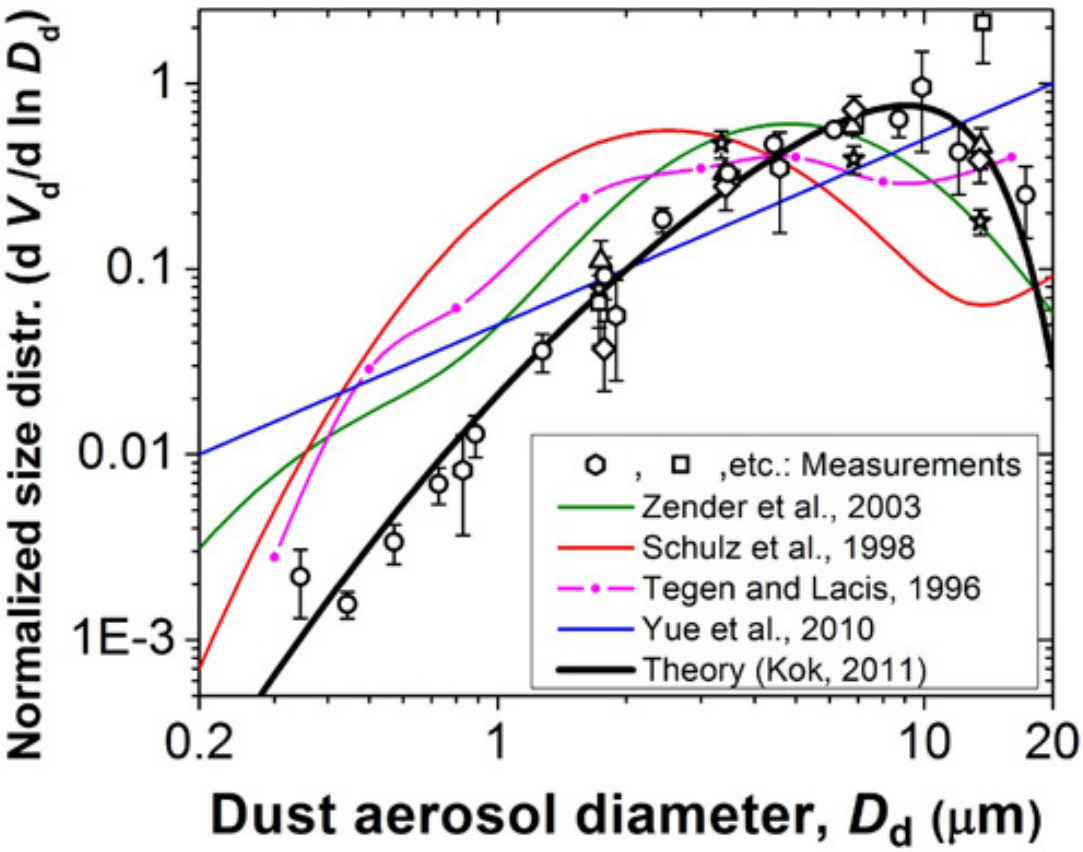


***Figure 2**: The normalized volume size distribution of emitted dust aerosols used in 4 climate modeling studies (colored lines), compared with measurements and our theoretical equation (black line). The theory is in excellent agreement with measurements, whereas climate models overestimate the emitted fraction of clay aerosols (< 2 μm diameter) by a*

factor of ~2–8 relative to measurements. Since clay aerosols produce a strong radiative cooling, this result indicates that climate models overestimate the radiative cooling of a given quantity of emitted dust.

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Log in

Advanced Study Program | ASP
2011 Annual Report

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
  - Sebastien Blaise
  - Jasper Kok
  - Matthew Long
  - Marielle Saunois
  - Julie Theriault
  - Hui Tian
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

Matthew Long

Impacts of shifting seasonality on Arctic Ocean carbon and nutrient cycles

Arctic sea ice decline provides perhaps the most dramatic illustration of anthropogenic climate change worldwide. Since 1979, September **sea ice extent** has declined by about 10 percent per decade, with recent indications of an increasing rate of change. Future climate-model projections suggest that the Arctic Ocean will become seasonally ice free by the middle of this century. A component of my ASP research addresses the question: How will sea ice decline affect other components of the climate system?

While sea ice plays an important role in the physical climate system, it also affects the ecosystem of the Arctic Ocean, with implications for biogeochemistry and climate feedbacks. I am using the **NCAR Community Earth System Model (CESM1)** to understand how changes in sea ice distributions will affect the Arctic Ocean ecosystem and its function as a biogeochemical system.

Phytoplankton, living in the surface ocean, are a fundamental component of the Arctic Ocean ecosystem. These organisms perform photosynthesis—fueled by the sun, they produce complex organic molecules from inorganic materials. This is called `primary productivity', because the organic matter produced provides food for the rest of the ecosystem. Primary productivity is sensitive to the availability of light; as sea ice begins to recede earlier in spring, returning later in fall, more light will be available for photosynthesis over the growing season (Figure 1). This might cause pan-Arctic rates of primary productivity to increase in the future.

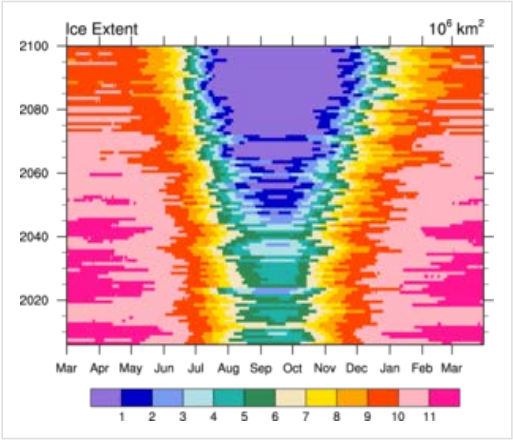

Figure 1: *Seasonal cycle of Northern Hemisphere ice extent over the 21st Century as predicted by CESM1 under* ***RCP 8.5*** *forcing.*

However, in addition to light, phytoplankton also require nutrients (i.e., nitrogen, phosphorus, silicon, and iron). Since the Arctic Ocean is highly stratified, nutrients are trapped in deep water; thus, as the growing season progresses, the surface ocean can run out of nutrients, relying on turbulent mixing to bring more up from below. Presently, the intial phase of the Arctic seasonal bloom is light-limited; later in the season, however, nitrogen (and silicon) limitation is an important factor regulating the bloom extent (Figure 2). Just as sea ice mediates the exchange of heat between the ocean and atmosphere, it also affects the exchange of momentum. Thus, as sea ice distributions change, the fluxes of energy driving turbulent mixing may increase, thereby impacting nutrient availability.

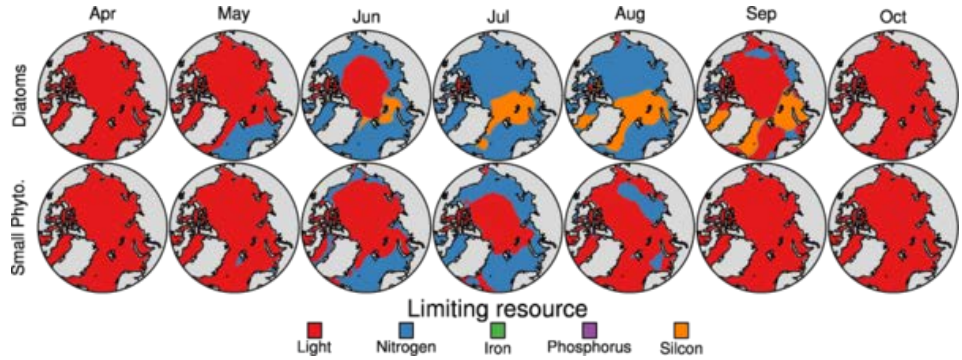

Figure 2: *Seasonal cycle of nutrient limitation for diatoms and small phytoplankton in the 20th Century Arctic, according to CESM1.*

Finally, the sinking flux of organic material (`export') forms an important link in the Arctic ecosystem, providing food to organisms living on the sea floor. These fluxes are also of great significance to global carbon and nutrient cycles. Sinking provides an additional pathway for carbon to get into the deep ocean, where it can be isolated from the atmosphere for centuries. Furthermore, burial of organic matter in sediments is an important sink for nitrogen and phosphorus, two macronutrients regulating global primary productivity. Continental shelves are the most important regions for burial (and sedimentary denitrification), since they receive much larger fluxes of organic matter than the deep ocean. Since 25% of all ocean sediments above 200 m depth are in the Arctic basin (Figure 3), sea ice perturbations may have an effect on nutrient cycles of global significance. However, it is presently unclear how rates of export will change in the future Arctic. On one hand, a longer growing season and more primary productivity would tend to increase export. Conversely, export is sensitive to rates of recycling in the upper ocean. Warmer sea surface temperatures and shifts in algal community composition may permit zooplankton to graze more efficiently, thereby reducing export.

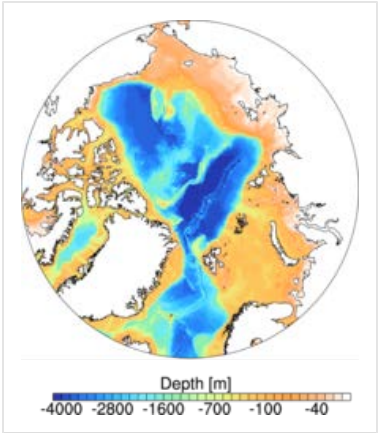

Figure 3: *Bathymetry of the Arctic Ocean from* ***ETOPO1****.*

Preliminary results from 21st Century simulations using CESM1 indicate that changes in the future Arctic ecosystem are complex. While pan-Arctic primary productivity is likely to increase with sea ice decline, export of organic material from the surface ocean to depth becomes less efficient. Algal community composition is sensitive to changes in light distributions; under future scenarios small phytoplankton become more prevalent at the expense of diatoms (Figure 4). These changes, in addition to warmer sea surface temperatures, lead to tighter trophic coupling in the surface ocean (Figure 4), with the net effect of reducing export ratios. Further investigation will focus on determining the impact these changes have on regional to global-scale carbon and nutrient budgets.

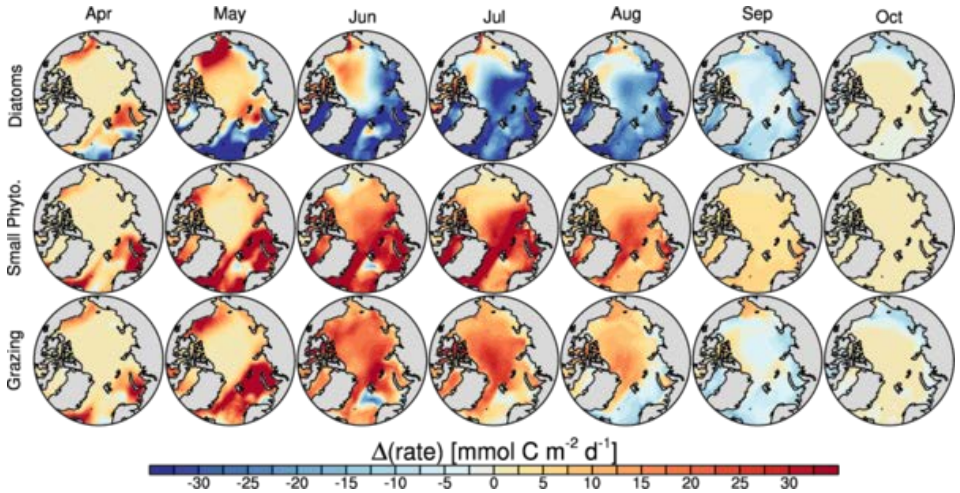

Figure 4: *21st Century changes (2091-2100 minus 1995-2005) in rates of net primary productivity for two phytoplankton taxa and zooplankton grazing rate, as predicted by the CESM1 under* ***RCP 8.5*** *forcing.*

In summary, declines in Arctic sea ice will affect both physical and biogeochemical components of the climate system. Sea ice mediates ocean-atmosphere exchanges of heat and momentum, and is an important determinant of the nature of the upper ocean habitat. Reduced sea ice may result in increased pan-Arctic primary productivity and enhanced fluxes of CO_2 from atmosphere to ocean. Greater rates of primary productivity may result in more surface-to-depth export of organic material—however, competing factors (warmer temperature and algal community composition shifts) are likely to increase upper-ocean recycling and induce changes of the opposite sign.

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Log in

Advanced Study Program | ASP
2011 Annual Report

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
  - Sebastien Blaise
  - Jasper Kok
  - Matthew Long
  - Marielle Saunois
  - Julie Theriault
  - Hui Tian
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

Marielle Saunois

Ozone distribution in the troposphere: changes and inter annual variability through modeling and data analysis

Studying trends and inter-annual variability of tropospheric ozone and its main precursors is of great interest when assessing the impact of human activities on atmospheric composition and climate changes. Tropospheric ozone is a direct greenhouse gas with strongest effect near the tropopause and also controls other reactive climate gases such as methane and interacts within aerosol chemistry, especially in cloud-oxidation of sulfate. Besides its climate-related characteristics, tropospheric ozone is the only source of hydroxyl radical, the main oxidant in the atmosphere, and a gas affecting local air quality.

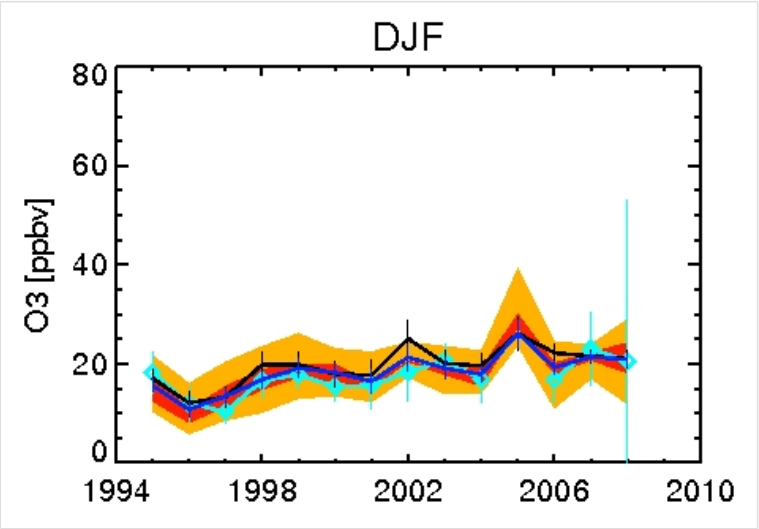
During the last decade, trends and inter-annual variability of tropospheric ozone have been inferred from various platforms (aircraft, ground-based network or satellites) and instrumentation. After the continuous increase of ozone concentrations over Europe until the 1980s or 1990s, a leveling-off with weak trends, both positive and negative is observed. Since the 1980s, the global anthropogenic emissions of ozone precursors increased due to rapid economic development in Asia, while European and North American emissions have been decreasing . Tropospheric ozone is also influenced by the high variability of biomass burning emissions, changes in atmospheric circulation and transport from the stratosphere.

Trends in ozone have been reported from independent studies without a thorough examination of the consistencies between the different sets of data. In particular, most of these studies were based on network measurements with poor temporal frequencies and limited spatial representation. Also these studies usually ignore the natural variability of the ocean-atmosphere system when deriving ozone trends and often relate the calculated trends to changes in anthropogenic emissions for example. Indeed natural modes of the climate such as El-Niño Southern Oscillation or the North Atlantic Oscillation have an influence on the transport, the stratosphere-troposphere exchange and even on emissions from biomass burning. Consequently the natural modes of the climate play a role in the inter annual variability of the trace gases concentrations and might influence the derived trends. Therefore these trends may not be exclusively related to human activities and the effect of inter annual variability might also be part of the aforementioned discrepancies.

Based on various data sets of measurements of ozone, one part of my project consists on answering the following questions: Why are the trends different when using different data sets? What part of the discrepancies is due to temporal frequency sampling and to a different instrumentation?

The effect of low time resolution on seasonal means of ozone and its inter-annual variability is investigated using the large set of tropospheric ozone profiles by the MOZAIC (Measurements of OZone, water vapor, carbon monoxide and nitrogen oxides by in-service AIrbus airCraft) program. Among the visited cities, Frankfurt, Germany is the most documented with more than two profiles a day in average. Frankfurt data set has been sub sampled at the typical ozonesonde frequencies (4 or 12 profiles a month). Then seasonal means and trends in ozone between 1995 and 2008 were derived from the numerous sub samples. The yearly seasonal means and the inter-annual variability change significantly with time resolution.

***Figure 1**: Time evolution of the winter ozone means at the surface in Frankfurt between 1995 and 2008 as observed by MOZAIC aircraft. Overall means from the complete data set (black), a morning (dark blue) and an afternoon (light blue and diamond) sub sets are in solid lines,*



error bars show 95% confidence limit. The shaded areas represent the range between the minimum and maximum of the seasonal means derived from the ensemble at a 4 (orange) and 12 (red) profiles a month frequency.

Also we found that trends in surface ozone can thus vary in magnitude and even in sign with the subsample, especially during the warm seasons when ozone daily variability is larger. Trends derived from ozone soundings or surface station measurements are compared with MOZAIC complete data set and to MOZAIC sub samples. This study suggests that apparent discrepancies between close sites may be due to both low time resolution and station specifics.

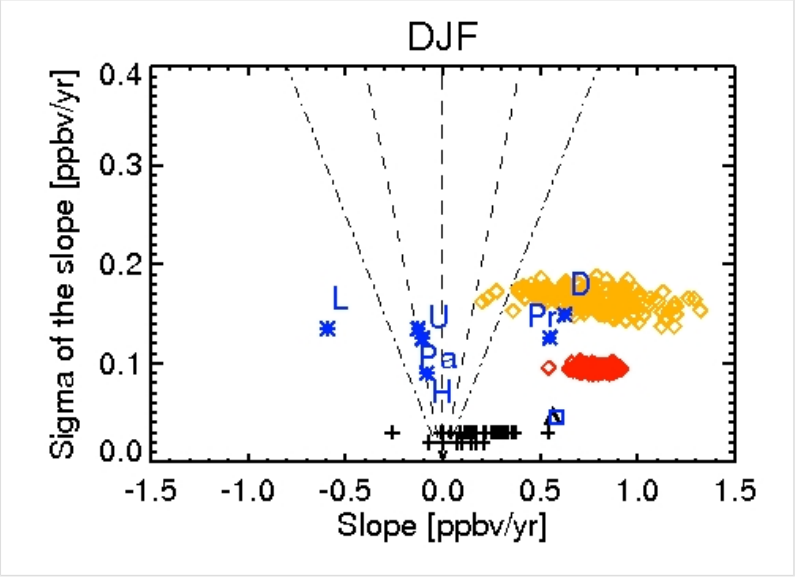


***Figure 2**: Slope of the winter trend in surface ozone against the 1-sigma uncertainty estimate of this slope. Black plus symbols give the trends at the 36 surface stations in Central Europe. Blue stars give the trends derived from ozone soundings at the six stations (D = Debilt, H = Hohenpeissenberg, L = Lindenberg, Pa = Payerne, Pr = Praha, U = Uccle) at 1000 hPa except for H and Pa, value at 900hPa. The black and blue diamonds correspond to the trends derived from the complete and morning MOZAIC data sets in Frankfurt respectively. 200 random time series were created from the ensemble of Frankfurt sub samples. The resulting trends are given by the cloud of diamonds in red (frequency of 12 profiles a month) and orange (4 profiles a month). The mean, minimum and maximum of the distributions are shown with the vertical and horizontal black thin lines. The dashed and dot-dashed lines show the 67% and 95% confidence limit lines.*

Further studies involving global models will help to better understand remaining discrepancies and also evaluate how the climate natural modes affect the variability and changes of tropospheric ozone. In particular the role of the North Atlantic Oscillation is discussed using MOZAIC data collected in the upper troposphere - lower stratosphere and chemistry climate simulations.

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Log in

Advanced Study Program | ASP
2011 Annual Report

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
  - Sebastien Blaise
  - Jasper Kok
  - Matthew Long
  - Marielle Saunois
  - Julie Theriault
  - Hui Tian
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

Julie Theriault

Winter Precipitation Study

The prediction of precipitation is critical for both weather forecasting as well as for associated climate impacts. In general, prediction models are quite deficient in regards to their handling of precipitation. The main reason is the lack of knowledge about the fundamentals of precipitation type formation and how the precipitation interacts with the environment. Winter storms associated with temperatures around 0°C are particularly difficult to predict because they can be associated with many types of precipitation. These can be in the form of freezing rain, ice pellets and/or snow. Such events can sometimes be catastrophic because they can lead to major disruptions to society by affecting transportation (ground or air) and power networks.

It is very common to observe many types of precipitation during winter storms. Both a melting layer (T >0°C) aloft and a refreezing layer (T<0°C) below are generally needed to form these various precipitation types. When snow falls through a melting layer, it will melt or partially melt and then form other types of precipitation. The melting of snow typically leads to an isothermal layer at 0°C, which can be up to a few hundred meters deep. The types of precipitation formed are then driven by the environmental temperature, which influences the rate of phase changes. This phase change in turn impacts the environmental temperature through diabatic heating/cooling. These diabatic effects will also induce a mesoscale circulation. While a few studies have started to address this issue *[e.g. Lin and Stewart (1986), Szeto et al. (1988)]*, this feedback loop is not yet fully understood.

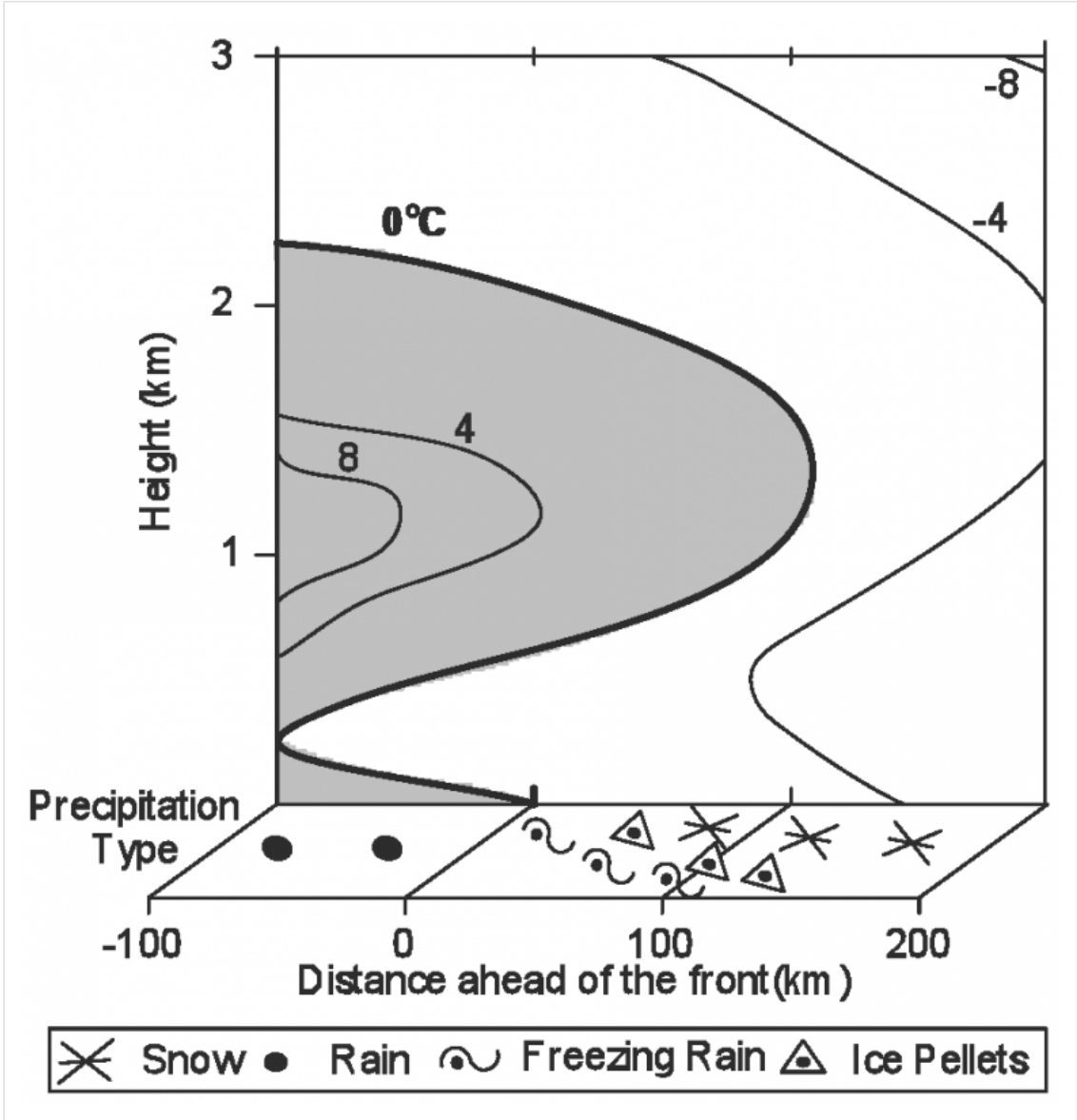

Figure 1: *A warm front cross-section often associated with a transition of winter precipitation types at the surface. Temperature lines are indicated as well as the associated precipitation types.*

Similarly, precipitation transitions from snow to rain are often observed along mountainsides. It is called the rain-snow line. The variation of its location has many climate and weather implications such as the flash floods and snowpack variability. Over flat terrain, rain can evolve into snow due to the cooling effects of melting snow on the atmosphere. The combined effects of diabatic cooling by melting snow and orographic factors influence the depth of the 0°C isotherm near the mountain surface. This can generate a major horizontal temperature difference (up to 7°C) between the mountain surface and several tens of kilometers away from the mountain *[Marwitz 1987]* at the same height. A few studies of the effects of melting on the mesoscale circulation over a sloped terrain have been carried out but most of these studies, however, were performed in the 1980's and very little has been done on the subject since then. To better understand the evolution and characteristics of the rain-snow line along mountain side detail weather observations were collected during the SNOW-V10 held in Vancouver area during the 2010 Vancouver Olympics. An example of Whistler Mountain after a storm associated with rain-snow line. This line is often observed in the middle of the ski downhill race therefore it was critical to be able to predict the type and intensity of precipitation for the event.

Figure 2: *An example of the rain-snow line along Whistler Mountain. The photo was taken on March 7th 2010. Detailed weather observations such as temperature, relative humidity and precipitation types were collected.*

Precipitation is not only diffcult to accurately simulate but measuring it is still a challenge. This is also for a wide variety of studies including snowpack, runoff and climate variability. It has been recognized that systematic errors in snowfall measurements are often observed due to the gauge geometry and the weather conditions, particularly wind. Typically during snowfall events, the higher the wind speed, the lower the collection effciency of the gauge because the snow tends to blow over the gauge instead of falling into it. To prevent this a shield is often installed around the gauge to slow the wind flow around the snow gauge.

Since the gauge and the shield are obstacles to the natural airflow pattern, smaller and lighter snow flakes may interact with the gauge and shield differently than larger flakes. To address this, a study was undertaken to determine if different types and sizes of snow flakes fall inside versus outside of a GEONOR snow gauge. Additionally, snow flakes were collected both with and without an Alter shield around the gauge. The collected snowflakes were photographed and the pictures analyzed to determine their characteristics. Finite element modeling (GAMBIT and FLUENT) was used to simulate the flow around a shielded snow gauge. To study the trajectory of various crystal types falling through the atmosphere a trajectory model was developed and initialized with the simulated flow. Based on the trajectory of each snow flake type, the collection effciency was computed and compared with observation. Preliminary results show that crystal type, in addition to wind speed, has an effect on gauge collection effciency.

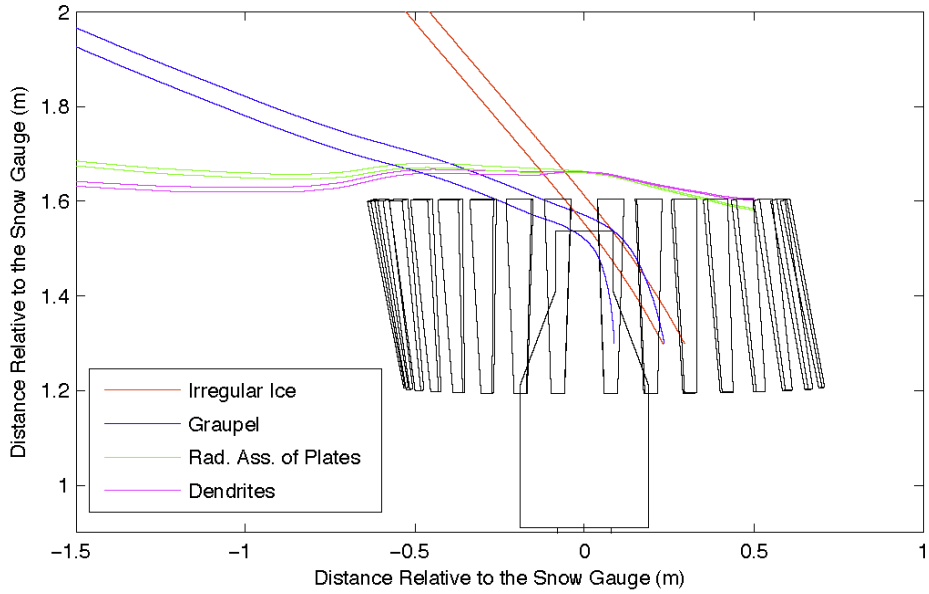

Figure 3: *Examples of the trajectory of different snowflake types in the vicinity of a shielded snow gauge.*

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Log in

Advanced Study Program | ASP
2011 Annual Report

ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
  - Sebastien Blaise
  - Jasper Kok
  - Matthew Long
  - Marielle Saunois
  - Julie Theriault
  - Hui Tian
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

Hui Tian

Ubiquitous high-speed solar coronal upflows revealed by both imaging and spectroscopic observations

The solar corona, the upper layer of the solar atmosphere, has a temperature exceeding one million degrees. How is the corona heated to such a high temperature? This is among the most important unresolved problems in solar physics. In the past several decades, people proposed basically two types of coronal heating mechanisms: nano-flare heating and magneto-hydrodynamic wave heating. In both mechanisms the coronal materials are heated in place. Recently, based mainly on EUV spectroscopic observations, Dr. Bart De Pontieu (from Lockheed Martin Solar and Astrophysics Laboratory) and Dr. Scott W. McIntosh (HAO/NCAR) and their collaborators proposed that the cool materials in the lower solar atmosphere are impulsively heated to million degrees and then rapid upflows resulted from this heating propagate upward into the corona.

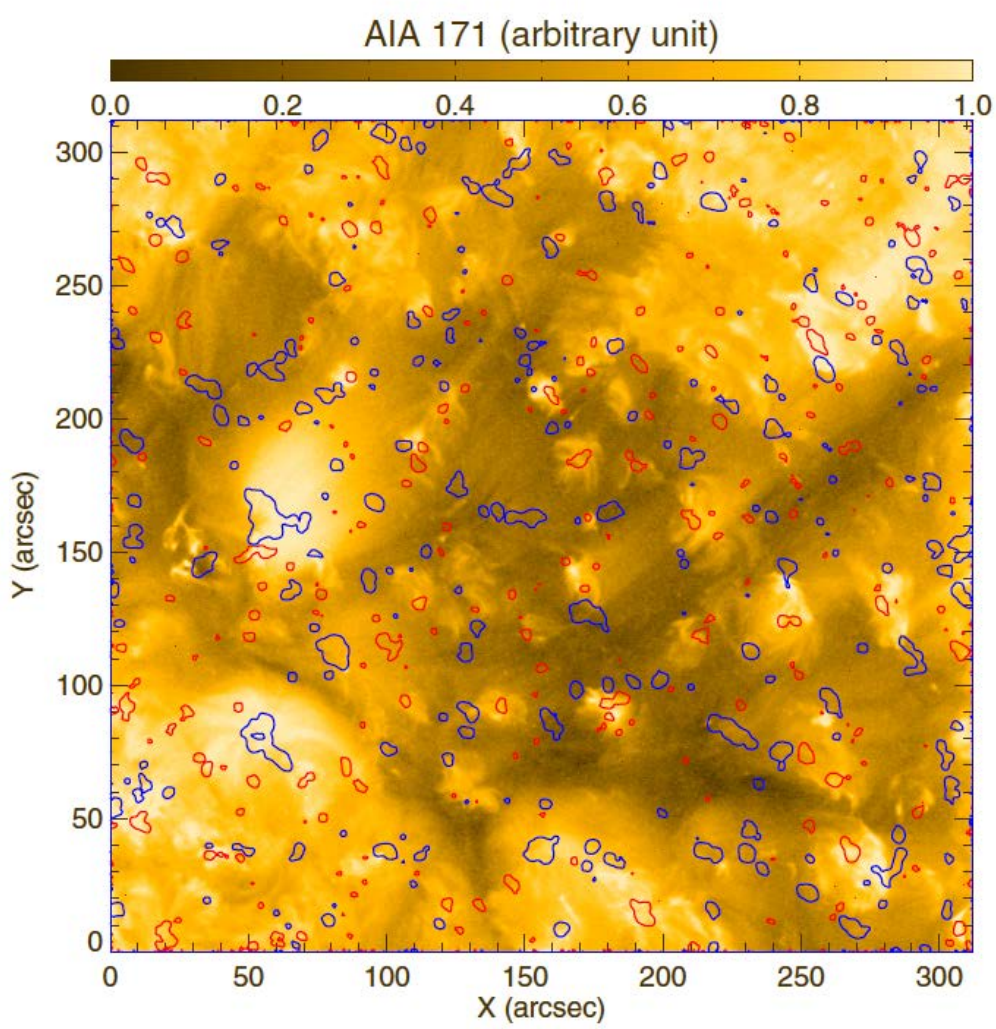

Figure 1. *A coronal image of a low-latitude coronal hole located on the northwest quadrant of the solar disk taken by SDO. Red (positive) and blue (negative) contours representing regions of magnetic field strength larger than 15 G are superimposed on the image.*

As an ASP postdoc, Hui Tian came to NCAR in August 2010 and works with Dr. Scott W. McIntosh to try to establish the properties of these rapid upflows. Using the very high-S/N EUV images taken by the newly launched Solar Dynamics Observatory (SDO), Hui found that rapid hot upflows with a speed of the order of 100 km/s are almost everywhere on the Sun, i.e., strong-emission active regions, weak-emission coronal holes and the normal quiet Sun regions. These weak dynamic upflows seem to be superimposed on the quasi-steady coronal background. Furthermore, the fine structures traced out by these flows continually exhibit transverse motions indicative of ubiquitous magneto-hydrodynamic waves. The ubiquitous presence of these upflows and the waves associated with them strongly suggests that these upflows may be an efficient means to provide heated mass into the corona to maintain the million-degree temperature and thus are likely to be the rapid upflows in the coronal heating scenario proposed by De Pontieu and his collaborators.

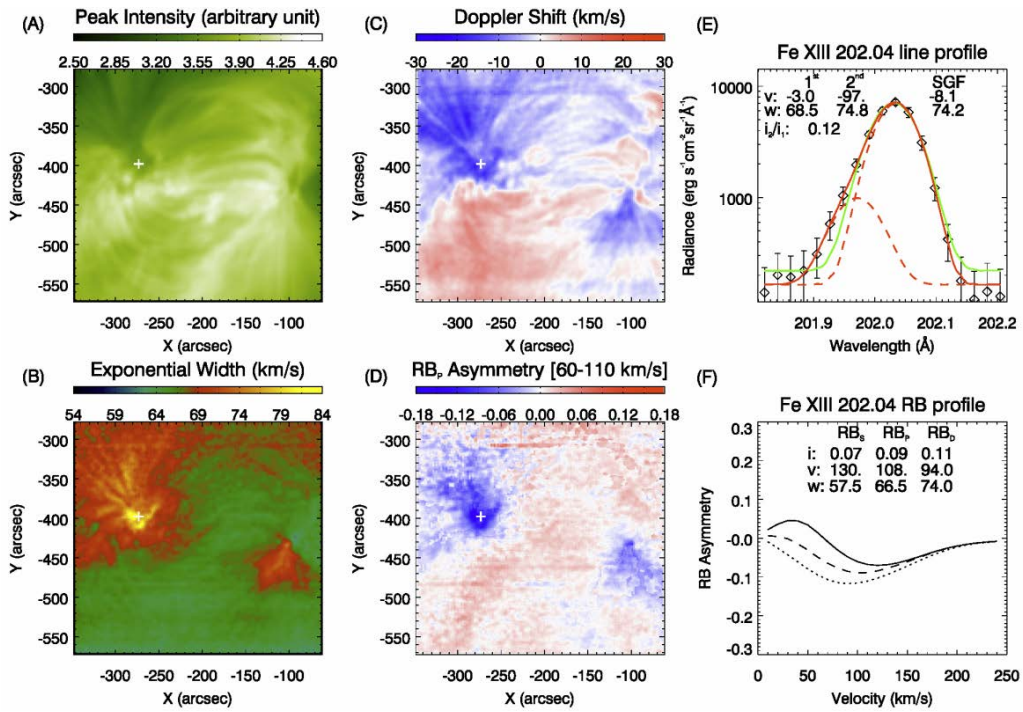

Figure 2. *Spatial distributions of the single Gaussian parameters (A,B,C) and profile asymmetries (averaged over the velocity interval of 60-110 km/s from the RBp asymmetry profiles, D) for Fe xiii 202.04Å in an active region. Panel (E): the Fe xiii 202.04Å profile at the marked location. The observed spectral profile and measurement errors are shown as the diamonds and error bars, respectively. The green line is the single Gaussian fit. The two dashed red lines represent the two Gaussian components and the solid red line is the sum of the two. Panel (F): the asymmetry profiles of the line profile in panel (E).*

By using joint imaging observations of SDO and spectroscopic observations made by the EUV Imaging Spectrometer (EIS) onboard the Japanese HINODE mission, Hui studied the properties of these upflows at boundaries of active regions in more detail. The EUV spectral line profiles clearly show an enhancement in the blue wings (at smaller wavelengths), suggesting at least one additional (secondary) weak outward-flowing emission component (the lower red dash curve in Figure 2E) besides the almost stationary primary emission component (the higher red dash curve in Figure 2E). It was proposed that the previously reported ~20 km/s blue shift and enhanced line width are actually caused by the superposition of these two components. Hui designed new methods of profile asymmetry analyses and double Gaussian fit and used them to study the properties of the secondary component, which turned out to be very consistent with the properties of the rapid upflows in images taken by SDO. The two were then suggested to be the same phenomenon.

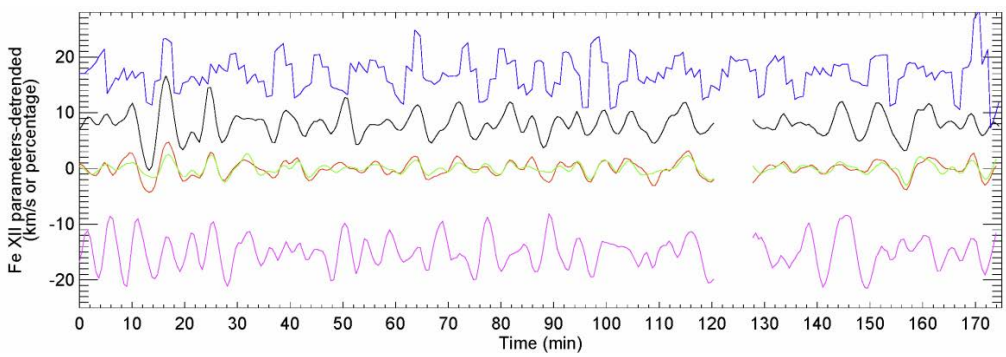

Figure 3. *Timeseries of EIS emission line (Fe xii 195.12Å) parameters and XRT intensity at the footpoint of an active region. The black, red, green, violet, and blue curves represent the Fe xii 195.12Å line intensity, Doppler shift, line width, profile asymmetry and XRT intensity, respectively. Note that the values of Doppler shift and profile asymmetry are inverted so that a large value indicates more blue-shifted emission or stronger blueward asymmetry. The intensity, profile asymmetry, and intensity ratio are shown in relative amplitude (percentage), while the Doppler shift and line width are shown in km/s. The Fe xii 195.12Å line intensity, profile asymmetry, and XRT intensity are offset by 8, -15, and 17 respectively on the y-axis.*

Time series observations also suggest a close association of the secondary component in spectral line profiles with the apparent upflows revealed by the X-Ray Telescope (XRT) onboard HINODE. As shown in Figure 3, different spectral line parameters show nearly in-phase (coherent) quasi-periodic (3-15 min) oscillations. Although the XRT and EIS instruments sample emission formed at different temperatures and their observational cadences are very different, we can still see a correspondence between the variations of XRT intensity and EIS line parameters, suggesting that the apparent upflows observed by XRT are responsible for the secondary component of EIS line profiles. Oscillatory (periodic) signals like those shown in Figure 3 were previously interpreted as magneto-acoustic waves which do not have enough energy to power the corona. However, Hui demonstrated that the quasi-periodic variations of these line parameters are consistent with the scenarios of recurring upflows (or periodically enhanced and weakened upflows) rather than waves. Calculations show that these upflows can provide enough heated mass to the corona.

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Log in

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2011 Annual Report

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ASP Annual Report 2011

- ASP Director's Message
- Table of Contents
- ASP Postdoctoral Fellowships
- Building Partnerships with University Faculty
- Providing University Students Access to the Resources of NCAR
- ASP Summer Colloquium
- Profiles in Science
- Supporting Diversity in the Atmospheric Sciences

2009-2014 Strategic Plan »

Supporting Diversity in the Atmospheric Sciences

The ASP continued its ongoing efforts to better serve diverse communities in FY2011 through two initiatives:

1. Cultivating a new collaboration between North Carolina Agricultural & Technical University (NCA&T), and
2. The new ASP Historically Black College and University (HBCU) postdoc exchange.

In Support of North Carolina Agricultural & Technical University

In FY2008, a Memorandum of Agreement (MOA) was signed between NCAR and four HBCU partner universities:

* Howard University
* North Carolina Agricultural and Technical University
* Hampton University
* Jackson State University

The MOA focuses on these areas of mutual agreement:

* Graduate student research and internship opportunities
* Faculty exchange and internship opportunities and faculty training.
* NCAR scientists serving as visiting faculty to increase instructional capacity and curricular breadth/
* Participation of NCAR scientists on graduate student committees.
* Collaborative research that results in proposal submission

In support of the MOA, the ASP supported 3 scientists to travel to NCA&T. Each of these scientists spent several days at NCA&T giving seminars and meeting with faculty and students to help build capacity. The main challenge for NCA&T is that it lacks enough faculty expertise to be able to teach several courses in support of its new Bachelor of Science program in Atmospheric Sciences and Meteorology. These lectures and seminars provided by NCAR staff have the potential to fill those holes.

In addition, the ASP sponsored a graduate student, Cheikna Baber, to come to NCAR for two months to work with Chris Snyder in MMM.

Initiating a new postodoc exchange with HBCU partners

In support of the Memorandum of Agreement referenced above, the ASP recruited two of its postdoctoral fellows to spend time teaching, conducting research, and collaborating with faculty and students at Hampton University and Howard University. The Howard University visit will happen in FY12, but the Hampton exchange began in FY11 and will continue into FY12. Jia Yue will teach “Principles of Atmospheric Physics” during fall semester at Hampton University.

The visit will establish a scientific relation where none exists currently between NCAR and this HBCU. Students at Hampton will become aware of the research at NCAR and Jia’s visit could dramatically increase the chances of one or more Hampton students visiting NCAR. There has also been preliminary discussion of Hampton applying to become a UCAR member institution as a result of this initiative (but this is not firm at present).

Jia Yue teaching a course at Hampton University

In addition to teaching, the link between NCAR and Hampton Univ. has been greatly strengthened during my visit. Since my first day at Hampton, I advocated for Hampton University to join UCAR as a member university. Now the Dean of the College of Natural Science is also in favor of joining. The seminars I gave at Hampton University will stimulate future collaborations with faculty members and graduate students at Hampton and HAO along with nearby NASA Langley Research Center.

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

CISL Director's Message

Message from CISL Director Al Kellie

CISL Director Al Kellie

Welcome to the FY2011 CISL Annual Report.

In addition to describing CISL's three strategic functions of providing service, science, and education, this year's report includes a new overview of our broader impacts on the research community. Many CISL activities are designed to broaden the laboratory's impact through outreach, collaboration, and community engagement, and through capacity building at regional, national, and international scales. CISL's outreach provides training and education opportunities aimed at broadening participation and helping develop the diverse workforce necessary to make effective use of high performance computing (HPC) resources. CISL also collaborates and exchanges information and expertise for developing shared cyberinfrastructure and standards that will advance HPC for both the geosciences and the HPC community.

CISL's most significant highlight this year is completing the NCAR-Wyoming Supercomputing Center (NWSC) and awarding the contract to provision it. Six years of planning and one year of construction have produced a highly efficient modern facility ready to house a petascale system that will provide large increments in simulation capability and capacity for atmospheric research and our Wyoming partners. Much remains to be done in the next half year before production computing begins, but the speed and thoroughness of our FY2011 effort to bring NWSC into reality have been remarkable. When operations start in mid-FY2012, NWSC will be a data-centric computational facility balanced for both data generation and data analysis, imperatives for scientific progress. We expect NWSC to underwrite new science discoveries for decades.

CISL's Technology Development Division and our math institute IMAGe have been making significant progress in scaling applications and introducing dynamical cores capable of scaling to over 100,000 processors. Unheard of for climate applications, this work has arguably helped produce the most scalable climate model available to today's scientists. For the recently completed assessment of the Intergovernmental Panel on Climate Change (IPCC), the data assimilation algorithms developed in CISL made it possible for CESM to use reanalysis data from DART/CAM4 that significantly improves the initial conditions used in ensemble decadal predictions.

Fundamental workflow improvements arose from CISL's centralized high-performance file systems that efficiently manage massive data flows. The success of this new architecture for Mesa Lab systems guided the design and procurement of equipment to be installed at NWSC. Further, CISL's ongoing development of science gateways provides additional benefits to modelers by simplifying the use of increasing data volumes through intuitive web-based user interfaces and automated workflows for experiments. Tied to major interagency, national, and international initiatives, CISL's science gateway framework (SGF) supports climate science, regional climate change, Arctic science, solar science, digital preservation, and international efforts to develop metadata and knowledge infrastructure. The SGF serves as a foundation for the Earth System Grid (ESG) and many other national and international science efforts including the WCRP Coupled Model Intercomparison Project (CMIP), the IPCC's most recent assessment report, and the Community Earth System Model (CESM). CISL integrates all of these resources and applies them to the processes of scientific discovery.

As a supercomputing laboratory at a national research center, CISL is in a unique position to integrate education into research spanning many scientific disciplines. CISL's educational efforts complement and supplement programs at universities and other centers. CISL's Summer Internships in Parallel Computational Science (SIParCS) program provides interns with meaningful hands-on research opportunities in computational science, applied mathematics,

and geostatistics to develop a workforce that can exploit the scientific potential of petascale computers. CISL's Research and Supercomputing Visitor Program (RSVP) allows prolonged engagement and collaboration between our staff, the university community, and researchers at peer centers around the world. IMAGe's Theme-of-the-Year (TOY) is a series of yearlong programs, each focused on a specific aspect of mathematics applied to the geosciences to stimulate education, research, and collaboration between the mathematical and geosciences communities. CISL also prepares for the coming petascale computing era by training young researchers to use high-performance cyberinfrastructure. CISL delivers this educational content through workshops, training classes, and via the web. By design, all of our education, outreach, and training efforts also broaden early-career researchers' opportunities to participate in Earth System science.

We will continue to provide balanced, easy-to-use computational and data environments that will support our traditional science community while sharing our resources via distributed facilities and new partnerships. As we look to the future, we continually adapt ourselves and our organization to maximize our contribution to understanding the complexities of the Earth System. This is how CISL renews its vigor and skill in supporting Earth System science. As you read this report, I hope you share our sense of expectation and excitement that with the advent of NWSC, CISL is "Back in the Game!"

With this in mind, it is my pleasure to invite you to review our accomplishments in this FY2011 CISL Annual Report.

‹ 2011 CISL Annual Report

CISL Annual Report Table of Contents ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

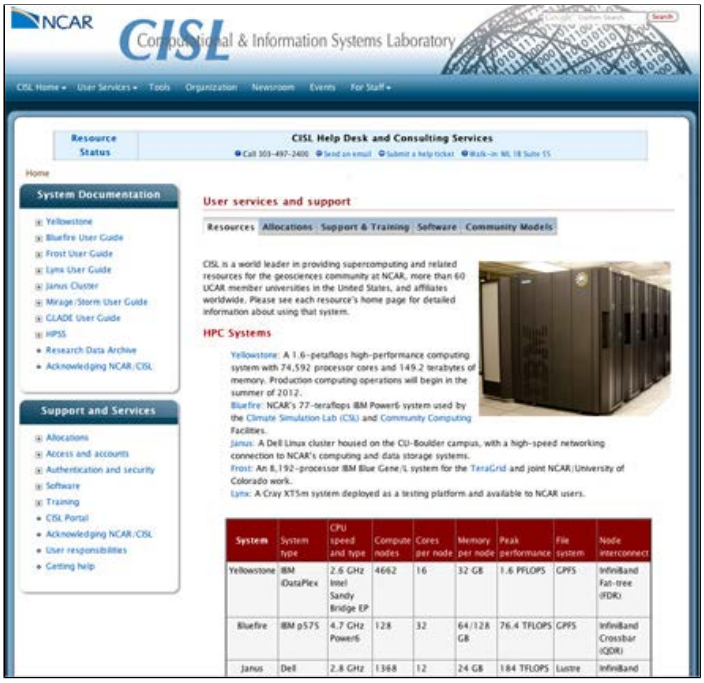
2009-2014 Strategic Plan »

Search

CISL Services

CISL has a proud tradition of providing world-class supercomputing and data services to its user community. The quality of these services is and will remain a core value of the laboratory. However, the makeup of these services is not static: they continually change in concert with rapid changes in the underlying technologies and scientific demands of our users. CISL:

- Maintains and operates the physical facilities and cyberinfrastructure needed to support the atmospheric and related sciences
- Curates, manages, and archives a rich set of data collections to which it provides free and open access
- Creates essential widely used software cyberinfrastructure such as data analysis and visualization tools and frameworks for modeling and science gateway construction
- Provides user support and training on all of these
- Strives to better integrate its resources and services with regional and national cyberinfrastructure and services, and with the organizations that maintain them, such as NSF's TeraGrid and XSEDE projects



Web page for CISL services and support.

At end FY2011, it is clear that CISL's dream of creating a data-centric, petascale supercomputing environment for our community is well on its way to become a reality. A particularly significant milestone marking progress to this goal is the on-time, on-budget construction of the new NCAR-Wyoming Supercomputing Center in Cheyenne, Wyoming. This world-class facility will enable the deployment of substantially larger high-performance computing and data storage resources to support Earth System science research. These resources will be critical tools enabling scientists to push back the research frontiers of weather phenomena, climate change, and more. Consistent with NCAR's mission, NWSC will showcase energy efficiency by using the newest and most efficient designs and technologies available.

During FY2011, CISL also executed a major procurement to acquire the HPC equipment for NWSC, with installation scheduled for early FY2012. The centerpiece of this new infrastructure will be an order 10-petabyte parallel central filesystem that will provide a common workspace for the scientific workflows that run on the petascale computing and data analysis and visualization systems attached to it. Finally, a many-petabyte tape archive will store critical data.

CISL's software CI capabilities made important advances in FY2011 as well, including ones that enable our tools to work with larger data sets, or integrate better, or operate with new kinds of scientific data. FY2011 also saw continued milestones for our portal-based data services. For example, the first data produced by the most recent Climate Model Inter-comparison Program is being shared with the community via the Earth System Grid. This data is stored in the 1.6-petabyte GLADE central filesystem, which entered production operation in the past year, another significant accomplishment.

‹ CISL Annual Report Table of Contents

CISL facilities ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
      - Mesa Lab Computing Facility
      - NCAR-Wyoming Supercomputing Center
    - CISL computing services
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

CISL facilities

CISL's first computing imperative is to provide world-class supercomputing facilities for its user community. A foundational element of CISL's mission is to deploy and operate the physical and virtual computational facilities needed to support the atmospheric and related sciences. Consistent with NCAR's environmental mission, CISL continually enhances the capability and capacity of NCAR's supercomputing facilities while maximizing their efficiency and usability. FY2011 was almost entirely focused on the construction effort for the NCAR Wyoming Supercomputing Center (NWSC). NWSC commissioning began in September 2011, with building commissioning and operational training planned for completion in October 2011. NWSC will be home to future generations of supercomputing systems for Earth System sciences.

NWSC is a world-class facility offering high-performance computing for the atmospheric and related sciences. Consistent with its mission, NWSC is a leader in energy efficiency, incorporating the newest and most efficient designs and technologies available. When operations commence in FY2012, it will enable NCAR and university researchers to advance scientific knowledge, education, and service through computing.

Construction and landscaping efforts were near full completion at end-FY2011. The computer room modules and central utility plant were fully enclosed by late fall 2010 to allow construction to continue unimpeded through the winter months. All major equipment was delivered during the winter, and the electrical systems were started. In the early spring all cooling equipment, the uninterruptible power supply, and standby generator systems were brought online. Functional testing and commissioning of the systems proceeded through the summer months in parallel with construction of the administrative building. The substantial completion milestone was reached on 31 August 2011. Finally, the Integrated Systems Test (IST) was successfully completed over two very long days on 20 – 21 September 2011.

The Mesa Lab computing facility continued its workhorse operations providing the building infrastructure to house the tape archive, storage, and supercomputing production systems. The ML computer room also started hosting computing equipment for other NCAR laboratories. In the former location of its equipment, the Climate and Global Dynamics (CGD) Division experienced a catastrophic failure in a critical air conditioning unit. In two days, CGD relocated their divisional equipment to the ML computer room.

For FY2012 the majority of facilities efforts will be focused on transitioning NWSC to production operations. Furniture is scheduled to arrive in October, followed by tape archive equipment, central storage, supercomputing, and the data analysis and visualization resources. CISL staff will continue to plan and prepare the Mesa Lab for its new role as a collocation facility to house both CISL systems and equipment for the rest of NCAR and UCAR.

This work is supported by NSF Core funding and other funds as described in the next section.

‹ CISL Services

Mesa Lab Computing Facility ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
      - Mesa Lab Computing Facility
      - NCAR-Wyoming Supercomputing Center
    - CISL computing services
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Mesa Lab Computing Facility

NCAR's Mesa Lab Computing Facility (MLCF) has served high performance computing in the atmospheric sciences since the mid-1960s. CISL continued to invest considerable effort in maintaining the facility while the NCAR-Wyoming Supercomputing Center (NWSC) was under construction. MLCF is positioned to continue providing significant value to researchers for many years into the future.

This hot aisle containment prototype was installed at MLCF during FY2011. This technology is a key part of CISL's strategy to maximize energy efficiency at NWSC. Its modular design facilitated testing a variety of concepts before full-scale deployment at NWSC. Cooling air enters the computer cabinets from floor vents outside the structure, and hot air is extracted through ceiling vents inside the containment structure. Hot air is ducted to nearby chillers that cool the air and return it to the outside of the computers under the raised floor. Power is delivered via rails above, while network cables are routed below the floor. All materials for the structure are standardized and can be cut to fit cabinets of any height and width. Containing the heated air greatly increases energy efficiency and provides numerous other benefits.

MLCF supports the Bluefire system and will do so well into FY2012. In addition, MLCF has been an ideal facility for testing and developing hardware and software platforms that will support NWSC. While MLCF infrastructure can't support modern large-scale HPC systems, the facility is fully capable of supporting conventional Information Technology (IT) equipment for NCAR divisions and UCAR programs. Ongoing planning has continued throughout FY2011 to prepare MLCF for this purpose.

In late FY2011, NCAR's Climate and Global Dynamics division IT equipment experienced a catastrophic cooling failure. Rather than repair that cooling equipment, CGD and CISL worked together to relocate CGD's equipment to MLCF. CISL now hosts that equipment and will support more medium-scale systems after Bluefire is decommissioned. This work is supported by NSF Core funding.

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
      - Mesa Lab Computing Facility
      - NCAR-Wyoming Supercomputing Center
    - CISL computing services
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

NCAR-Wyoming Supercomputing Center

In partnership with the University of Wyoming (UW), the State of Wyoming, Cheyenne LEADS, the Wyoming Business Council, and NSF, NCAR completed construction of the NCAR-Wyoming Supercomputing Center (NWSC) in Cheyenne, Wyoming. NWSC is designed to meet the rapidly growing high-performance computing (HPC) needs of Earth System scientists and to encourage broader participation in this scientific enterprise. Earth System scientists are calling for petascale computing, data analysis, and visualization resources combined with exascale data management capabilities to support greater model resolution, increased model complexity, better statistics, more predictive power, and longer simulation times. NWSC has been designed and built with a focus on sustainability and energy efficiency consistent with NCAR's and UW's strong commitment to environmental stewardship.

This end-FY2011 photo shows the office area of the completed NWSC. Construction of the facility was declared substantially complete in August 2011 and building commissioning began in September 2011. NWSC will enable NCAR to support critical Earth System sciences research through high-performance computing for decades.

NWSC is fully aligned with NSF's larger CI vision and will directly contribute to the creation of a national petascale cyberinfrastructure. The facility will be a peer with other NSF Track-2 facilities and will serve as a "stepping stone" for Earth System science investigators to fully utilize NSF's multidisciplinary, one-petaflop-sustained Track-1 facility. CISL's first strategic imperative is to provide HPC facilities for the Earth System sciences: "A foundational element of CISL's mission is to deploy and operate the physical and virtual computational facilities needed to support the science community. Essential to this mission is the design, construction, and operation of a new data center capable of meeting future scientific computing challenges in the atmospheric sciences."

From October 2010 to August 2011, NCAR staff provided support for the NWSC construction effort. Under an aggressive schedule for construction completion, major activities included: steel erection, cast-in-place and precast concrete work, roofing, mechanical and electrical systems installation, plumbing, flooring, drywall installation, electrical wiring, window installation, paving, and landscaping. On 26 August 2011, a Temporary Certificate of Occupancy (TCO) was awarded by Laramie County after final building inspections were completed and passed. Next, Substantial Completion was achieved on 31 August 2011, marking the point at which CISL assumed financial responsibility for NWSC insurance and utilities. Attainment of Substantial Completion also allowed the formal building commissioning period to begin in September 2011. A major element of facility commissioning –- the Integrated

Systems Test (IST) –- was conducted from 20-21 September 2011. Over this two-day period, electrical and heat load banks on the computer room floor were used to test the facility's ability to handle a full computing load. NWSC mechanical, electrical, and control systems were subjected to a variety of tests, and intentional equipment and power failures were instituted to ensure that all primary and backup systems performed individually and collectively as required by project specifications. The IST was declared complete and successful at end of day 21 September 2011, with subcontractor personnel receiving a list of items to be addressed to ensure full compliance with specifications.

Successful completion of the IST and receipt of the final Certificate of Occupancy (CO) for NWSC are required for UCAR acceptance of the building. Receipt of the CO and facility acceptance are targeted for October 2011. The building commissioning and operational training phase are scheduled for completion at the end of October 2011, approximately two months ahead of the originally planned date for construction and commissioning completion. The project's transition to operations phase will begin in November 2011, with installation of the first HPC system to take place early in calendar year 2012. NWSC will begin providing supercomputing support to Earth System scientists by mid-2012.

During FY2011, NSF informed NCAR that construction contingency funds provided as part of the NSF award for NWSC construction can be retained and applied to cover the costs of approved physical infrastructure preparation efforts. The NWSC Project Office (NPO) worked with the NSF NWSC Program Officer to develop and implement a process for the submittal, review, and approval of contingency fund usage requests. As of end-FY2012, two such requests had been approved by the NWSC Change Control Board (CCB) and NSF: mechanical and electrical design work required for installation of the first HPC system, and purchase and installation of audio/visual equipment and directly related services required for the facility. During FY2012, NPO personnel will oversee additional requests for these construction contingency funds as well as the usage of all funds for approved requests.

NPO expenses in FY2011 were met using American Recovery and Reinvestment Act (ARRA) funds awarded by NSF in FY2009. Costs associated with NWSC construction in FY2011 (building construction, required Board of Public Utilities construction fees, construction administration, and commissioning expenses) were met using NSF Special and Wyoming Business Council (WBC) funds.

‹ Mesa Lab Computing Facility

CISL computing services ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

CISL computing services

CISL's world-class supercomputing and data services continually change in concert with underlying technologies and scientific demands. For example, CISL infrastructure is evolving to provide significantly improved support for data-intensive computing. The challenges of managing data have become an increasingly important challenge for our scientific research community. Fundamental CISL computing services include:

- Hardware cyberinfrastructure resources: CISL's current hardware environment includes a 77 TFLOPS production supercomputing resource and a 1.6 PB high-speed central filesystem supported by a 14 PB HPSS archival system. A procurement was conducted this year to replace the hardware resources with a 30-fold increase in computing capacity, a 15-fold increase in high-speed storage capacity, and a tripling of the archival system to support more than 40 PB of storage. This new equipment will all be located at NWSC with production usage scheduled for summer 2012.
- User services: CISL places paramount importance on providing high-quality support to our user community. User support efforts include a broad range of activities including HPC training, on-call support for specialized campaigns, help desk, and consulting services. Three allocation communities are now served: NCAR, member universities, Climate Simulation Laboratory, and Wyoming allocations will begin soon. Funding was also received this year to provide specialized support for projects in EaSM and CRI to ensure that these users are able to use CESM, WRF, RDA, and NCAR resources effectively. NSF sponsors the programs Earth System Models (EaSM) and Computing Research Infrastructure (CRI).
- National and regional supercomputing services: CISL is an active collaborator on the TeraGrid and its follow-on project, XSEDE. These national NSF efforts are constructing open, large-scale, distributed high-performance CI for U.S. scientific and engineering research.

‹ NCAR-Wyoming Supercomputing Center

Hardware cyberinfrastructure ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
        - Data-intensive computing architecture
        - NWSC-1 computing procurement
        - AMSTAR storage procurement
        - Production supercomputing status
        - NCAR's Globally Accessible Data Environment
        - Archival systems
        - Data analysis and visualization environment
        - Network engineering and telecommunications
        - Cybersecurity
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
    - Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

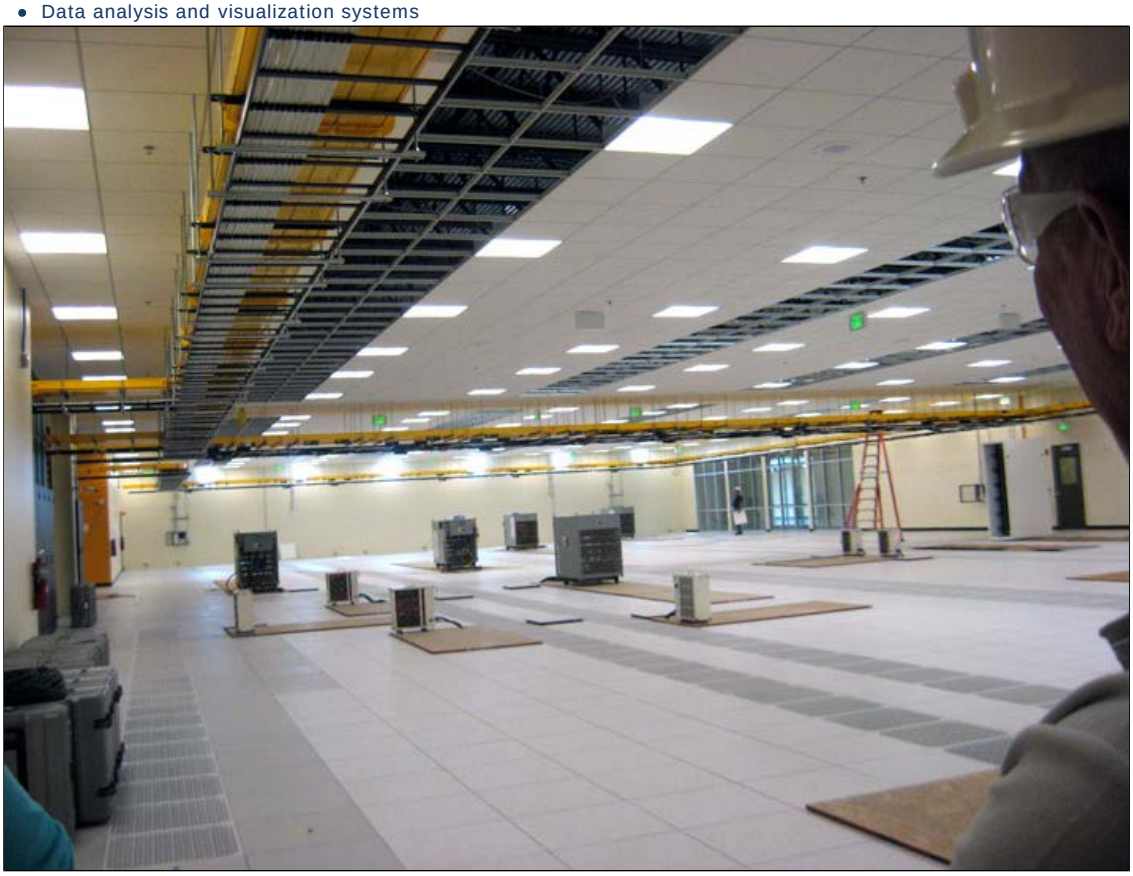
2009-2014 Strategic Plan »

Search

Hardware cyberinfrastructure

CISL fulfills its computing imperative to provision computing, storage, data analysis, visualization, networking, and archival systems customized to support the atmospheric and related sciences by delivering robust and reliable resources and services in an end-to-end research environment. For over 1,300 users in a wide variety of disciplines, CISL provides:

- High performance production computing
- Data storage and archival environments
- Local and wide-area network connectivity
- Data analysis and visualization systems



The NWSC facility construction progressed rapidly from groundbreaking in June 2010 to infrastructure systems testing in late August 2011. Shown in this photo is a 3 MW load test of the power and cooling systems in the facility's data center.

CISL also actively participates in projects designed to provide advanced services and tools to enable Earth System science for a diverse community of users, including:

- Collaboration on national and regional supercomputing initiatives
- Science gateways for climate, environmental, and astrophysical research initiatives
- Experimental computing systems

The most notable events for CISL during FY2011 included the completion of NWSC construction in Cheyenne, Wyoming. Official groundbreaking took place on 15 June 2010, with a ceremony highlighted by statements from Wyoming Governor Dave Freudenthal, UCAR Director Rick Anthes, NCAR Director Roger Wakimoto, CISL Director Al Kellie, and officials from the University of Wyoming and the National Science Foundation. At the end of FY2011, construction was completed and final testing of the building infrastructure systems was in progress.

Development continued during the year for the RFP specifications and processes that will lead to the acquisition of

the HPC computing, data analysis, and centralized data storage equipment to be installed at the facility during FY2012. Contract negotiations and NSF approval were completed and the vendor delivery schedule is being developed.

CISL enhanced three important technologies in the NCAR computational environment in FY2011:

- Acquisition and deployment of equipment for a 1.2 PB expansion of the GLobally Addressable Data Environment (GLADE) centralized data storage filesystem
- Augmentation of the NCAR High-Performance Storage System (HPSS) archive with additional capability to support the NCAR MSS production workload
- Transition to HPSS of over 12 PB of data from the NCAR MSS

CISL's main supercomputer, Bluefire, remained the primary production system for the Climate Simulation Laboratory (CSL) and the NCAR/UCAR user community. It has proven to be a reliable and efficient computational platform. During the year, several projects were provided the opportunity to study especially challenging problems through special computational campaigns on Bluefire.

CISL is committed to deploying and maintaining a highly productive, end-to-end computational environment, and during FY2011 CISL enhanced the data analysis and visualization environment by deploying a centralized home filesystem capability. CISL deployed HPSS in production, ingesting all NCAR MSS data into HPSS, and decommissioned the NCAR MSS system after 25 years of service. In addition, CISL completed the development of, released, evaluated, and completed vendor negotiations for the acquisition of HPC, high-speed file systems, and disk storage equipment for the NWSC. Finally, and most importantly, CISL completed the NWSC construction and began facility commissioning.

NCAR's supercomputers are managed by CISL under the UCAR/NSF Cooperative Agreement and are supported by NSF Core funds including CSL funding.

‹ CISL computing services

Data-intensive computing architecture ›

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Log in

2011 CISL Annual Report

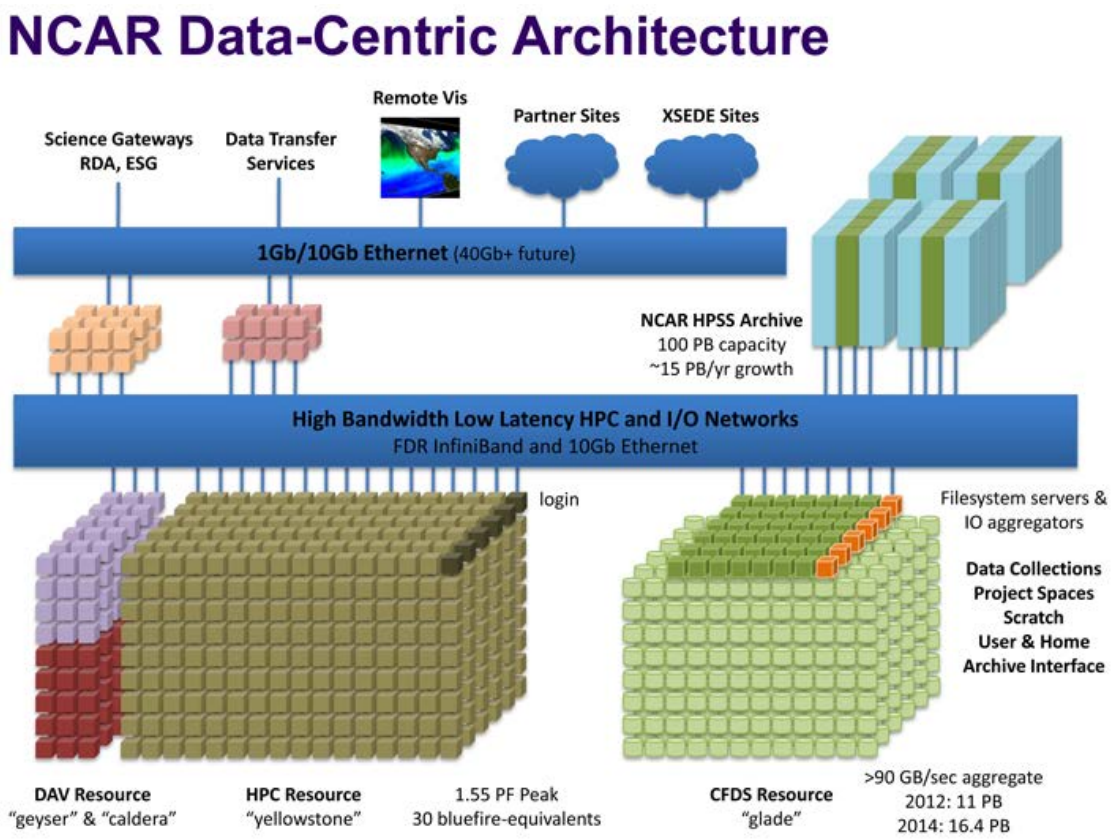
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
        - Data-intensive computing architecture
        - NWSC-1 computing procurement
        - AMSTAR storage procurement
        - Production supercomputing status
        - NCAR's Globally Accessible Data Environment
        - Archival systems
        - Data analysis and visualization environment
        - Network engineering and telecommunications
        - Cybersecurity
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Data-intensive computing architecture

Traditionally, high-performance storage is procured and tightly associated with individual computing systems. This conceptual model leads to a processor-centric design where each computer must be surrounded by a collection of services: online data, archived data, data management, data analysis, visualization, external interfaces, and networking. To complete multistep workflows, this design requires data to be copied between the separate filesystems of the various components supporting the supercomputer.

Recently, computing power increases have been outpacing data system performance, dataset sizes are increasing exponentially, and this significantly increases the cost of duplicating data and maintaining multiple copies of it to support user workflows. Because of these changes in computing power and dataset sizes, the processor-centric model is becoming untenable, especially for the long term. In its place, CISL has adopted a data-centric model in which a common, high-speed, central filesystem holds all data for shared access by all the computing and support systems required to complete scientific workflows. This design improves scientific productivity and reduces costs by eliminating the need to move or maintain multiple copies of data.



This diagram shows the foundational CISL architecture for the equipment to be deployed in the new NWSC facility. It shows the integration and relative sizes of systems for computing, data analysis and visualization, online and archived data, data management, external interfaces, and networks.

In FY2010, CISL deployed the GLADE file system at NCAR's Mesa Lab Computing Facility (MLCF) to confirm the value of this design and provide common, centralized, high-speed access to user data from CISL's CI resources. GLADE streamlines user workflows and minimizes time-consuming data movement tasks. The GLADE architecture currently operating at ML is a precursor to the data-handling environment designed for NWSC. The diagram above shows the foundational architecture for NWSC's data-centric design: the large (15 PB) high-speed (>90 GB/s) central filesystem is the centerpiece of the design.

CISL's data-intensive computing strategy extends past the CI hardware and includes a full suite of community data

services. CISL is leading the community in developing data services that can address the future challenges of data growth, preservation, and management. CISL also leads in supporting NSF's new requirement for data management plans. Our disk and tape-based storage systems provide an efficient, safe, reliable environment for hosting datasets, and CISL anticipates that its data services will be further streamlined, improved, and expanded through its new data-centric CI design.

‹ Hardware cyberinfrastructure NWSC-1 computing procurement ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
        - Data-intensive computing architecture
        - NWSC-1 computing procurement
        - AMSTAR storage procurement
        - Production supercomputing status
        - NCAR's Globally Accessible Data Environment
        - Archival systems
        - Data analysis and visualization environment
        - Network engineering and telecommunications
        - Cybersecurity
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

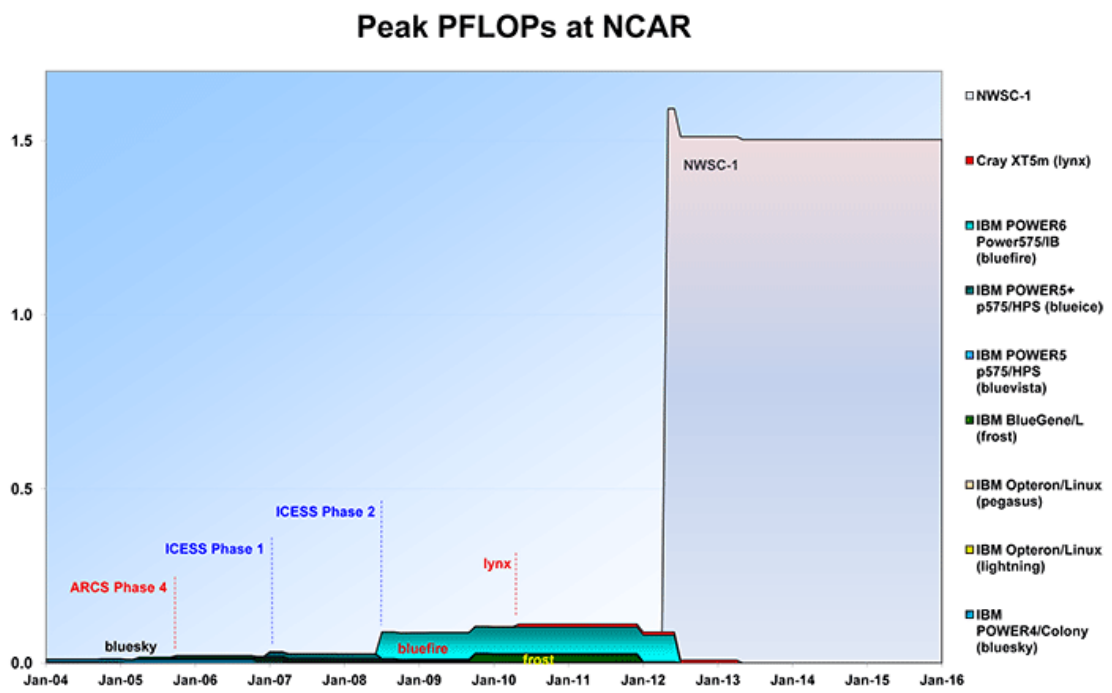
Search

NWSC-1 computing procurement

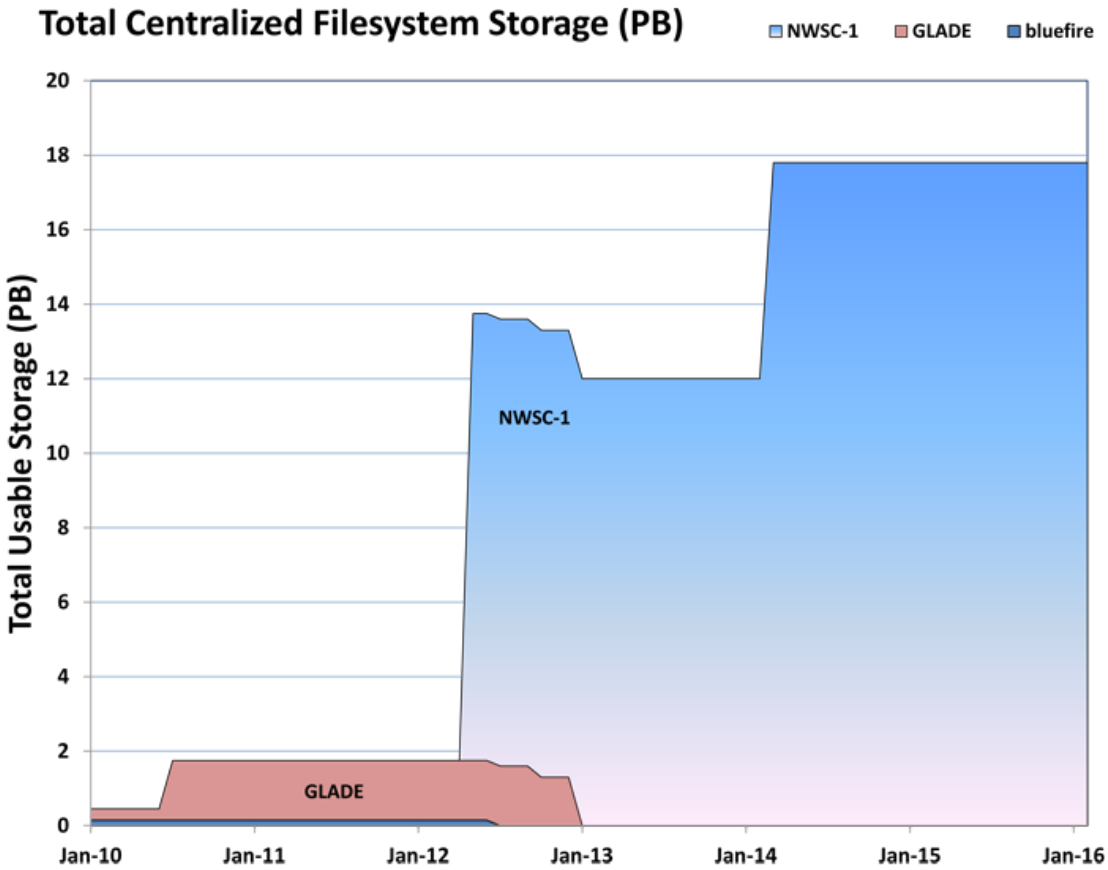
During FY2011, CISL executed and nearly completed the NWSC-1 procurement process for which it has been preparing since FY2008. That process included the instantiation of advisory and evaluation teams for science, technical, and business procurement. It also included the development of technical, management, and financial specifications for acquiring three interoperating yet independently administrable resources that will define the initial high-performance computing environment in the NCAR-Wyoming Supercomputing Center, namely:

- High-Performance Computing (HPC) resources
- Centralized Filesystem and Data Storage (CFDS) resources
- Data Analysis and Visualization (DAV) resources

The NWSC-1 procurement's resource specifications were driven by NCAR and community science requirements and informed by input from the science goals in the NCAR Strategic Plan, the NWSC Science Justification, the CISL Strategic Plan, the NCAR-Wyoming Partnership, CISL user surveys, and a major workflow study conducted by CISL. Through the efforts of the NWSC-1 science team, well-defined workload projections and scientific evaluation criteria were established for the NWSC-1 procurement. This anticipated science workload formed the basis for the benchmarks distributed with the NWSC-1 Request For Proposal (RFP), and the performance of those benchmarks on the proposed supercomputer systems, filesystems, and data storage resources was a major evaluation factor in the NWSC-1 procurement process.



This chart shows the anticipated increase in high-performance computing resources after the NWSC-1 procurement.



This chart shows the anticipated increase in centralized filesystem resources with the NWSC-1 procurement.

The NWSC-1 RFP's technical specifications and benchmark codes and instructions were iterated and refined through fall 2010, with the science, technical, and business evaluation teams agreeing on the specifications and the evaluation criteria and methodologies to be used during the proposal evaluation process. Key technical attributes specified in the RFP included:

- The initial equipment must be delivered during the first calendar quarter of 2012.
- The HPC resource must have a computational capability exceeding 1 PFLOPS as measured by the High-Performance LINPACK benchmark (HPL) by the first calendar quarter of 2014 and may be delivered in phases. If delivered in phases, the initial HPC system must exceed 0.5 PFLOPS. (One PFLOPS is one quadrillion -- 1,000,000,000,000,000 -- floating point operations per second.)
- The HPC resource's capacity would be measured by the NWSC-1 benchmark suite in terms of Bluefire-equivalents. A key evaluation factor was to maximize the total Bluefire-years over the four-year lifetime of the resulting subcontract. (A Bluefire-equivalent is the computational capacity of NCAR's current IBM POWER6 supercomputer as measured by the NWSC-1 benchmark suite. A Bluefire-year is one Bluefire-equivalent times one year.)
- The CFDS resource must have an initial usable data storage capacity exceeding six petabytes and a total usable capacity exceeding 15 petabytes by the end of the first calendar quarter of 2014.
- The CFDS resource must have an initial sustainable aggregate I/O bandwidth capability exceeding 30 GB/second and a sustainable aggregate I/O bandwidth exceeding 60 GB/second by the end of the first calendar quarter of 2014.
- The DAV resource must be comprised of two systems: a cluster of large-memory nodes (with 1 TB of memory each) and a small computational cluster, both containing Graphics Processing Units (GPUs) designed for use as both computational processors and graphics processors.

The RFP was released on 17 December 2010 to 16 prospective bidders, and four proposals were received by the 5 April 2011 deadline. Three proposals were complete bids for HPC, CFDS, and DAV resources, and one proposal was for the CFDS resource only.

With oversight by the NWSC-1 science team, the technical and business evaluation teams reviewed the proposals and tendered benchmark results. After numerous analyses, meetings, and proposal intercomparison discussions, the teams mutually agreed that all four tendered proposals were within the competitive range, and a 9 June 2011 request for submission of a final revised proposal was made to each of the four vendors. Guidance regarding proposal improvements was provided to each vendor. Revised proposals were received from the four vendors on 8 July 2011. Again, the technical and business teams evaluated the revised proposals and submitted their analyses and

findings to the science team, who in turn submitted a recommendation to CISL management and UCAR.

After further evaluation, CISL management recommended negotiations be commenced with the chosen vendor. Subcontract negotiations were successfully concluded on 2 September 2011, and the subcontract and accompanying justification for award documents were submitted for approval by the National Science Foundation on 12 September 2011. At end-FY2011, CISL and UCAR were waiting for NSF approval.

The NWSC-1 subcontract specified a 1.5 PFLOPS HPC system with 30 times the workload throughput of NCAR's current Bluefire supercomputer, CFDS resources with 15 times the sustained I/O bandwidth and 12 times the capacity of CISL's current GLADE system, and combined DAV systems that will provide a 20-fold increase in CISL's dedicated DAV resources. Initial equipment delivery will commence in January 2012, with initial HPC resource equipment delivery to NWSC in February 2012. Production computing operations are currently expected to begin at NWSC in May 2012.

‹ Data-intensive computing architecture

AMSTAR storage procurement ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
        - Data-intensive computing architecture
        - NWSC-1 computing procurement
        - AMSTAR storage procurement
        - Production supercomputing status
        - NCAR's Globally Accessible Data Environment
        - Archival systems
        - Data analysis and visualization environment
        - Network engineering and telecommunications
        - Cybersecurity
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

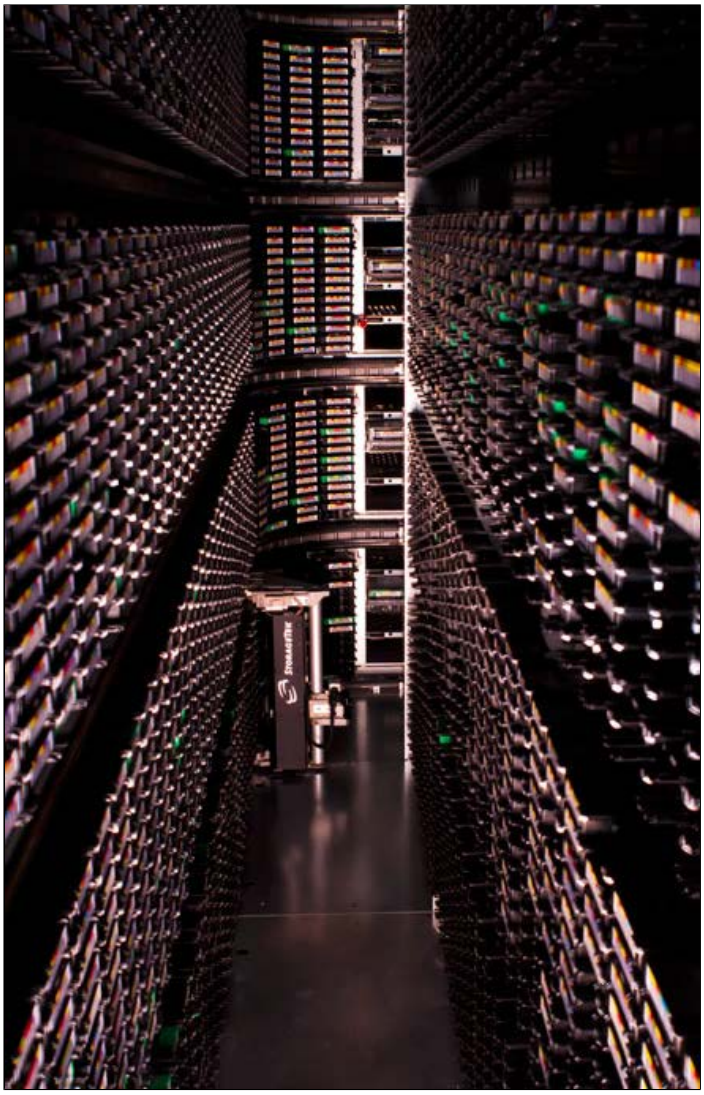
Search

AMSTAR storage procurement

In late 2010 -- after evaluating the state of the high-performance archive industry and determining initial NWSC archive growth requirements -- the NWSC Archive Technical Evaluation Team (TET) recommended delaying the release of the NWSC Archive RFP by two years and extending NCAR's existing Augmentation of the Mass Storage Tape Archive Resources (AMSTAR) subcontract to provide initial tape archive resources for NWSC. The NWSC-1 science team therefore recommended that CISL establish a separate NWSC archive procurement track.

In addition to minimizing the technical risk associated with deploying a new archival system simultaneously with the NWSC-1 deployment, CISL will gain two years of practical NWSC HPC, CFDS, and operational HPSS experience that the NWSC Archive TET can use to more accurately estimate archive capacity and throughput requirements. Historically, these requirements have been largely correlated with the capacity and capability of the HPC computing resource. They are expected to be reduced with the large-capacity CFDS. The NWSC Archive RFP is scheduled for a January 2013 release with equipment delivery by January 2014.

AMSTAR Modification M03 was executed in mid-FY2011. It extended the subcontract period of performance to December 2014 and included a technology upgrade and specified tape library equipment to be delivered to NWSC in early FY2012. With the technology upgrade, the two tape libraries at NWSC will have a total compressed capacity of 130 PB.



The interior of an Oracle SL8500 Tape Library. CISL extended the AMSTAR subcontract and will upgrade the tape technology in support of the NWSC-1 procurement.

‹ NWSC-1 computing procurement

Production supercomputing status ›

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Log in

2011 CISL Annual Report

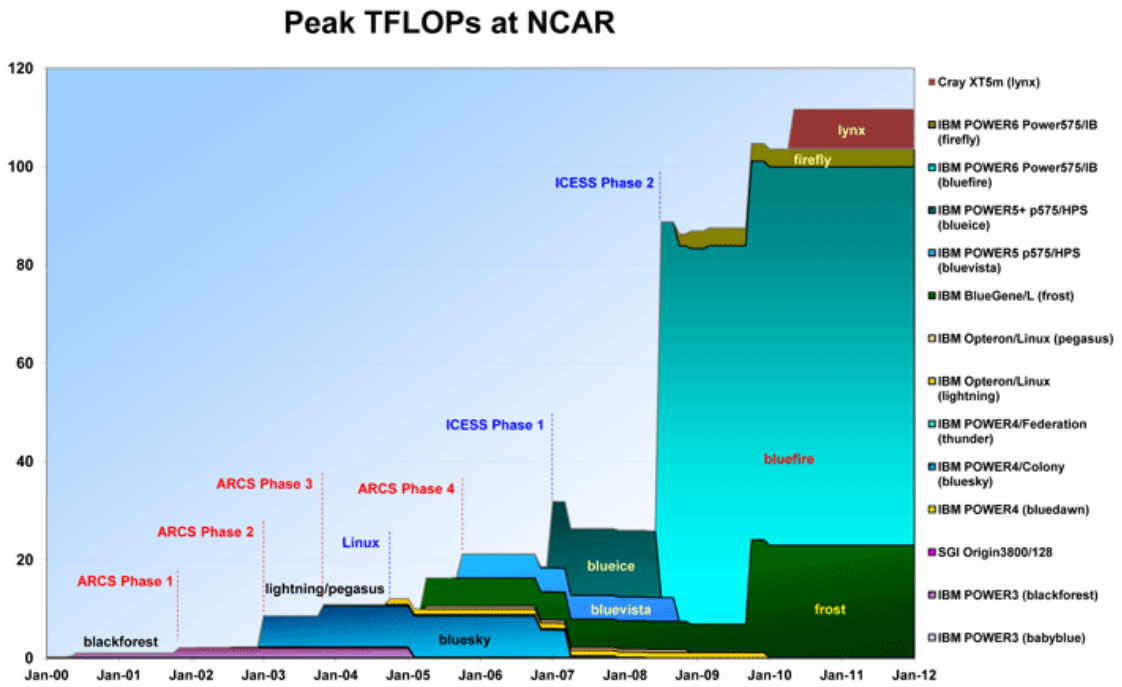
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
        - Data-intensive computing architecture
        - NWSC-1 computing procurement
        - AMSTAR storage procurement
        - Production supercomputing status
        - NCAR's Globally Accessible Data Environment
        - Archival systems
        - Data analysis and visualization environment
        - Network engineering and telecommunications
        - Cybersecurity
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Production supercomputing status

To achieve its computing imperative for hardware cyberinfrastructure, CISL provisions robust, reliable, secure high-performance computing resources that provide a production research environment for more than 1,450 users in a wide variety of disciplines related to the atmospheric sciences. These resources catalyze and empower the research community to pursue more innovative investigations. Computational resources are balanced for the needs of the numerical simulation communities served by CISL to provide the most useful combination of computational capability and capacity with scientific data analysis, visualization, and archival services that can be used effectively.



This diagram shows the growth of aggregate peak computing capacity available to the NCAR user community over the last 12 years. Regular increases in computational resources empower scientists to pursue more innovative research.

While maintaining a production supercomputing environment, CISL also works to provide equitable access to reliable computing resources while minimizing user wait times and maximizing resource utilization. These are key elements in production supercomputing services. Providing such equitable access while maintaining high utilization requires CISL to continuously monitor and maintain a proper balance of resource allocation, priority-based intelligent job scheduling, a well-tuned job queue structure, and single-job resource limits.

Bluefire and Firefly are IBM Power 575 production and test supercomputers. Firefly also provides backup production services, if needed, to support operational forecasts for the NSF's Office of Polar Programs' Antarctic Mesoscale Prediction System (AMPS). Further, CISL also provides the organizational focus, capabilities, and skill sets required to support important field and computational campaigns. Special computational campaigns that used Bluefire in FY2011 include IPCC AR5 Simulations, Ensemble-based Hurricane Predictability, Real-time Hurricane Forecast Demonstration Project, Snowfall & Snowpack Simulations for Colorado Headwaters, Storm-scale Analyses of Severe Convection, DART-POP Reanalysis, Real-time Explicit Convective Forecasting with WRF-ARW, Informing Climate-Related Decisions with Earth System Models, campaigns driven by unfolding natural disasters. Bluefire supports the CISL-developed on-demand capability computing model that enables the entire cluster, or portions of it, to support dedicated or shared special computing campaigns.

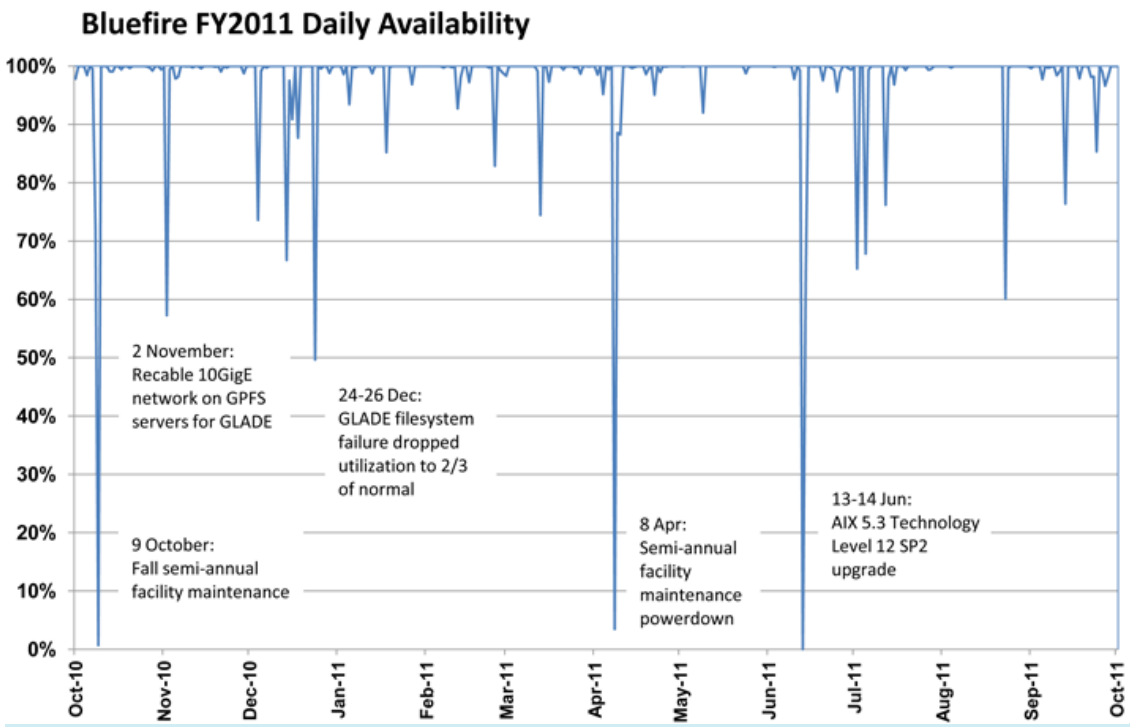
When possible, CISL works to regularly increase the computational capacity available to the community. To appropriately match the growth in computing capacity, CISL also upgrades and enhances peripheral resources that complement and supplement the high-end computing environment, such as data storage, networking, and data analysis and visualization systems. Computing capacity available for scientific research remained level during FY2011. Major enhancements will occur during FY2012 when NCAR's supercomputing facility will transition to NWSC

in Cheyenne, Wyoming. NWSC will provide very large increases in computing capacity, data storage, and data analysis and visualization resources to meet the growing demands of the community.

Supercomputer status

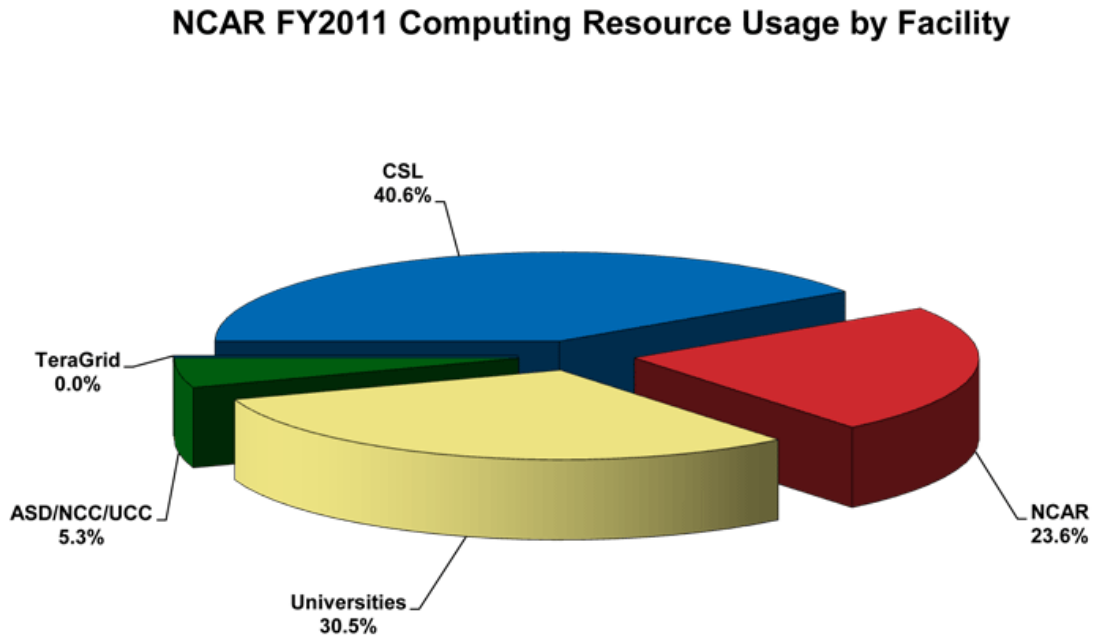
The primary computational workhorse at NCAR is Bluefire, an IBM POWER6 575 system with 77 TFLOPS of peak supercomputing capacity with 4,096 processors, 12 TB of memory, 150 TB of local disk storage, and a clock speed of 4.7 GHz. It began production at the end of June 2008, and CISL plans to keep it running through June 2012, after new supercomputing resources are in production at NWSC. During FY2011, CISL performed a number of software upgrades on Bluefire and Firefly. CISL continued to dedicate three Bluefire nodes, with Firefly as a backup, for the twice-daily operational forecasts in support of the NSF's Office of Polar Programs' Antarctic Mesoscale Prediction System (AMPS).

Bluefire remained highly utilized throughout FY2011, delivering 35.19 million CPU-hours of the total 35.88 million CPU-hours possible. Its overall availability was 98.07%, and the average user utilization was 91.9%. The average queue-wait time for the year was less than one hour.



Bluefire availability during FY2011. Keeping scientific productivity at a high level meets NCAR's charge to providing reliable and robust computational services to our scientific community.

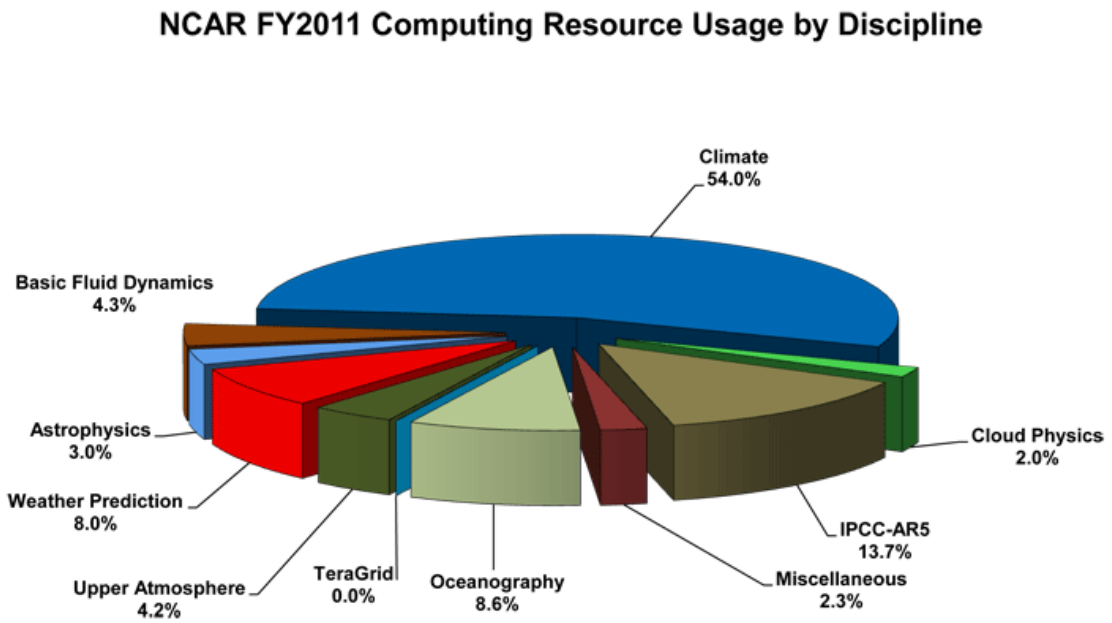
Since April 2010, CISL also operates an 8-TFLOPS, 912-processor Cray XT5m supercomputer named Lynx. This system provides a local development platform for UCAR community users who have access to larger Cray XT systems at other supercomputing centers. Although Lynx was acquired as a test system, users received access to the system and have been using it for research. During FY2011, Lynx delivered 7.89 million CPU-hours out of a total of 8.16 million CPU-hours possible, thereby yielding an overall availability of 96.7% and an average user utilization of 57.8%.



This chart shows how Bluefire was shared during FY2011 by Climate Simulation Laboratory projects, NCAR users, University Community users, and special campaign projects.

Impact on science

Scientists at NCAR and across the country continued using Bluefire to accelerate research into climate change, and to improve weather forecasting models for more accurate predictions of where and when extreme storms may develop or hurricanes may strike.



This chart shows how Bluefire was shared among various research disciplines during FY2011.

Looking ahead

During FY2012, CISL anticipates a continuing increase in demand for computational resources that will stress the existing systems and likely contribute to higher queue-wait times. CISL will augment computing capacity when new equipment is deployed at NWSC in FY2012. In FY2011, CISL executed and had almost completed the NWSC-1 procurement process that began in FY2008. NWSC-1 will provide a 1.5 PFLOPs HPC system capable of 30 times more workload throughput than Bluefire, a shared file system that will increase storage capacity by 12 times and offer 15 times the sustained I/O bandwidth of the current system, and a data analysis and visualization system that will have 20 times the capacity of current DAV resources.

Funding sources

This work is made possible through NSF Core funds, including CSL funding.

‹ AMSTAR storage procurement

NCAR's Globally Accessible Data Environment ›

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Log in

http://nar.ucar.edu/2011/lar/cisl/ncar%E2%80%99s-globally-accessible-data-environment Go

2011 CISL Annual Report

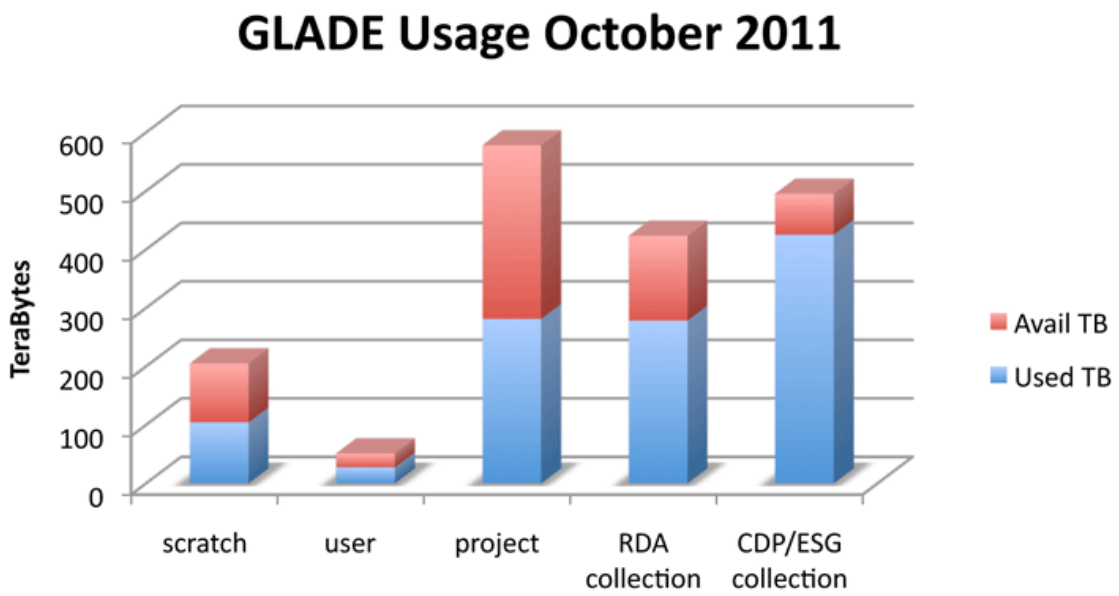
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
        - Data-intensive computing architecture
        - NWSC-1 computing procurement
        - AMSTAR storage procurement
        - Production supercomputing status
        - **NCAR’s Globally Accessible Data Environment**
        - Archival systems
        - Data analysis and visualization environment
        - Network engineering and telecommunications
        - Cybersecurity
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

NCAR’s Globally Accessible Data Environment

The GLobally Accessible Data Environment (GLADE) provides centralized high-performance file systems spanning supercomputing, data post-processing, data analysis, visualization, and HPC-based data transfer services. GLADE provides computation, analysis, and visualization work spaces common to all CISL HPC resources. Project space is allocated through NCAR’s allocation panels, while scratch and user space is available to all users of NCAR HPC resources. GLADE also hosts data from NCAR’s Research Data Archive (RDA), NCAR’s Community Data Portal, and the Earth System Grid, which curates CMIP5/AR5 data.



GLADE is fully allocated, and end-FY2011 utilization is shown in the chart. The GLADE storage cluster provides high-performance data services for NCAR’s HPC resources. GLADE provides large amounts of data storage for individual user projects as well as NCAR’s Research Data Archive, Community Data Portal, and the Earth System Grid. GLADE has significantly improved workflows for research.

The goals of this effort are focused on shifting data workflows from a process-based design to an information-based design. Through a globally accessible storage infrastructure, users now structure their workflows to use stored data directly without first needing to move or copy it. Additional services like high-performance data transfer protocols enhance our ability to bring computational data from other sites to NCAR for post-processing, analysis, and visualization.

In FY2011 we focused on enhanced data transfer protocols, allocation processes, charging mechanisms, and space management tools. This architecture became the backbone for the storage resource procurement as part of the NWSC-1 RFP process. Lessons learned from GLADE are being used to guide the deployment of NWSC resources.

This work supports CISL’s computing imperative for hardware cyberinfrastructure by provisioning storage and networking systems customized to support efficient workflows for the atmospheric and related sciences. Specifically, GLADE facilitates typical user workflows plus special efforts like supporting data flows for the IPCC AR5. GLADE also advances CISL’s computing imperative for facilities by demonstrating high-performance data services that will be critical for the next-generation resources that will operate at NWSC. By using GLADE-enabled workflows now, users are preparing for a smooth transition to NWSC’s new environment. GLADE equipment was purchased with NSF Special funds, and it is supported by NSF Core funds including CSL funding.

‹ Production supercomputing status

Archival systems ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
        - Data-intensive computing architecture
        - NWSC-1 computing procurement
        - AMSTAR storage procurement
        - Production supercomputing status
        - NCAR's Globally Accessible Data Environment
        - **Archival systems**
        - Data analysis and visualization environment
        - Network engineering and telecommunications
        - Cybersecurity
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Archival systems

The National Science Foundation TeraGrid used high-performance networks to integrate supercomputers, data archives, and data analysis facilities around the country. Its coordinated work environment enabled researchers throughout the U.S. to collaborate on especially challenging scientific questions and to process vast amounts of data that would not be manageable on smaller or isolated computing systems. Deployed by NCAR and other TeraGrid Resource Providers, the IBM High Performance Storage System (HPSS) enables a homogeneous storage solution that allows potential data archive connectivity directly with Wide Area Network (WAN) filesystems on the TeraGrid. HPSS also provided a data management system administration learning opportunity in a security environment external to the UCAR security perimeter.

NCAR's HPSS robotic tape libraries were acquired through the AMSTAR subcontract. The NCAR archival service was transitioned to HPSS on March 29, 2011. At that time, control of all the tape libraries was transferred to HPSS which is now managing over 14 PB of data stored in more than 80 million files.

In FY2009 CISL deployed an HPSS system directly accessible from outside the UCAR security perimeter and provide higher-performance lower-latency access to archive data than what was currently available with the NCAR MSS. Also in FY2009 a decision was made to replace the NCAR MSS with HPSS by January 2011 in preparation for transitioning archive services to a new data center. A transition plan was developed in late FY2009 that was executed in FY2010 and FY2011. The NCAR MSS was decommissioned on March 29, 2011, at which time, the existing 12 PetaBytes of data was made available via HPSS. The existing NCAR MSS tape archive equipment acquired under the "Augmentation of the Mass Storage Tape Archive Resources" (AMSTAR) subcontract was reused by HPSS after the decommissioning of the NCAR MSS. Additionally, HPSS server capacity was enhanced in early FY2011 to prepare for supporting the NCAR MSS workload after the transition.

The decision to delay the release of the NWSC Archive RFP by two years was made in December 2010 due to the uncertainty of the capacity and archive needs of the NWSC-1 procurement. The two year delay allows NCAR to gain experience with NWSC-1. The release of the NWSC Archive RFP is now scheduled for January 2013. To fill the 2 year gap, CISL exercised options to extend the AMSTAR subcontract period of performance. New tape technology increasing the total HPSS capacity 5 fold over the existing tape technology was included in the AMSTAR subcontract extension. The subcontract extension will meet NCAR's projected needs until 2014 when it is expected that the NWSC Archive RFP will be completed.

This effort supports CISL's computing imperative for hardware cyberinfrastructure by deploying a production HPSS instance and transitioning to HPSS as an alternative to the existing NCAR MSS system. The NCAR HPSS is managed by CISL under the UCAR/NSF Cooperative Agreement and is supported by NSF Core funds.

‹ NCAR's Globally Accessible Data Environment

Data analysis and visualization environment ›

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Log in

2011 CISL Annual Report

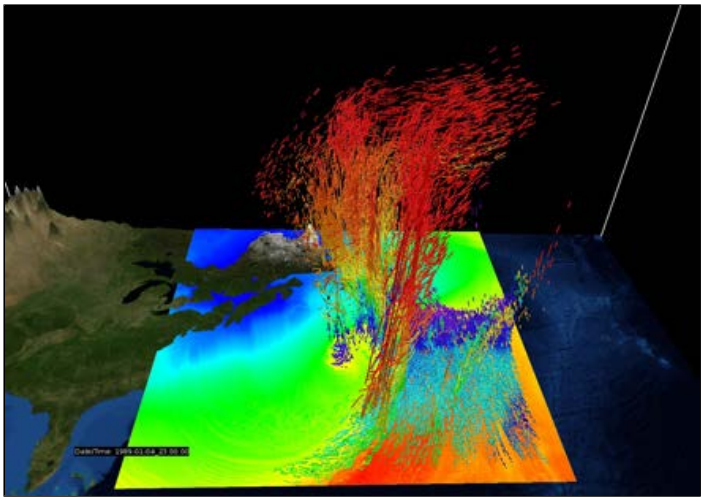
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
        - Data-intensive computing architecture
        - NWSC-1 computing procurement
        - AMSTAR storage procurement
        - Production supercomputing status
        - NCAR's Globally Accessible Data Environment
        - Archival systems
        - **Data analysis and visualization environment**
        - Network engineering and telecommunications
        - Cybersecurity
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Data analysis and visualization environment

The Data Analysis and Visualization Lab enhances scientific workflows by providing UCAR's research community with a highly advanced, unified computing environment tailored for the specialized needs of interactive data post-processing, analysis, and visualization. This evolving environment is comprised of powerful, closely coupled, interactive processing and visualization engines and large-capacity, high-performance global file systems. We provide direct support to the research community by developing algorithms for relevant visualization and analysis methods and by producing animations and imagery on behalf of the scientific staff.



On 3 January 1989, a strong extratropical cyclone formed off the coast of North Carolina and transported a large mass of arctic air over the Atlantic ocean. The storm underwent rapid intensification as it traversed the warm waters of the Gulf Stream, where water temperatures exceeded 70 degrees F. Its central pressure fell 66 mb in 18 hours to an astounding 936 mb -- a pressure typical of a Category 3 or 4 hurricane. Post-analysis of the NOAA aircraft reconnaissance research flight revealed a central pressure of 928 mb. This was the lowest pressure ever observed in an Atlantic extratropical cyclone south of 40 degrees latitude in the 20th century. This storm was visualized in VAPOR with atmospheric trajectory markers, colored by potential temperature, where changes in colors reflect latent heating or cooling of parcels due to sea-surface interactions and condensation. The flow is seeded with parcels within the warm sector at sea level. Reference: "A Planetary-Scale to Mesoscale Perspective of the Life-Cycles of Extratropical Cyclones: The Bridge between Theory and Observations," Melvin Shapiro et al., in The Life Cycles of Extratropical Cyclones, edited by M. Shapiro and S. Gronas, American Mathematical Society, Boston, 1999. (Click image for 28 MB animation.)

The goals of this effort are focused on addressing the growing size and complexity of scientific problems being researched at NCAR. Significant increases in resolution and data set sizes require not only the enhancement of NCAR computational resource capability and capacity, but also challenge CISL to provide advanced services and tools. The Data Analysis Services Group works directly with users to help develop new techniques and algorithms that allow scientists to push the boundaries of discovery.

In FY2011 we continued to support the current computational, visualization, and data transfer service offerings. This architecture was enhanced and designed to more tightly couple with the supercomputing resources for the NWSC-1 RFP process. Lessons learned from these efforts are being used to guide the deployment of NWSC data analysis and visualization resources.

This work supports CISL's computing imperative for hardware cyberinfrastructure by provisioning computing, storage, data analysis, visualization, networking, and archival systems customized to support the atmospheric and related sciences. It also supports CISL's computing imperative for software cyberinfrastructure by developing and supporting software infrastructure specific to the simulation, analysis, and forecasting needs of the atmospheric and related sciences. Finally, the Data Analysis and Visualization Lab advances CISL's science frontier in understanding large and heterogeneous data sets by developing new methods and tools to visualize and extract information from such data sets. This ongoing service is supported by NSF Core funds including CSL funding.

‹ Archival systems

Network engineering and telecommunications ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
        - Data-intensive computing architecture
        - NWSC-1 computing procurement
        - AMSTAR storage procurement
        - Production supercomputing status
        - NCAR's Globally Accessible Data Environment
        - Archival systems
        - Data analysis and visualization environment
        - **Network engineering and telecommunications**
        - Cybersecurity
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Network engineering and telecommunications

The Network Engineering and Telecommunications Section (NETS) plans, engineers, installs, operates, maintains, develops strategy, and performs research for NCAR and UCAR's state-of-the-art data networking and telecommunications facilities. NETS provides a vital service to NCAR's research communities by linking scientists to supercomputing resources. These activities are essential to the effective use of NCAR/UCAR's scientific resources, and they foster the overall advancement of scientific inquiry. This work supports CISL's computing imperative to provision hardware cyberinfrastructure for the atmospheric and related sciences. It also supports CISL's computing frontier of center virtualization by providing infrastructure for science gateways and other Grid-based technologies.

NETS pursued these LAN projects in FY2011:

- UCAR network infrastructure re-cabling
  - Foothills Lab Building A (FLA, 3375 Mitchell Lane) rewiring
  - Foothills Lab Building 4 (FL4) rewiring design and demolition
- Network monitoring
  - CISL Nagios centralization design and testing
- NETS project management transition from MSProject to wiki-based method
- CPG staff training
- Multicast support activities
- Business continuity
- UPS, grounding, wireless networking, IPT, Collocation Facilities Management (CFM)
  - Wireless 802.1x certificates
  - NWSC IPT design and implementation
  - ML and FLA grounding
  - FLA wireless LAN
  - 802.11n surveyor
- CISL LAN and SAN projects
  - Cisco end-of-service and GigE upgrades
  - FL/MAR: Pedestal switch upgrade
  - FLA-FL2 fiber installation
  - SaSS access control system upgrade
  - Supercomputer RFP team
  - Participated in the CISL Change Control project team
- Security redesign projects
- NWSC LAN network design and construction
- UIS database project (PeopleDB)

NETS pursued these MAN projects in FY2011:

- MFS WWAN wireless replacement
- NWSC wireless MAN
- Boulder Point-Of-Presence (BPOP)
- Boulder Research and Administration Network (BRAN)
- Boulder Valley School District fiber partnership
- Remote-working and home-access
- SPOL wireless
- RAF wireless upgrade
- Mesa Lab 15KV fiber
- Mesa Lab road and parking lot cabling
- FL parking lot repaving cable location and fiber repair

NETS pursued these WAN projects in FY2011:

- Front Range GigaPoP (FRGP)
- UCAR Point of Presence (UPoP)
- National LambdaRail (NLR)
- Internet2
- Bi-State Optical Network (BiSON)
  - NSF ARI proposal and upgrade
- NWSC WAN

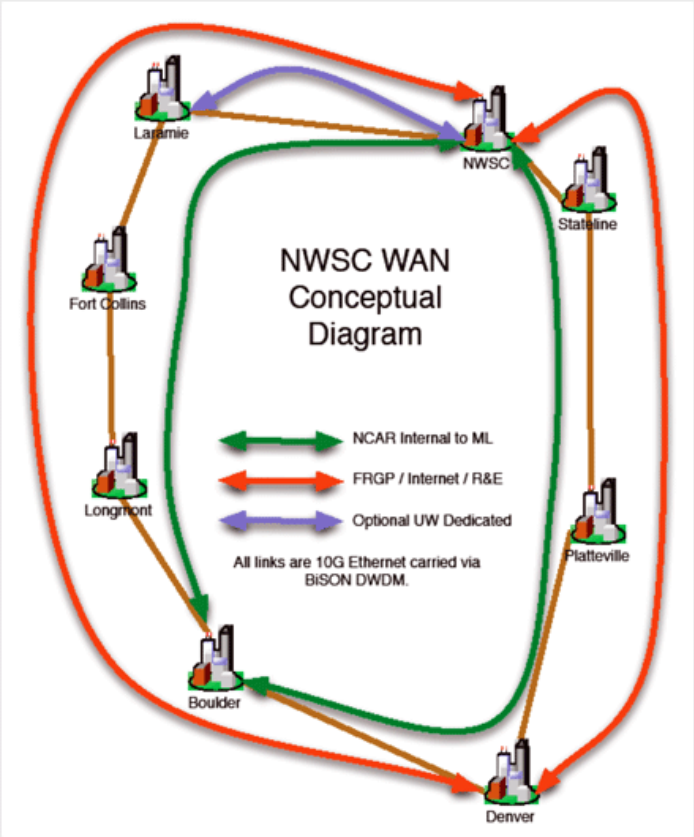
- NWSC fiber design
- XSEDE
- Western Regional Network (WRN)
- NOAA Research Network (N-WAVE)
- The Quilt Project -- National Regional Networks Consortium

In FY2012, NETS will continue to provide support and enhancements for all of these essential networking services. NETS activities are primarily supported through UCAR Communications Pool indirect funds.

Detailed project descriptions appear below for four of these projects: The Bi-State Optical Network (BiSON) NSF ARI proposal and upgrade, the Western Regional Network (WRN), the NCAR-Wyoming Supercomputer Center (NWSC) network design and construction project, and the NETS directory project.

Bi-State Optical Network (BiSON) NSF ARI proposal and upgrade

UCAR submitted and was awarded $430,000 for an NSF ARI proposal to upgrade BiSON. The BiSON partners contributed $160,062 to this project. The Bi-State Optical Network (BiSON) is a high-speed optical network of fiber optic links that serves a collaboration of research and educational institutions in Colorado and Wyoming. The purpose of BiSON is to provide robust, redundant access to regional and Wide Area Network (WAN) services to its members. The Front Range GigaPoP (FRGP) participants using BiSON Network Services include Colorado State University (CSU), the National Oceanic and Atmospheric Administration-Boulder (NOAA-Boulder), the University of Colorado-Boulder (CU-Boulder), the University Corporation for Atmospheric Research (UCAR), and the University of Wyoming (UW).



This shows the BiSON network with expanded fiber paths to integrate NWSC into the fiber optic ring. The paths are fully redundant with diverse building entrances to protect the facility from fiber cuts, and there are redundant WDM shelves to protect the facility from hardware failures. It is expected that at least four 10 Gbps paths will connect NWSC to the Mesa Lab, FRGP, and XSEDE. It is also expected that the other BiSON partners will install dedicated 10 Gbps paths to NWSC utilizing this infrastructure.

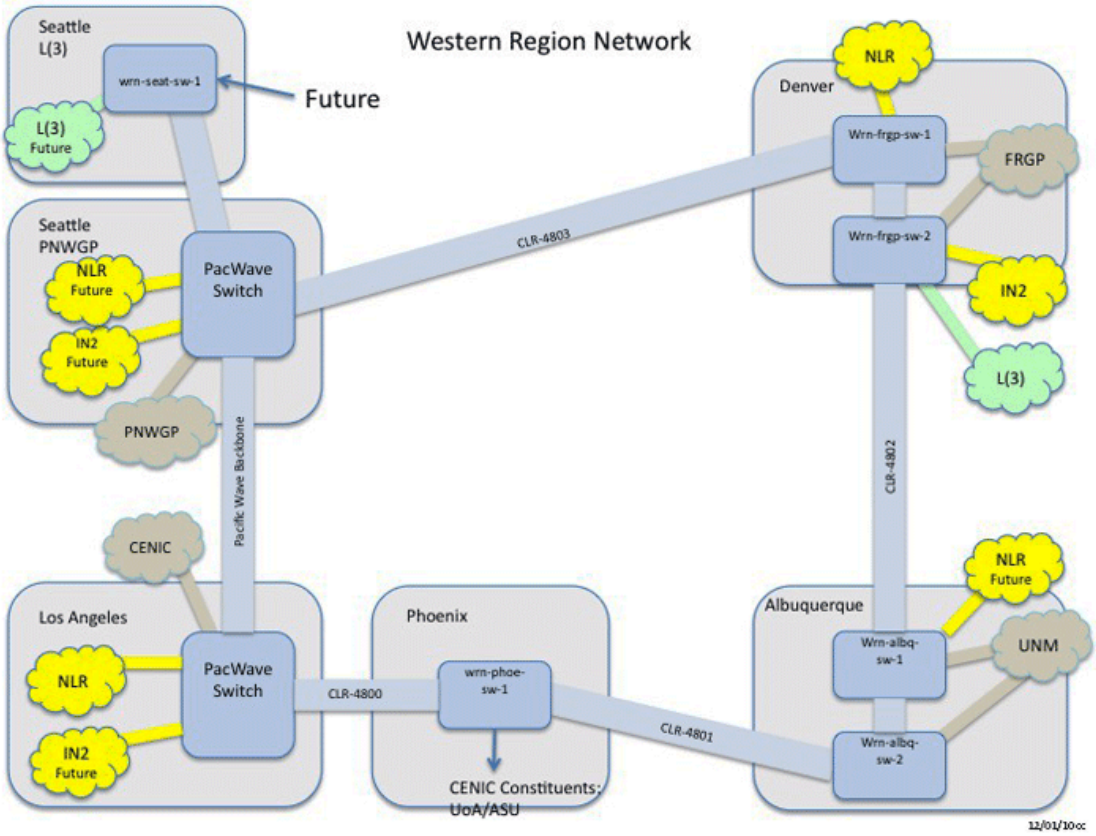
BiSON is a valuable piece of cyberinfrastructure connecting researchers at participating organizations to multiple sources of observations and data throughout Colorado, Wyoming, and the broader community via interconnections with Internet2, National LambdaRail (NLR), WRN, ESnet, and XSEDE. BiSON will also provide redundant, very high-speed connectivity for all FRGP participants to NWSC in Cheyenne, Wyoming.

This proposal funded the upgrade of BiSON's ADVA equipment from a single 2 Gbps ring to a WDM solution capable of supporting up to forty 10/40/100 Gbps lambdas. The resulting cyberinfrastructure will greatly increase the efficiency of scientists, educators, and researchers who transport enormous amounts of data both intra-BiSON and over the WAN, collaborate with others in the community, and access high-end resources such as NWSC, XSEDE, NASA, and Department of Energy (DOE) data and computing resources, including the Earth System Grid (ESG).

This project is complete. The bulk of the installation occurred the week of 4 October 2010. The installations at NWSC and 910 15th Street R7 were completed in summer 2011. The CSU R7 installation was completed in fall 2011. Dedicated 10 Gbps lambdas were installed for Boulder Point of Presence (BPoP), N-WAVE, CSU, and CU by fall 2011.

Western Regional Network (WRN)

The goal of WRN is to promote, advance, and sustain advanced networking services in support of research, education, and the members' respective missions. This includes participating in and sharing access to national research and education networks, commodity networks, transit/peering connections, and other similar services. Members and affiliates are located in Alaska, Arizona, California, Colorado, Hawaii, Idaho, Nevada, New Mexico, Washington, and Wyoming. WRN established, maintains, and sustains networking interconnections and shares services among the members. Each member operates advanced networks for, and on behalf of, themselves, their members, and other affiliates.



This shows the WRN at its final phase. Most of the components of the network are ordered, all circuits are installed and operational, and the hardware is being installed for Layer 2 network support. The WRN network enables the FRGP to super-aggregate WAN connections to purchase larger bandwidth at significantly lower costs. WRN also builds a significant geographical consortium, which will allow increased influence over vendors and R&E network providers. By participating in WRN, UCAR will have access to more and higher-speed networks at lower cost.

The principal goal of this collaboration is provide an opportunity for the members to share services in a manner that appropriately balances the effectiveness and efficiency of subscription to, delivery of, and sharing of, the services. This includes the potential to reduce costs, enhance services, and coordinate participation in activities of mutual interest.

In FY2011, the development and implementation of this project was completed. The project is now in an operational state. The Level3 commodity Internet service was transferred to CENIC via WRN at significant cost and administrative savings. Intra-WRN peering is active. Network construction was complete by 31 October 2010. The University of Hawaii (UH) amendment was written, and UH joined WRN. TR/CPS service was transitioned to WRN I2 infrastructure to save costs and simplify design.

NWSC network design and construction project

NETS is the lead to design, test, verify specifications and standards, and install network hardware for the NWSC LAN, MAN, and WAN. State-of-the-art networking is a critical component for NWSC, and the implementation must include high speed (4x10 Gbps initially), secure, redundant, and robust elements.

Network engineers Jim Van Dyke (left) and Del Harris (foreground) help prepare the NWSC facility for operation.

Extensive work continued at NWSC. Detailed network LAN, MAN, and WAN designs were fine tuned, including attending detailed weekly design and construction meetings. Construction proceeded on the NWSC networking infrastructure and was largely completed and verified, and NETS staff were intimately involved in the construction meetings and construction review to ensure that specifications were met and design changes were reviewed and approved. NETS also assisted CISL with the

specification, design, and integration of
network-dependent systems into NWSC, including building automation, cellular, public address, video, and security.

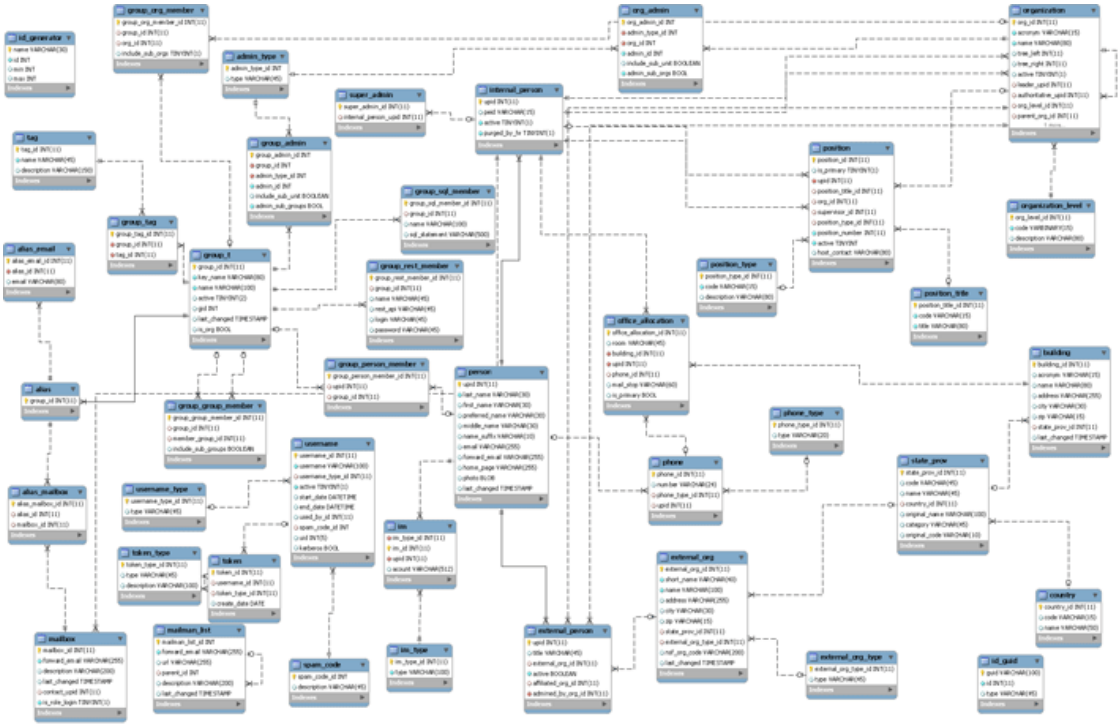
An RFP was issued by the University of Wyoming for the construction of the WAN fiber in September 2010 and was awarded by the end of October 2010. Construction of phase one was completed by 1 August 2011, and construction of phase two will be complete by 1 November 2011. A 10 Gbps network path is active on phase one as of mid-August 2011.

NETS worked with the University of Wyoming to install, test, and activate a backup wireless MAN system. NETS also participated on the NWSC supercomputer RFP team.

NETS completed the installation and activation of the production LAN and IPT infrastructure by 30 September 2011, provided a test network for the Building Automation System in May 2011, and finalized the BAS LAN system by 1 September 2011. This project will be completed in FY2012.

NETS directory project

This project's goal is to provide accurate, up-to-date, centralized directory information from a single database. In addition to bringing together disparate elements not previously in any single location, NETS has eliminated the manual and often redundant steps involved in manipulating directory information. NETS emphasized secure solutions and worked to keep directory data in formats that can easily be exported and shared with other systems both now and in the future.



This shows the data flow for the web-based UCAR "Find People" application. The NETS directory provides an authoritative, continually updated source for UCAR room number and telephone extension information. This directory is part of a larger project to improve the efficiency of creating and maintaining people data while improving accuracy.

This effort addressed issues specific to NETS as well as larger, organization-wide issues. NETS provides UCAR's authoritative source for room number and telephone extension data.

The PeopleDB project developed an automatic method to integrate all the sources of staff information into one location and removed the hand-entry or correction of "people (or directory-type) data." This required new methods to obtain the data from text files and ways to export it into the NETS databases (Call Manager, ExtraView, and Cabling Database).

Stakeholders for these processes include the space planning office, the Archibus facilities database, the ExtraView work request system, the NETS cabling database, and IP Telephony team. In FY2011, the PeopleDB project, including the NETS portion, was completed and successfully launched.

‹ Data analysis and visualization environment

Cybersecurity ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
        - Data-intensive computing architecture
        - NWSC-1 computing procurement
        - AMSTAR storage procurement
        - Production supercomputing status
        - NCAR's Globally Accessible Data Environment
        - Archival systems
        - Data analysis and visualization environment
        - Network engineering and telecommunications
        - **Cybersecurity**
      - User services
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Cybersecurity

Infrastructure cluster designed to support security monitoring at NWSC. Computer systems work together to collect and analyze network traffic, then issue alarms for abnormal activity.

UCAR manages and maintains a large and diverse set of compute, data, email, web, and network servers that form the core information technology within the institution. Not only are these systems valuable monetarily, they comprise vital scientific research tools and business continuation systems used throughout UCAR and the university communities. To pursue the scientific mission of the organization without hindering the free exchange of information, CISL is committed to maintaining a security posture that appropriately balances usability with the security of the systems.

Providing secure information technology systems within CISL and across UCAR supports CISL's computing imperatives to provision hardware and software cyberinfrastructure for the atmospheric and related sciences. Cybersecurity is also critical to CISL's computing imperative for data curation and to its computing frontier for center virtualization. The security strategy we employ must be balanced by the goals of openness and ease of access. CISL proactively strives for zero security incidents on its systems, and CISL responds and reports an incident analysis if one occurs.

It is vital to the organization that we take appropriate measures to ensure the confidentiality, integrity, and availability of intellectual property, data, and systems. Appropriate measures balance the needs for availability and usability with those for integrity and confidentiality.

During FY2011, these factors were vital to the continued security of IT systems at UCAR:

- Coordinated consistent security policies and procedures across UCAR by the Computer Security Advisory Committee (CSAC), with the goal of maintaining the appropriate balance between reasonable protection and pursuit of the scientific mission of the institution.
- Filled vacancies for security engineers, resulting in a four-person Security Engineering Group (SEG).
- Continued to encourage UCAR staff to engage with SEG early in the process of developing or purchasing systems that will be accessible across the UCAR network security perimeter, or that will require UCAS token or password authentication.
- Maintained UCAR-wide token authentication using one-time password (OTP) tokens.
- Remained engaged in collaborative efforts with peer and TeraGrid/XSEDE centers to share cybersecurity information, best practices, and incident notification.
- Built on new Kerberos infrastructure, providing usability enhancements and enabling additional services to use the common authentication service.
- Designed, acquired, configured, and tested infrastructure to provide network monitoring and authentication for NWSC.
- Collaborated with peers to develop and refine policies and procedures for secure operation of high-performance computing resources at NWSC.
- Enhanced our network and host monitoring tools to support increased traffic loads and provide redundancy using our other campuses.

Cybersecurity at NCAR is supported by a combination of NSF Core funding and UCAR Communications Pool indirect funds.

‹ Network engineering and telecommunications

User services ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
        - User community
        - Special computational campaigns
        - Help desk and consulting
        - Allocating supercomputing resources
        - Earth System Model support
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

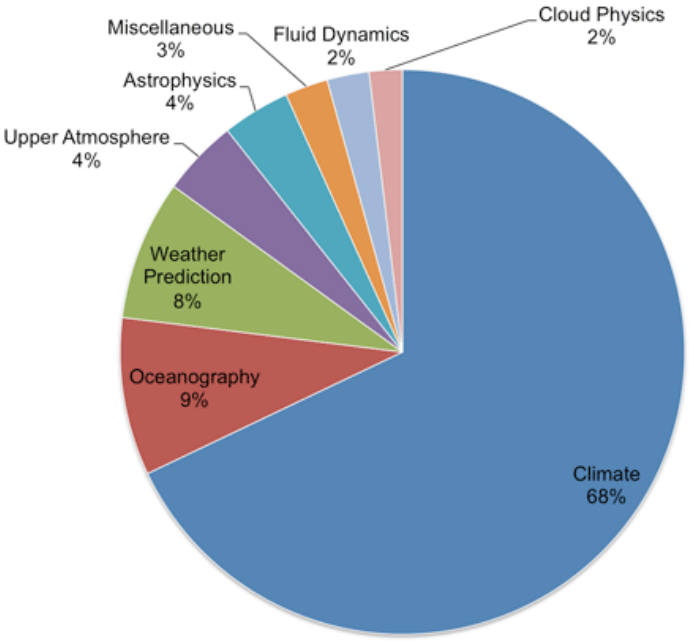
2009-2014 Strategic Plan »

Search

User services

CISL has a strategic commitment to provide robust, accessible, and innovative services and resources to researchers in the atmospheric and related sciences, including the broad university community, CSL users, and NCAR researchers. CISL works to provide our users with equitable and efficient access to reliable computing resources and with responsive and knowledgeable support services.

NCAR is one of only a small number of institutions with the resources necessary to conduct high-end climate research, model development, and campaigns such as the Intergovernmental Panel on Climate Change (IPCC) assessments. CISL's success in supporting scientific goals and enabling scientific impact depends in equal measure on understanding the needs and research objectives of its user community, and on integrating CISL's resources, capabilities, and services in response to those needs. Our success can be measured in part by the continued high demand for CISL resources in FY2011, far in excess of available resources.



This diagram shows how CISL computing resources are allocated among various disciplines in the Earth System sciences. User Services staff provide computational and data management support services tailored to needs of this research community.

As a discipline-specific computing center, CISL is able to provide the capabilities and skill-sets required to support important field and computational campaigns with on-demand resources that include those driven by unfolding natural disasters. CISL works to accelerate scientific discovery through numerical simulation by providing a significant portion of the Bluefire system to special campaigns.

In FY2011, CISL restructured its user services functions to prepare for the transition to the NWSC resource environment. This restructuring has joined the CISL Help Desk, Accounts and Allocations, and Consulting Services to streamline user-oriented procedures and activities. In addition to staff realignment, CISL has significantly redesigned and re-engineered its allocation policies and accounting system in preparation for NWSC. These allocation and accounting efforts recognize the rapidly emerging data-centric nature of computational science and are designed to improve the management of storage, analysis, and visualization resources in CISL's CI environment, thereby enhancing CISL's ability to support our user community.

This work supports CISL's computing imperative to provide hardware cyberinfrastructure customized for the atmospheric and related sciences. This ongoing service for users is supported by NSF Core funds including CSL funding.

‹ Cybersecurity User community ›

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Log in

2011 CISL Annual Report

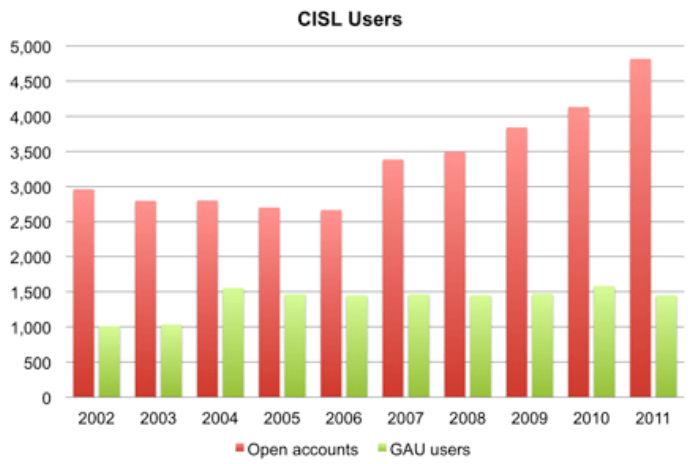
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
        - User community
        - Special computational campaigns
        - Help desk and consulting
        - Allocating supercomputing resources
        - Earth System Model support
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

User community

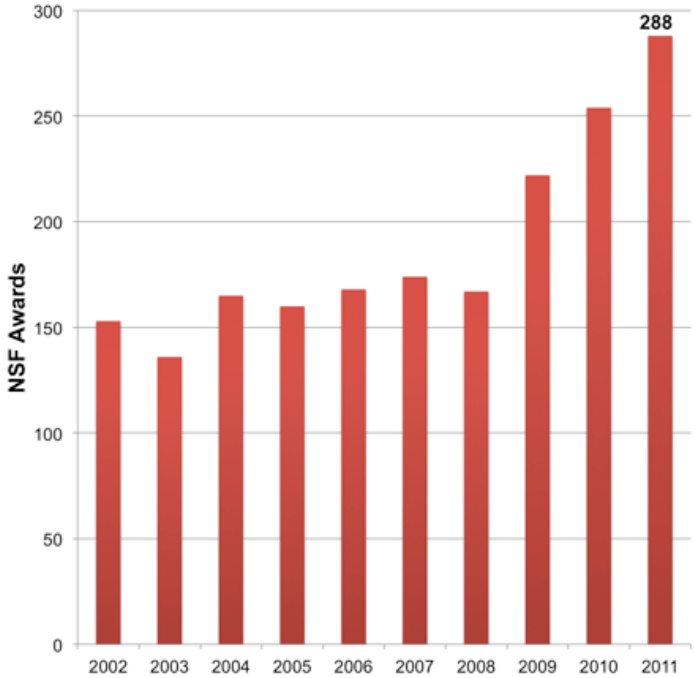
CISL's success in supporting scientific goals and enabling scientific impact depends in equal measure on understanding the needs and research objectives of its user community, and integrating CISL's resources, capabilities, and services in response to those needs. In FY2011, that user community included more than 1,400 users at 161 universities and other institutions who took advantage of CISL's high-performance cyberinfrastructure (CI) and services. These active users represented about one-fourth of the more than 4,800 users who had computing or storage accounts during that year.



CISL's strong HPC user community (including HPSS and MSS users) has grown over the past 10 years.

A discipline-specific approach to supercomputing allows us to tailor system design and services for our user community and satisfy the highly specialized technical requirements of scientific applications such as climate system models. A well-defined workload allows CISL and NCAR scientists to optimize the most heavily used models and applications on current and future systems. It also ensures that model development and research in Earth System processes can occur in a controlled yet responsive environment where researchers can prepare complex models and perform the computationally demanding tests required to validate them.

The size, breadth, and disciplinary pursuits of the CISL user community offer perspectives on the scientific impact enabled by CISL's HPC, data analysis, and archival resources. This user community reported more than 700 publications and more than 70 dissertations and theses resulting from CISL HPC support between FY2009 and March 2011 (the timeframe of our most recent survey). Approximately 80% of CISL's HPC users run NCAR-provided climate and weather applications.



CISL allocations to university researchers have supported the scientific objectives of more than 150 different NSF awards each year for the past decade. In FY2011, active projects supported 288 unique NSF awards.

Scientifically, our user community spans more than 30 areas of interest in the atmospheric and related sciences. In geographic scope, the user community for CISL's HPC environment spans hundreds of different universities and collaborating institutions, primarily in the U.S. as defined by our HPC mission. In terms of serving the NSF research community, CISL allocations to university researchers have supported the scientific objectives of more than 150 different NSF awards each year for the past decade. In FY2011, active projects supported 288 unique NSF awards.

This work is a crucial part of CISL's computing imperative to provide hardware cyberinfrastructure customized for the

atmospheric and related sciences. This ongoing service for users is supported by NSF Core funds including CSL funding.

‹ User services

Special computational campaigns ›

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Log in

2011 CISL Annual Report

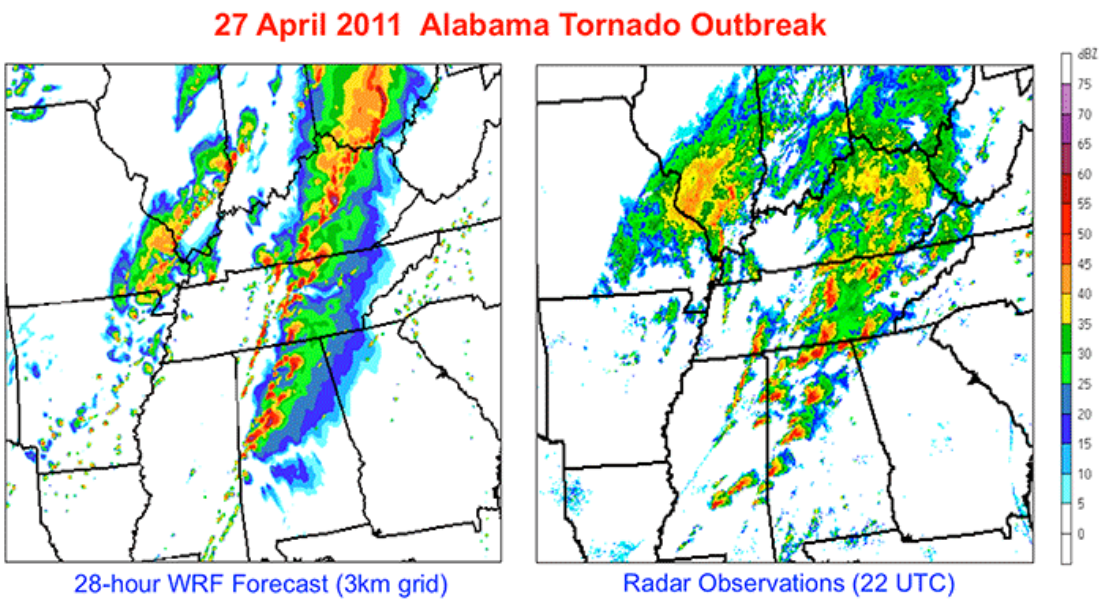
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
        - User community
        - Special computational campaigns
        - Help desk and consulting
        - Allocating supercomputing resources
        - Earth System Model support
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Special computational campaigns

The CISL production supercomputing environment supports special computational campaigns for ongoing and short-term computational projects, as well as on-demand capability computing, all via a priority-based and near-real-time job scheduling mechanism. These campaigns are managed to minimize the impact on the capacity computing delivered to NCAR, university, and CSL scientists.

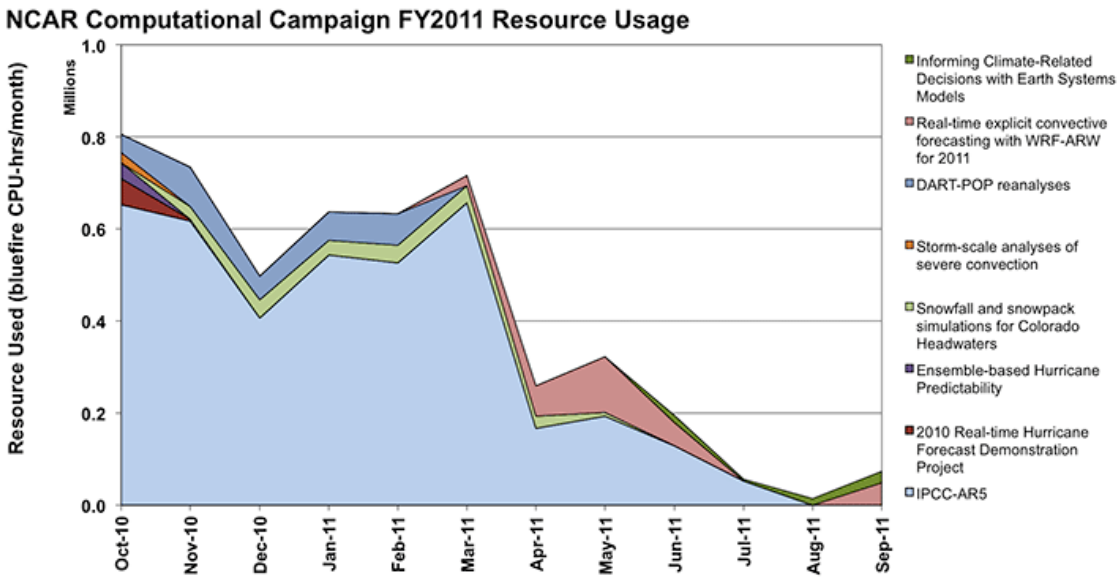


Example of a WRF-ARW 28-hour radar reflectivity forecast for the 27 April 2011 Alabama tornado outbreak. With CISL support for special campaigns, MMM scientists produced real-time explicit convective forecasts to test the latest improvements in the WRF-ARW modeling system and supported the Deep Convective Clouds and Chemistry (DC3) test-phase field campaign and the SPC/NSSL (Storm Prediction Center/ National Severe Storms Lab) Spring Program for severe weather forecasting.

The following table lists the special computational campaigns supported by CISL during FY2011. Bluefire continued running the IPCC AR5 simulations and control runs, two on-demand projects -- the 2010 real-time hurricane forecast project and the spring 2011 real-time explicit convective forecasts with WRF-ARW -- and projects related to snowfall and snowpack predictions, data assimilation to produce ocean initial conditions, and climate change simulations for use in water resource adaptation planning.

FY2011 Special Campaigns	Principal Investigator	Begin	End
2010 Real-time hurricane forecast demonstration project	Chris Davis, Wei Wang	11-Jun-10	31-Oct-10
IPCC-AR5	multiple PIs	1-Jun-09	31-Dec-10
IPCC-AR5 CCSM control runs	John Wolfe	10-Aug-09	31-Dec-10
IPCC-CORE ESM 20th century with emissions	M. Vertenstein	24-May-10	31-Mar-11
IPCC-CORE ESM 20th century with concentrations	M. Vertenstein	25-May-10	31-Mar-11
IPCC-TIER1 CCSM4 LGM	M. Vertenstein	20-May-10	3-May-11
IPCC-TIER2 CCSM4 Last Millennium	M. Vertenstein	20-May-10	31-Mar-11
IPCC-TIER1 CCSM4 Mid-Holocene	M. Vertenstein	20-May-10	31-Mar-11
NCC-Core ESM control (1850 conditions) with concentrations	M. Vertenstein	2-Aug-10	31-Mar-11
NCC-Core ESM 21st century RCP 8.5 with emissions	M. Vertenstein	22-Oct-10	31-Mar-11

NCC-Core ESM 21st century RCP 8.5 with concentrations	M. Vertenstein	22-Oct-10	31-Mar-11
NCC-ESM 1% CO2 Experiments	K. Lindsay	17-Feb-11	31-Mar-11
ASD-GeoMIP Integrations with CESM	J.-F. Lamarque	10-Mar-11	11-Jul-11
Snowfall and snowpack simulations for Colorado Headwaters	R. Rasmussen	4-Oct-10	31-May-11
Storm-scale analyses of severe convection	G. Holland	1-Oct-10	31-Oct-10
DART-POP reanalyses	G. Danabasoglu, J. Tribbia	20-Oct-10	28-Feb-11
Real-time explicit convective forecasting with WRF-ARW for 2011	M. Weisman	4-Mar-11	31-Oct-11
Informing Climate-Related Decisions with Earth Systems Models	L. Mearns	1-Jun-11	-



This chart shows the monthly usage of Bluefire for special computational campaigns during FY2011. CISL works to accelerate scientific discovery through numerical simulation by providing a significant portion of the Bluefire system to special campaigns.

Using CISL computing resources during FY2011, the Community Earth System Model (CESM) project continued to tackle an extremely ambitious set of climate change simulations in support of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) due in late 2013. As in other major international modeling centers, CESM is following the CMIP5 experimental design. CMIP5 describes a set of coordinated climate model experiments designed to address outstanding scientific questions that arose from the IPCC's last assessment report (AR4): to improve understanding of climate, and to provide estimates of future climate change that will be useful to those considering its possible consequences. CMIP5 is a 5-year experimental design, but CISL support means that a significant fraction of the CESM experiments can be completed in time to be included in AR5.

Under the CMIP5 strategy, two types of modeling experiments are being conducted: near-term, initialized decadal prediction simulations (10-30 years) with relatively high-resolution climate models; and long-term simulations from about 1850 through the end of the current century and beyond, using both physical climate system models and Earth System models (such as CESM) that include a coupled carbon cycle.

NCAR's MMM division ran real-time explicit convective forecasts at 3-km grid resolution from 27 April through 15 June to test the latest improvements in the WRF-ARW modeling system and to support the Deep Convective Clouds and Chemistry (DC3) test-phase field campaign and the SPC/NSSL (Storm Prediction Center/ National Severe Storms Lab) Spring Program for severe weather forecasting. Forecasts to 48 hours were produced once a day from 27 April to 12 May. New this year was the use of WRF-DART (Data Assimilation Research Testbed) to produce a 15-km horizontal resolution analysis, chosen from a 50-member ensemble, to initialize the 3-km explicit convective forecast. WRF-DART had been applied to real-time hurricane forecasting during the 2009 and 2010 seasons, but this marked the first use of this system for real-time convective forecasting. Initial results suggest that this technique produces a competitive forecast compared to forecasts using more standard operational analyses, and it offers a valuable new addition to the convective guidance that is produced using various physics and analysis options. Also new this year was the inclusion of passive boundary layer tracers, offering guidance to DC3 investigators on the anticipated transport of chemical species by convective storms. Based on the success of these tests, WRF-ARW will again be used to support the full field phase of DC3 in spring 2012.

These special computing campaigns serve CISL's computing imperative to provision on-demand and real-time

services support for hardware cyberinfrastructure. Further, special computing campaigns support CISL's strategic action item to provision the CI necessary to support the IPCC AR5. This work is made possible through NSF Core funds, including CSL funding.

‹ User community

Help desk and consulting ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
        - User community
        - Special computational campaigns
        - Help desk and consulting
        - Allocating supercomputing resources
        - Earth System Model support
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Help desk and consulting

NCAR has a strategic commitment to provide robust, accessible, and innovative information services and tools to our customers, with end-to-end services for NCAR's supercomputer users that include both 24/7 frontline user support as well as consulting services for in-depth expertise. Over the past year, CISL has restructured its user services functions to prepare for the transition to NWSC operations. This restructuring united four functions, the CISL Help Desk, Consulting Services, Documentation, and Accounts and Allocations, under the User Services Section to streamline and fully coordinate user-oriented procedures and support activities.

The CISL Help Desk became part of the User Services Section in June 2011. The help desk team of Susan Albertson and Scott Baker review a user help request.

CISL's consulting experts supply customized, one-on-one service for:

- Special campaigns on the IBM Power 575 cluster Bluefire
- Special projects including performance benchmarking, evaluation, and user support for CISL's Cray XT5m system Lynx
- Benchmarking and planning efforts related to the next-generation HPC environment to be deployed at the NCAR-Wyoming Supercomputing Center (NWSC) in 2012

The consulting group continued to:

- Maintain documentation and lead training courses for CISL's supercomputing, storage, and data analysis and visualization resources
- Provide support to users of NCAR flagship models such as the Community Earth System Model (CESM) and the Weather Research and Forecasting model (WRF)
- Augment its support for the NSF's Decadal and Regional Climate Prediction Using Earth System Models (EaSM) program

The consulting group also assisted users with TeraGrid-allocated projects on CISL's IBM BlueGene/L system Frost until it was retired from TeraGrid service on July 31, 2011.

During FY2011, CISL user services staff supported the user community through several major transitions and enhancements to the CISL environment. Users have been transitioned to the new GLADE file system environment and were assisted in migrating from the former Mass Storage System (MSS) to the current HPSS archive. User support efforts in FY2012 will focus on preparing for the new resource environment at NWSC and ensuring a smooth transition for users.

In FY2011, 1,041 users joined the CISL computing community, with 386 university projects active during the year on CISL resources, along with ongoing NCAR and large-scale Climate Simulation Laboratory (CSL) projects. User support activity for this growing community is tracked using an ExtraView trouble ticket system. In FY2011, the ticket system recorded 7,589 tickets to the CISL Help Desk. The average number of log entries per ticket was 4.71, and communication with users was highest on complex cases. Of the total tickets submitted, the Help Desk team resolved 607 tickets in an average 0.82 days between June 2011 when they formed and September 2011, less than four months. In the same interval, consulting services staff resolved 935 requests with an average response time of about 5.2 days due to their more complex nature. An additional 393 support tickets were fielded related to managing user accounts and allocations, with an average response time of 0.2 days.

This work supports CISL's computing imperative to provide hardware cyberinfrastructure customized for the atmospheric and related sciences. This ongoing service for users is supported by NSF Core funds including CSL

funding.

‹ Special computational campaigns

Allocating supercomputing resources ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
        - User community
        - Special computational campaigns
        - Help desk and consulting
        - **Allocating supercomputing resources**
        - Earth System Model support
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

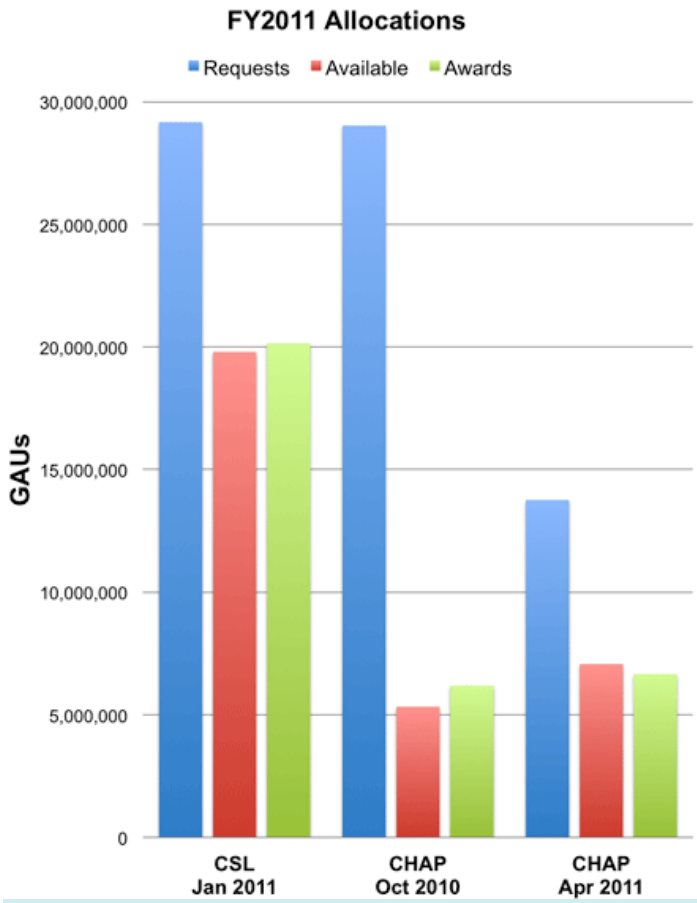
Allocating supercomputing resources

CISL works to provide equitable and efficient access to reliable computing resources for several distinct communities of researchers in the atmospheric and related sciences, including the broad university community, Climate Simulation Laboratory (CSL) users, and NCAR researchers. The demand for CISL resources continued to exceed available resources in FY2011, and CISL manages several allocation processes to distribute resources and ensure access by the most meritorious projects.

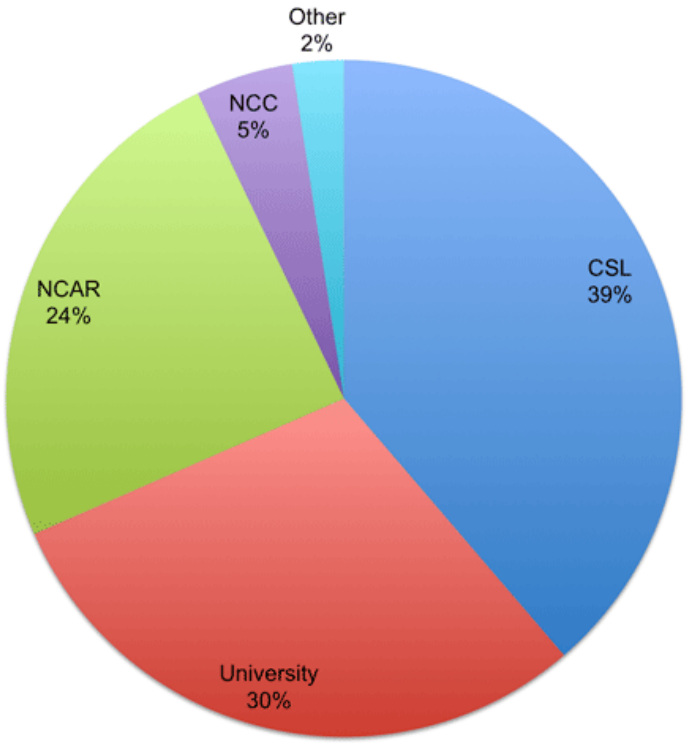
CISL provides approximately 30% of Bluefire to any U.S.-based researcher applicant who has an NSF award in the atmospheric or related sciences. A comparable portion of CISL's resources is also allocated to NCAR researchers in support of the computational needs of the NCAR laboratories. University requests are reviewed twice per year by the CISL HPC Advisory Panel (CHAP), and in FY2011, the CHAP faced requests 3.5 times greater than could be accommodated on Bluefire. In late FY2011, CISL offered the university and NCAR communities access to the Janus cluster, recently deployed as part of a collaboration between the University of Colorado and NCAR. The Janus system served to meet some of the demand for Bluefire at the October 2011 CHAP meeting, and it helped enable CISL to support meritorious projects at recommended levels.

About 39% of Bluefire is dedicated to the CSL at NCAR; it supports large-scale simulations of Earth's climate system in support of the multiagency U.S. Global Change Research Program, and it is open to researchers funded or supported by a U.S. university, U.S. federal or state agency, or U.S. not-for-profit research laboratory. The CSL Advisory Panel met in January 2011 to make allocations for the remaining 15 months of Bluefire, and faced requests 1.5 times greater than the resources available.

In FY2011, CISL developed plans for revised allocation processes for NWSC resources. Preparations included the creation of a Wyoming-NCAR Allocation (WNA) process (to be led by the University



The CSL Allocation Panel and the CISL HPC Advisory Panel faced the challenge of allocation requests that far exceeded the GAUs available on Bluefire.



The actual FY2011 GAUs delivered by Bluefire to CISL's major user communities aligned almost exactly with the percentages targeted by the allocations process.

of Wyoming) with support for disk and tape allocations, and the development of a new, more strategic process for NCAR-internal allocations. In FY2011, CISL made its first project disk space allocations on the central GLADE file system; this process is a prototype for allocating NWSC's much larger centralized filesystem and data storage (CFDS) resource. To support enhancements to the allocation and accounting processes for the next generation of resources at NWSC, CISL spent much of FY2011 collecting requirements for and engineering a new accounting system. The new system will provide more automation, allow CISL to support more users, and support new features such as DAV and GLADE allocations and accounting.

This work supports CISL's computing imperative to provide hardware cyberinfrastructure customized for the atmospheric and related sciences. This ongoing service for users is supported by NSF Core funds including CSL funding. The Janus cluster is supported by NSF MRI Grant CNS-0821794 to the Front Range Consortium for Research Computing (FRCRC), with additional support from the University of Colorado and UCAR non-federal funds.

‹ Help desk and consulting

Earth System Model support ›

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Log in

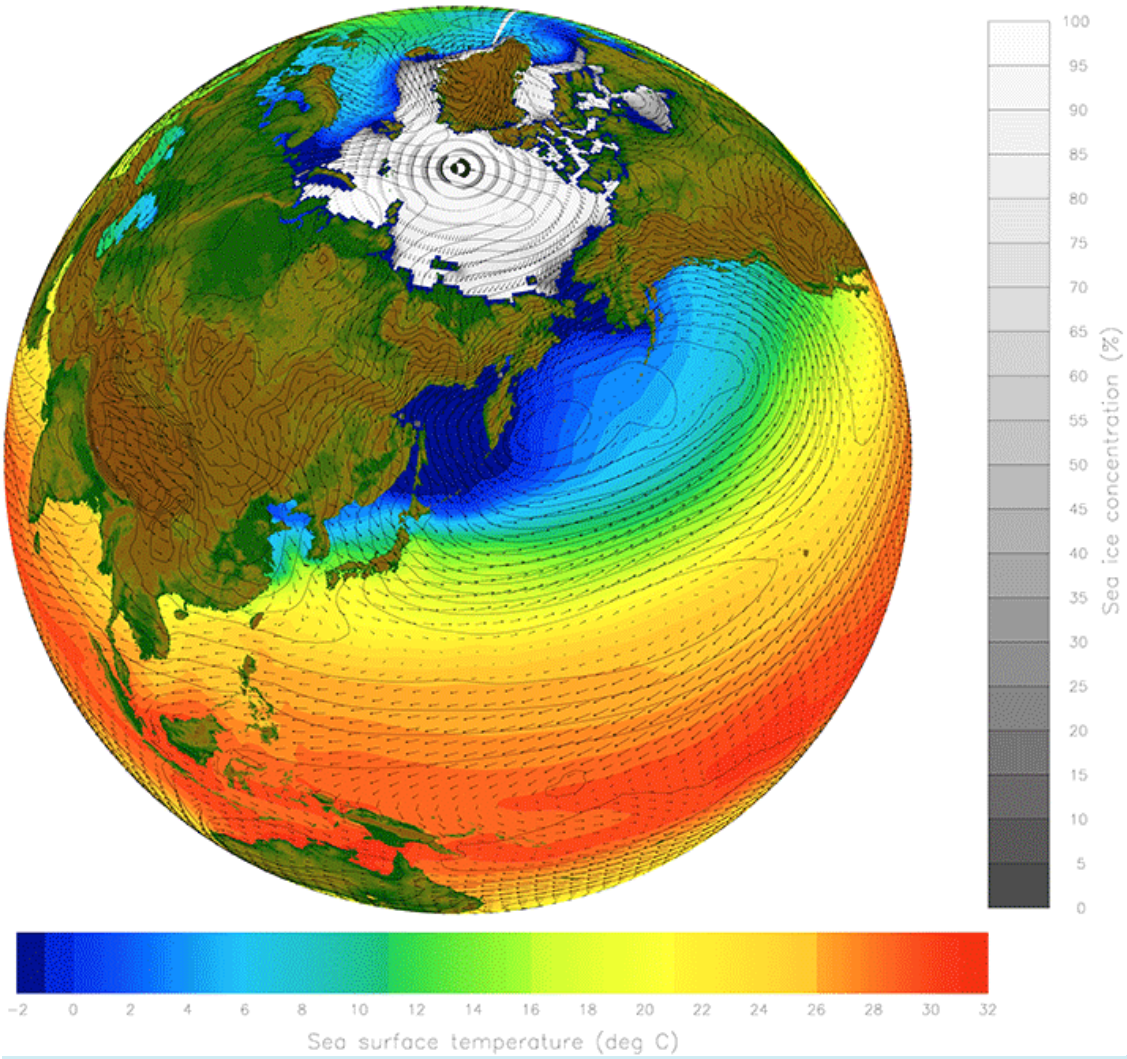
2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
        - User community
        - Special computational campaigns
        - Help desk and consulting
        - Allocating supercomputing resources
        - **Earth System Model support**
      - National and regional supercomputing services collaborations
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Earth System Model support

To support NSF grant winners from the Decadal and Regional Climate Prediction Using Earth System Models (EaSM) program, CISL has partnered with the NCAR Earth System Laboratory (NESL) to offer enhanced data and modeling support to this community. CISL provided a coordinated EaSM entry point for this new service.



The figure depicts a single month from a simulation of the 20th century from the Community Earth System Model (CESM), a coupled model that integrates atmosphere, ocean, land, and ice components. The figure shows wind vectors (arrows) from the lowest atmosphere layer and contours of sea level pressure. The ocean model surface temperatures are shown in orange to blue colors (see color key at bottom), and sea ice is shown in grayscale (see key at right).

Following expert guidance from NCAR scientists, a selection of global model outputs have been identified and will be made available through CISL's Research Data Archive (RDA). A targeted web portal (currently under construction) will simplify the user tasks of selecting time, space, and other parameters from the global data. Initially, the data system will offer access to the 3D global atmospheric, six-hourly, CESM output parameters (temperature, specific humidity, wind components, and geopotential height on 26 pressure levels) from the 20th century run (1850-2005) and four concomitant Representative Concentration Pathway (RCP) future scenarios spanning 2005-2100. As understanding of community needs evolves through meeting interactions and tutorials, the spectrum of model data offered and linkages to other climate datasets in the RDA may be expanded to further support EaSM research.

EaSM modeling will take place either at CISL's new NWSC facility, which has been explicitly enhanced by the NSF for

this program, or at the grantees' home institutions. Eligible PIs who want to use NWSC resources can request allocations through University or Climate Simulation Lab (CSL) processes. The CISL Consulting Services Group and NESL development teams for CESM and NRCM will provide user support. Hands-on and online training in using NCAR community models such as CESM, NRCM, and WRF will be developed for the EaSM community. NCAR expertise and resources will be combined to produce these formal tutorials and training that will be delivered via online modules, live webcasts, and hands-on activities held both at NCAR and other venues. Further, individualized help to port and install community codes at or outside NCAR will be provided. This assistance will encompass guidance for carrying out initial functionality tests and a validation run, assistance in determining the successful validation of the model on the targeted platform, suggestions for appropriate load-balancing layouts to achieve optimal efficiency and throughput, and help in resolving problems that arise as part of these efforts.

During the first year of EaSM support, the data service will come online, the consulting teams and processes will be coordinated, and user education and support will begin. Proactive engagement with the EaSM community will inform them of the support opportunities available at NCAR.

The EaSM support effort received one-time NSF funding to augment NWSC resources and is receiving NSF Core funding.

‹ Allocating supercomputing resources

National and regional supercomputing services collaborations ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
      - **National and regional supercomputing services collaborations**
        - TeraGrid services
        - XSEDE services
        - Computational gateway development
        - Collaboration on CU cluster system
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

National and regional supercomputing services collaborations

As part of its charge as a national center, NCAR has a strong presence in regional and national CI development, including both the HPC and networking communities. NCAR's work with regional HPC CI leverages unique regional resources and partnerships to tackle regional problems. CISL actively participates in the NSF's broader national high-performance CI through NSF-funded high-performance CI projects, such as the TeraGrid project and its successor, the eXtreme Science and Engineering Discovery Environment (XSEDE) project. As part of these programs, CISL deploys science gateways, which serve to lower the technical barriers to using the models, data, and computing resources needed by specific communities to solve scientific problems.

This work is supported by NSF Core funding, with supplemental funding supplied by other sources as noted in the following reports.

‹ Earth System Model support

TeraGrid services ›

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Log in

2011 CISL Annual Report

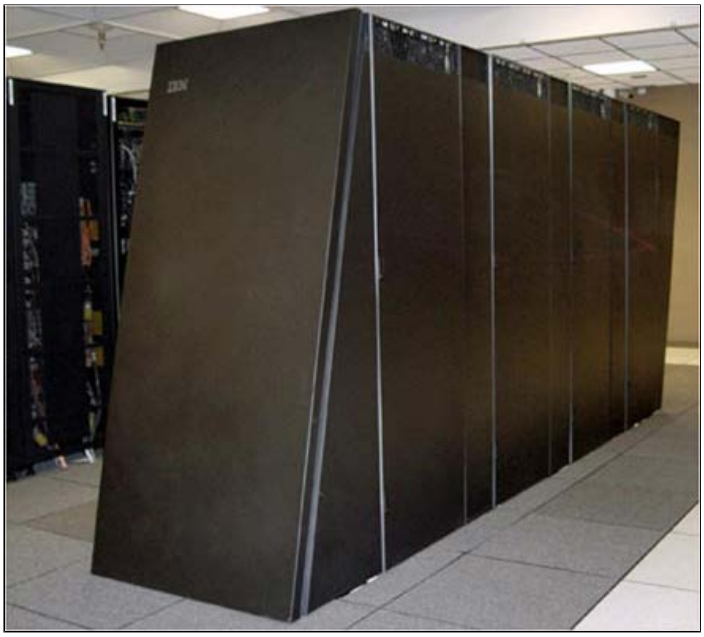
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
      - National and regional supercomputing services collaborations
        - TeraGrid services
        - XSEDE services
        - Computational gateway development
        - Collaboration on CU cluster system
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

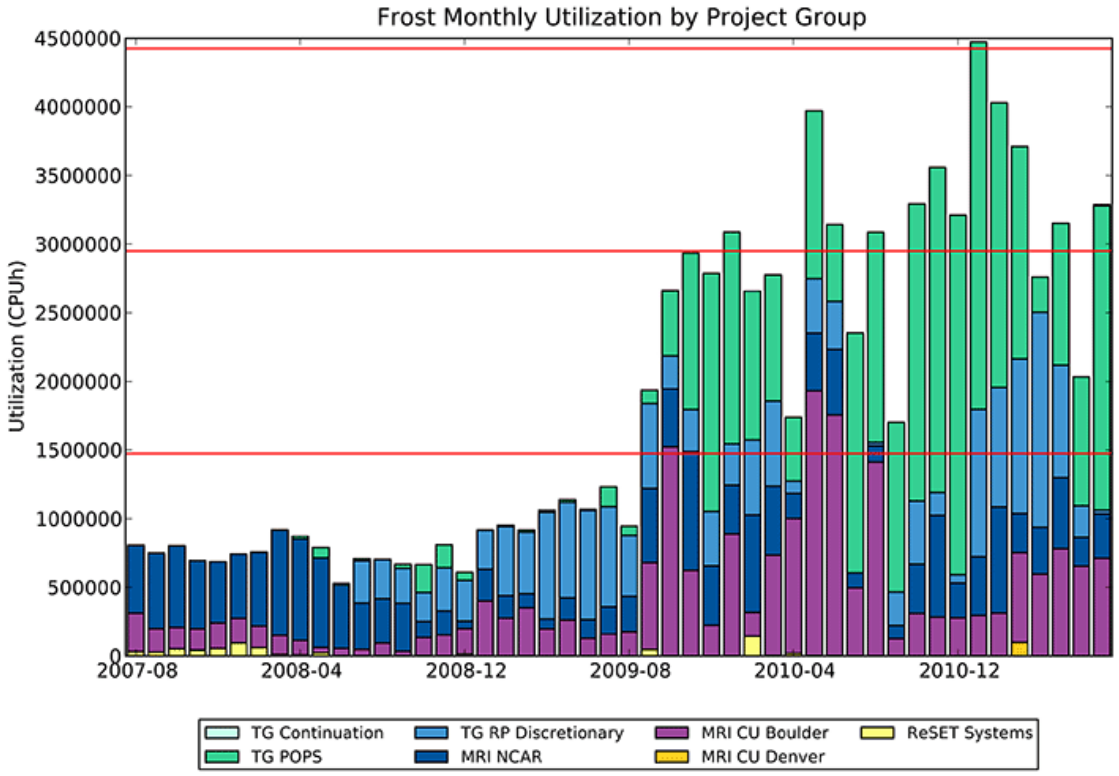
TeraGrid services

The National Science Foundation's 10-year TeraGrid program used high-performance networks and grid software to integrate supercomputers, data repositories, and special-purpose data analysis and visualization facilities throughout the United States. NCAR participated in the TeraGrid project from 2006 through 2011 in a variety of roles. For example, some NCAR projects and scientists used TeraGrid resources at other institutions for their research, and NCAR's data collections and science gateways (such as the Earth System Grid) interoperated with TeraGrid resources and users. As a TeraGrid resource provider (RP) starting in June 2006, NCAR also made a portion of its computational resources available to researchers who requested support from NSF through TeraGrid's quarterly allocation process. Also, CISL's Consulting Services Group (CSG) provided support for users of NCAR's TeraGrid resources.



The IBM Blue Gene/L supercomputer at NCAR is designed to run parallel jobs using up to 8,192 processors with high performance and low power consumption. In addition to serving NCAR's traditional charter as a resource provider for the atmospheric and related sciences, Frost served researchers across a broad range of disciplines as a TeraGrid resource from June 2006 through July 2011.

NCAR's primary TeraGrid computational resource was Frost, a four-rack IBM Blue Gene/L supercomputer, with an associated visualization cluster named Twister and a 100-TB disk system called Maelstrom. In FY2011, CISL continued to operate Frost (integrated with Twister) as a TeraGrid resource through the conclusion of TeraGrid's production operations on July 31, 2011. At that time, Frost entered a sunset period with anticipated full system decommissioning in first quarter 2012. Although Frost retired from TeraGrid service after the conclusion of the TeraGrid project, existing review-allocated TeraGrid users on Frost and Twister were given the opportunity to transition to NCAR allocations and continue using these systems to conclude their work during the sunset period. Overall, in its ~62 months of service as a TeraGrid resource from June 2006 through July 2011, Frost delivered 49.86M CPU-hours via 53,630 jobs to TeraGrid-allocated projects. After augmenting the capacity of the Twister cluster in FY2010, this dedicated visualization and analysis resource saw a doubling of its user community in its final year of service.



This figure shows Frost's utilization for its last four years of operation. Since Frost's expansion from one to four Blue Gene/L racks in late 2009, a substantial amount of the system's computational time has been utilized by TeraGrid users with allocations from the TeraGrid TRAC/POPS review process.

NCAR continues to participate in new cyberinfrastructure federation initiatives at the regional and national levels, ranging from collaborations with universities to participation in XSEDE, TeraGrid's successor. These activities may include more diverse interoperability technologies -- such as new authentication and data management tools like Globus Online -- that are operational outcomes of prior TeraGrid-related experience. Moreover, the Frost and Twister resources will be replaced with newer data-intensive platforms for research and development and for production computing.

This work supports CISL's computing imperative to provision hardware cyberinfrastructure for the atmospheric and related sciences, as well as CISL's computing frontier of developing center virtualization through Grid technologies and participation in national cyberinfrastructure initiatives. The acquisition and operation of Frost was made possible through NSF MRI Grants CNS-0421498, CNS-0420873, and CNS-0420985; through the IBM Shared University Research (SUR) program with the University of Colorado; and through NSF Core funding. The enhancements to Frost's storage system were funded by NSF Core funds, and Frost's FY2009 expansion was made possible by NSF Special funds.

‹ National and regional supercomputing services collaborations

XSEDE services ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
      - National and regional supercomputing services collaborations
        - TeraGrid services
        - XSEDE services
        - Computational gateway development
        - Collaboration on CU cluster system
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

XSEDE services

The Extreme Science and Engineering Discovery Environment (XSEDE) has replaced TeraGrid as the NSF's high-performance computing, data, and networking infrastructure for scientific and engineering research. As part of the Community Capabilities support component of the XSEDE Extended Collaborative Support Services (ECSS) activity, NCAR provides support aimed at deploying, hardening, and optimizing software systems necessary for the geoscience community to create new knowledge using XSEDE resources and related technologies. NCAR's Community Capabilities projects will include supporting geoscience communities that want to use XSEDE resources via science gateways and/or data repositories, as well as collaboration with the developers of widely used community codes and tools.

XSEDE Extreme Science and Engineering Discovery Environment

XSEDE is a single virtual system that scientists can use to interactively share computing resources, data, and expertise. People around the world use these resources and services to improve our planet.

Currently NCAR staff are working with XSEDE to support two portal development activities. The first involves continuing support of the Asteroseismic Modeling Portal (AMP), a science gateway with funding through an XSEDE community allocation. Its user community currently consists of 24 users from 9 countries. In calendar year 2011, AMP's user interface and automated workflow have managed computational jobs that consumed 701,000 SUs on Kraken (TRAC allocation) and 6.1 million SUs on Frost (discretionary allocation).

The second portal activity builds on and integrates community efforts in the Purdue Community Earth System Model (CESM) modeling portal, the Earth System Grid (ESG), the Earth System Modeling Framework (ESMF), and the Earth System Curator. The TeraGrid GIG funding to this project ended on 31 July 2011, but it received a no-cost extension to Purdue, NCAR, and NOAA CIRES through 31 March 2012, for integrating community Earth System modeling and data management. The XSEDE funding remains to be allocated to specific priorities. In FY2011, the first version of the Purdue CESM gateway was completed.

The team also completed the integration of a data and metadata publishing workflow linking the Purdue CESM gateway and the NCAR ESG Gateway, and added prototype analysis and visualization product services to the environment. Modelers can now publish their model output and metadata from the CESM portal and other users can search and access the published data and metadata from the ESG gateway. Additional collaborative work supports the 1.0.3 release of the Community Earth System Model (CESM). This portal project was presented at the science gateway track of the TeraGrid 2011 conference in July and won best paper. The project was also presented at the Computing in Atmospheric Sciences Workshop (CAS2K11) in September in Annecy, France.

NCAR staff also works with the XSEDE management team to analyze and report system usage data, develop new approaches for analyzing and presenting information, and develop new data streams with the accounting and account management team as new usage modalities arise. The analysis and reports generated are included in the XSEDE quarterly and annual reports.

This work is supported by NSF Core funding, with supplemental funding supplied by XSEDE.

‹ TeraGrid services Computational gateway development ›

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Log in

2011 CISL Annual Report

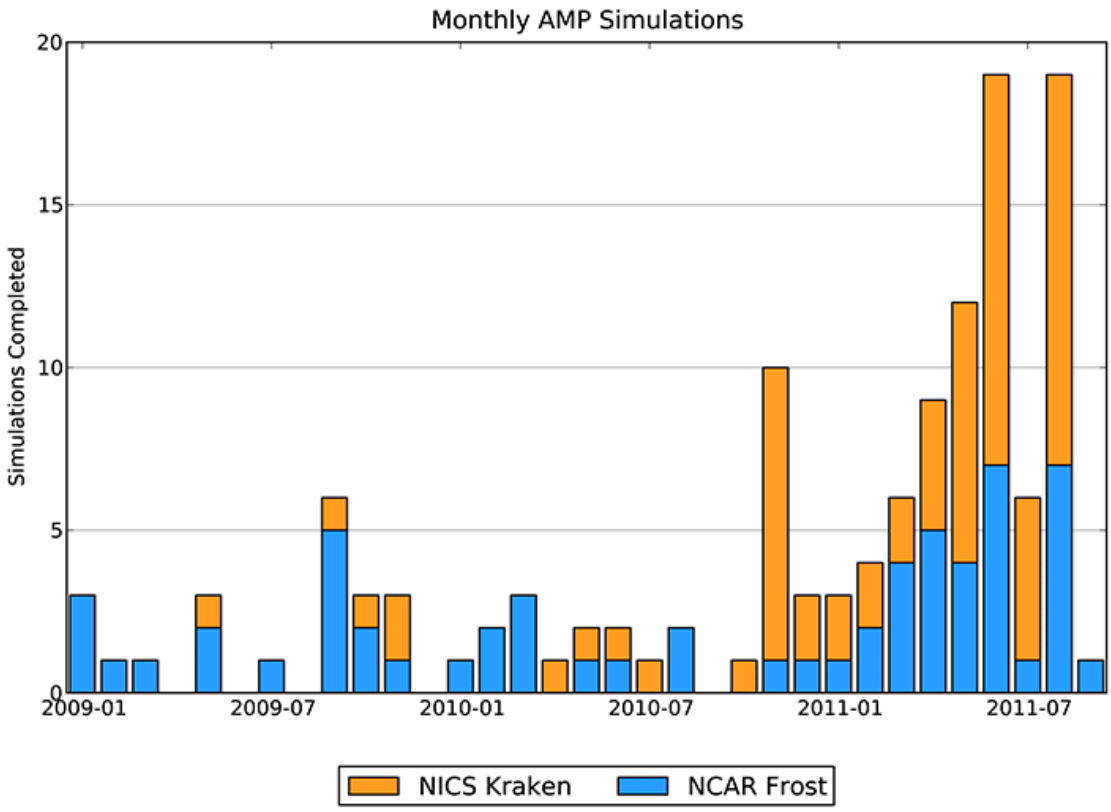
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
      - National and regional supercomputing services collaborations
        - TeraGrid services
        - XSEDE services
        - Computational gateway development
        - Collaboration on CU cluster system
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Computational gateway development

Setting up and running modern computational models is often an involved process for scientists. A complete experiment may require the orchestration of multiple steps on computational resources at different institutions, generally referred to as a workflow. Typical workflow steps involve gathering and preprocessing the required input data, executing the simulation itself, gathering and post-processing the output data, and finally running separate programs to analyze and visualize the results. Often, the workflow must be repeated for multiple experiments, and the mechanism employed to perform each step may vary between different computer systems. The overhead of simply running a computational experiment is thus quite high, as many mechanical tasks must be performed just to coordinate the work on the computers. Science gateways are intended to simplify the use of complex software models by providing an intuitive web-based user interface and automating the workflow required to perform the experiment.



This plot shows the number of AMP simulations that completed every month since 2009 on two TeraGrid systems, NICS Kraken and NCAR Frost. AMP's user community has grown, and the gateway is now serving coordinated campaigns as well as individual investigations. Kraken can complete a simulation several times faster than Frost, so the availability of Kraken has reduced the turnaround time for coordinated research of community interest.

In FY2011, CISL's Computer Science Section (CSS) continued to maintain the Asteroseismic Modeling Portal (AMP), a web-based interface and automated processing pipeline that makes an asteroseismology model available to an international community of researchers. After roughly two years of development -- one year of gateway development and one year of end-to-end model testing and verification -- the AMP gateway experienced a surge of activity in 2011 for production research submitted by the asteroseismology community. While Frost continued to be available for processing, a large number of simulations were directed to the NICS Kraken supercomputer for faster turnaround times.

Behind the scenes, AMP was used as a platform for investigating the deployment of several new Grid-based technologies for science gateways. For example, AMP's back-end grid job management engine was updated to support the Globus GRAM5 job manager in addition to the prior GRAM4 version. This update was performed just as

NICS deployed GRAM5 on Kraken, and NICS included a new job submission attribute to enable the specification of job dependency chains. Similarly, AMP was used as a configuration target for the “commsh” community shell security prototype installation at NICS. This work provided the foundation for a published case study regarding security techniques for Grid-enabled science gateways.

The development and maintenance of the AMP science gateway is supported by NSF Core funds. Supplemental funding to integrate AMP with TeraGrid resources was provided by NSF through the TeraGrid’s Grid Integration Group (GIG) Science Gateways program.

‹ XSEDE services

Collaboration on CU cluster system ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
      - Hardware cyberinfrastructure
      - User services
      - National and regional supercomputing services collaborations
        - TeraGrid services
        - XSEDE services
        - Computational gateway development
        - Collaboration on CU cluster system
    - CISL data services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Collaboration on CU cluster system

Janus, the 152.2 TFLOPS Dell Linux cluster system at the University of Colorado, was acquired under an NSF MRI proposal in a collaboration between CU Boulder, CU Denver, and NCAR. Under a memorandum of understanding between CU and NCAR, NCAR controls 9.8% of this resource and uses it to benefit NCAR and university users in the atmospheric and related sciences.

The Janus supercomputer system is a Dell Linux cluster consisting of 1,368 compute nodes. Each compute node contains two, 2.8 GHz, 6-core Intel "Westmere" processors and 24 GB of memory. The system thus has a total of 16,416 cores, 32.8 TB of main memory, and a peak speed of 183.9 TFLOPS. In high-performance Linpack tests, the system has demonstrated 152.2 TFLOPS, making it the 52nd fastest supercomputer in the world according to the June 2011 list of top 500 supercomputers. The nodes are interconnected by a 40 Gbps QDR infiniband network fabric in a fully non-blocking, fat tree configuration. A high-speed DDN disk storage system provides 960 TB of storage and between 16 and 20 GB per second of I/O bandwidth. Another interesting aspect of the system is that it is housed in a data center assembled from a series of custom-built modules located on the CU Boulder campus.

In FY2011, NCAR's role in the Janus system transitioned from design to deployment, configuration, and operational testing, then to the current role of consulting and collaboration with CU. Specifically, on 28 April 2011, lead responsibility for Janus operations transferred from CISL's Computer Science Section to CU's Research Computing (RC) group. In July, CU accepted the Janus system from Dell and is currently in a friendly-user phase, with allocations scheduled to begin in fall 2011. NCAR worked with CU RC to establish the necessary software configurations required by atmospheric scientists, and CISL's networking section, consultants, and others worked with CU staff to establish and test a dedicated 10 Gbps WAN connection and Globus Online endpoints. This enables efficient data transfer capabilities to NCAR's GLADE central storage system and HPSS tape archive.

NCAR's 9.8% share of the resource provides roughly 14 million core-hours of computer time per year. Converted to NCAR's General Accounting Units (GAUs), NCAR's share of the Janus resource represents nearly 20 million GAUs per year. Janus is allocated for three purposes. First, the system will support the research interests of the Earth System scientists who originally participated in the CU-NCAR MRI proposal to the NSF. Second, since the aging Bluefire system is severely over-requested, a portion of the Janus resource will be temporarily used to help meet the demand for compute cycles by the CISL university user community, at least until the NWSC system is brought online. Finally, the system is available through discretionary allocation to users not in either category, but whose activity on the system furthers the mission of NCAR's participation in the MRI project.

The Janus system is funded, in part, by the NSF MRI grant CNS-0821794. Support for the initial Janus design, setup, and operation was provided by NCAR core funds.

‹ Computational gateway development

CISL data services ›

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Log in

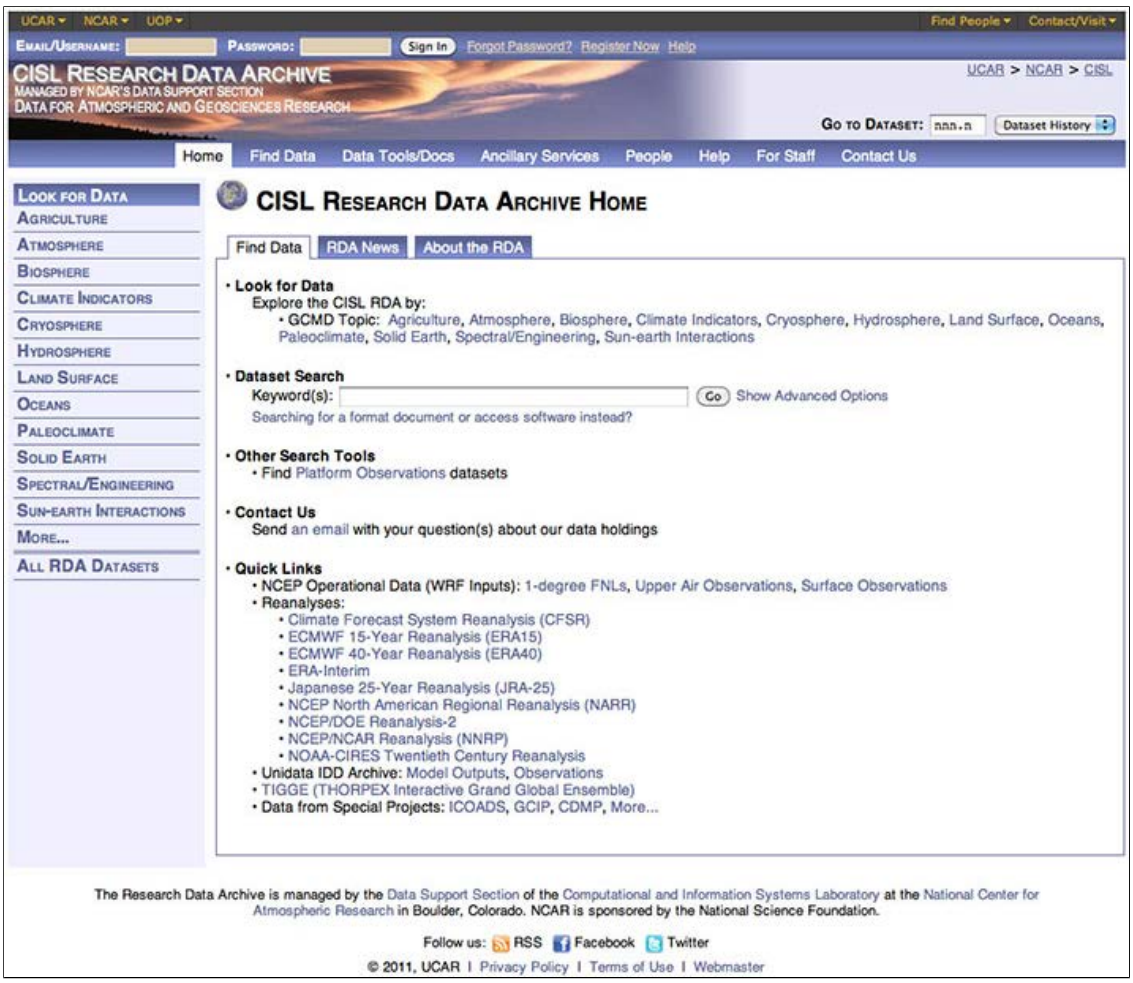
2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
      - Research Data Archive
      - THORPEX Interactive Grand Global Ensemble
      - CISL data infrastructure enhances IPCC AR5
      - Science gateway services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

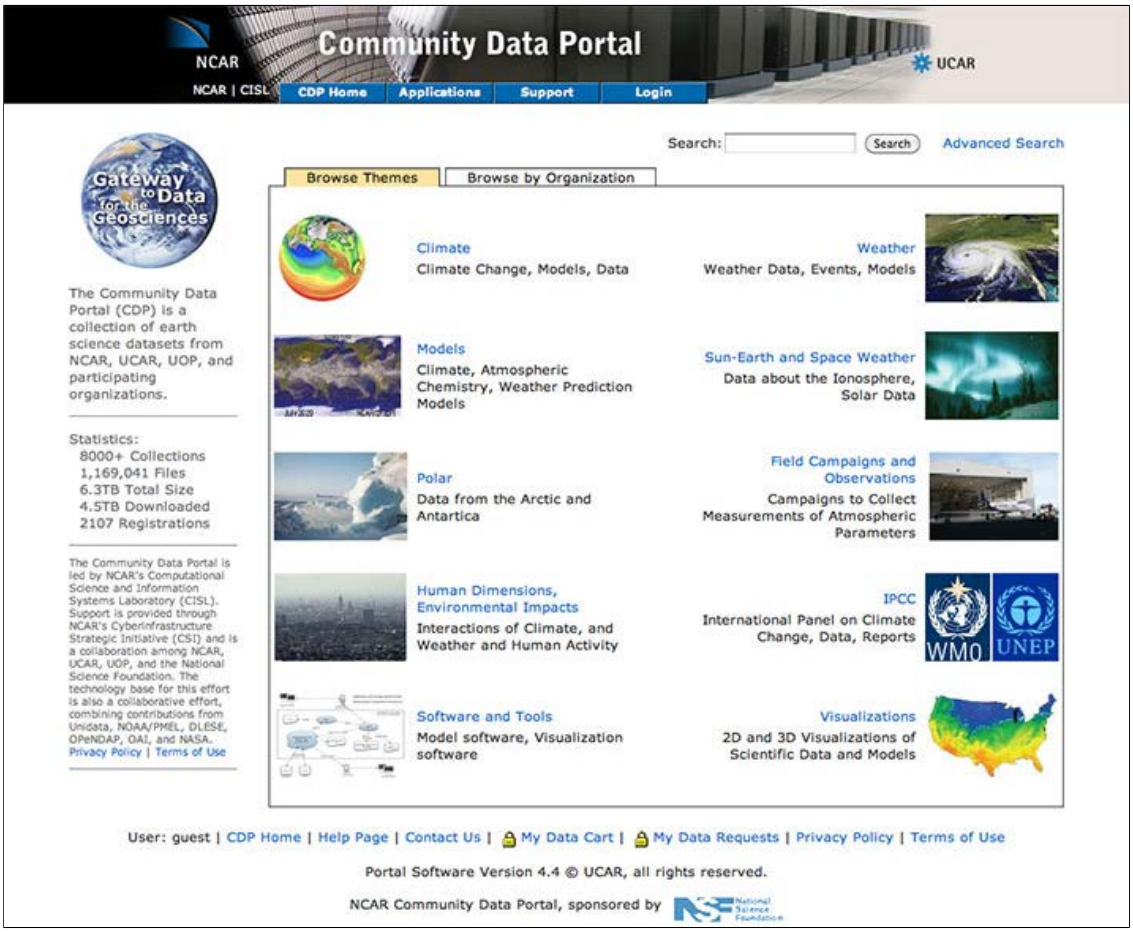
CISL data services

CISL has 40 years of experience providing data services to the atmospheric and related sciences community. The Research Data Archive (RDA) provides well-curated observational, analyzed, and model-generated datasets that support studies in climate, weather, and increasingly, other related disciplines. RDA development is designed to serve the research needs at NCAR and its associated university community, but since it is an open data access resource, the worldwide community also uses it.



The Research Data Archive (RDA) entry page emphasizes three ways to "find" data: a simple keyword text search, a faceted search using a standard metadata vocabulary, and direct links to the most popular and featured datasets. These options improve the RDA's usability for researchers.

NCAR is also active in deploying a broad portfolio of science gateways for the scientific community including the Earth System Grid (ESG), the Cooperative Arctic Data and Information Service (CADIS), the North American Regional Climate Change and Assessment Program (NARCCAP), and the Community Data Portal (CDP). These facilities host data from collaborating partners while the CISL teams focus on gateway software development.



The Community Data Portal supports PI data publication and access in a broad set of themes and alternately referenced by contributing organization. It also supports easy text and advanced searches across the complete CDP. Data access may come directly from the CDP or from links found during the search.

CISL is a community leader in developing data services that address the current and future challenges of data growth, preservation, and management, and in supporting NSF's new required data management plans. CISL data-centric CI design logically positions computer, disk, and tape-based storage systems to provide an efficient, safe, reliable environment for hosting and serving datasets.

The RDA is known for essential reference datasets and long-term preservation. The CDP system is designed to support the data management needs of individual researchers or larger projects, and it allows them to manage their own data and user communities easily. The ESG system is used to manage large-scale climate simulation data and serves the needs of data managers who provide CCSM, NARCCAP, and CMIP5/IPCC to the global community. The CADIS system, a joint endeavor with EOL and NSIDC, supports polar researchers with an environment to publish their data and metadata into a community repository. Finally, the Chronopolis digital preservation system can be used to geographically replicate important datasets.

‹ Collaboration on CU cluster system

Research Data Archive ›

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Log in

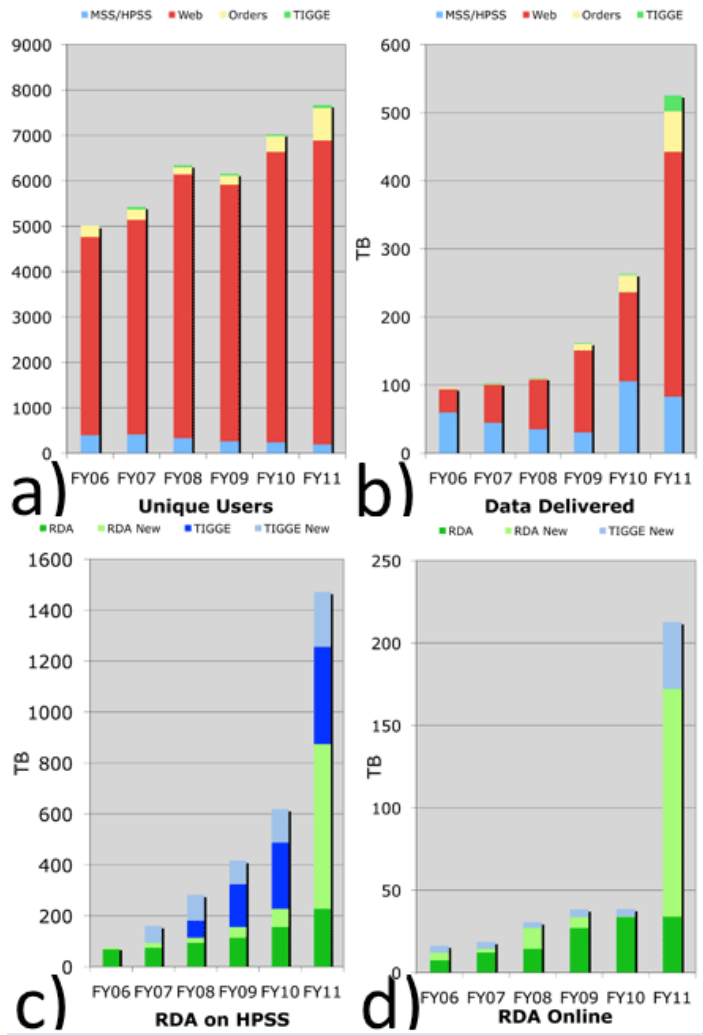
2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
      - Research Data Archive
      - THORPEX Interactive Grand Global Ensemble
      - CISL data infrastructure enhances IPCC AR5
      - Science gateway services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Research Data Archive

The Research Data Archive (RDA) is a key part of CISL's computing imperative for data curation. It provides a rich information resource through a large collection of datasets that support scientific studies in climate, weather, Earth System modeling, and increasingly, other related sciences. The RDA is developed to serve the research needs at NCAR and in the associated UCAR community, but since it is an open resource, the global community also uses it. The RDA activities can be viewed from two different perspectives: user data access and archive content development, both of which are equally important.



These charts show the data access and growth metrics for the Research Data Archive (RDA) during FY2006-FY2011: a) The number of unique users specified by access pathway: the NCAR HPSS, publicly available web servers, one-time special requests (orders) prepared for individual users, and TIGGE. b) The amount of data delivered to customers, by access pathway. c) The amount of data in the HPSS archive, showing annual growth. d) The amount of data on public web servers, showing annual growth. Charts a) and b) indicate the RDA's great significance to the community, and charts c) and d) show the annual progress toward building more valued content into the RDA.

In FY2011, about 7,600 unique persons were provided 525 TB of data through various primary access pathways: the NCAR HPSS, public servers on the web, one-time special requests prepared for individuals, and the THORPEX (THe Observing system Research and Predictability EXperiment) Interactive Grand Global Ensemble (TIGGE) archive (see charts a and b). This amount of data delivered is twice that of FY2010. Web users form the largest group, with 6,700 people downloading 360 TB of data. Next in size are more than 700 users who collectively received 60 TB through individually prepared requests (either by subsetting large archives or staging data to be online from the tape archive). This user group has doubled in size over the past year. There are fewer HPSS and TIGGE users, 190 (83 TB) and 60 (23 TB), respectively. Since its transition to a larger-capacity, data-centric IT infrastructure, the RDA has a new and convenient access pathway for CISL computer users. The newest and most popular RDA collections are directly available from GLADE to the DAV and supercomputer environments. We currently cannot estimate the metrics for this pathway, but it could be substantial because the access from the tape-based archive system has dropped and anecdotally our local users are pleased. These metrics indicate that the RDA is an important growing data resource for a broad community.

The RDA content expanded by over 400 TB in FY2011 (see chart c). TIGGE is part of the RDA, but it is shown separately because it alone added over 200 TB. The complete RDA is now over 1.4 PB, and 200 TB of it is readily available via GLADE (chart d), a 5.5x increase relative to the previous year. TIGGE is shown separately, and although it is capped at a rolling three-month archive, it is over 40 TB. NCAR users can access the portion of the RDA not available on GLADE directly from the HPSS, and the Data Support Section has automated procedures in place to

assist outside users with data access from HPSS.

As a whole, the RDA is constantly changing; curation extends and adds to existing datasets; and stewardship improves the documentation, creates systematic organization, applies data quality assurance, and develops user access. Many routine tasks and background infrastructure developments are necessary to maintain the RDA. Some of the major accomplishments for FY2011 include:

- Transitioned the RDA data services to new servers, GLADE, and the HPSS archive. This involved re-tooling many data workflows.
- Operated and maintained the TIGGE Archive and access on a 24×7 basis, and added portal features to extract observational data to match spatial and temporal requests for any selected model. This promotes model verification and validation research.
- Completed the ECMWF ERA-Interim archive from 1989-2010 and began automated updates going forward, now current into 2011.
- Completed the NOAA Climate Forecast System Reanalysis (CFSR) Version 1 and began the automatic collection and publication of CFSR v2, now current into 2011.
- Completed publishing the ECMWF Year of Tropical Cyclone (YOTC) high-resolution operational model output dataset.
- Updated and extended the time series of many datasets, including ongoing observational, operational model, and reanalyses; for example JRA-25, NCEP/NCAR Reanalysis, and more.
- Added an automated update procedure to augment the upper-air sounding database (UADB) to keep it within one month of real-time.
- Reached an agreement and established procedures to acquire high-resolution operational analyses directly from ECMWF's storage system.

Some major activities for FY2012 will include:

- Add observational precipitation datasets to the TIGGE validation portal.
- Manage the RDA data services transition to NWSC with zero downtime for users.
- More extensively deploy subsetting data services to gridded and observational datasets leading to increased data access.
- Add high-resolution ERA-Interim Reanalysis for 1979-1988, pre-pending the current 1989-2011 time series with newly released data.
- Run routine update procedures on more than 70 collections across the RDA.
- Extend the UADB data availability to earlier time periods, possibly back to 1920, complementing the existing service period (1973-2011).
- Deploy new ECMWF high-resolution operational analyses datasets. This includes transforming T1279 N640 model output to 2560x1280 (nominally 0.14-degree global resolution) full Gaussian grids to improve the data's convenience for users.
- Build NCAR CESM datasets and services to support NSF grant winners from the Decadal and Regional Climate Prediction Using Earth System Models (EaSM) program. The datasets will include the 20th century (1850-2005) run and four Representative Concentration Pathway future scenarios spanning 2005-2100.

The RDA is nationally and internationally respected for its staff, data management practices, and ability to positively affect outcomes in the data arena. This position is advantageous to building collaborations that continually strive to provide better scientific data resources and access.

RDA maintenance and development within CISL are almost entirely supported by Core funding. A two-year NSF grant is now partially supporting TIGGE, and a small NOAA grant is supplementing development of the International Comprehensive Ocean-Atmosphere Dataset.

‹ CISL data services

THORPEX Interactive Grand Global Ensemble ›

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Log in

2011 CISL Annual Report

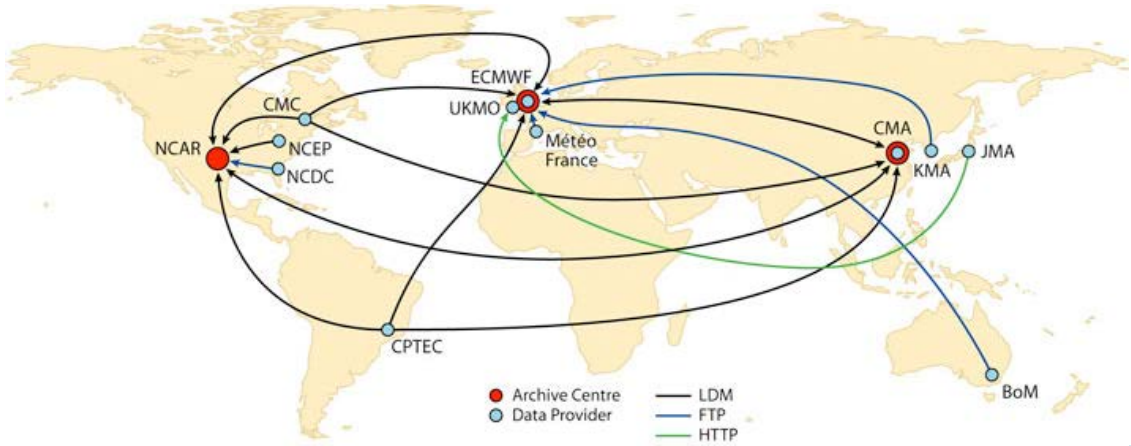
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
      - Research Data Archive
      - THORPEX Interactive Grand Global Ensemble
      - CISL data infrastructure enhances IPCC AR5
      - Science gateway services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

THORPEX Interactive Grand Global Ensemble

The NCAR TIGGE Archive functions in collaboration with the European Centre for Medium-range Weather Forecasts (ECMWF) and the China Meteorological Administration (CMA). The Archive Centers receive data from many international providers in real time and on a 24×7 basis. The data system is a range of software, hardware, and network communications that receive, archive, and provide user access.



This image indicates data flow from the providers to and between the TIGGE Archive Centers. NCAR, the European Centre for Medium-Range Weather Forecasts (ECMWF), and the China Meteorological Administration (CMA) are Archive Centers that each hold near-identical data copies from all data providers. ECMWF, CMA, Bureau of Meteorology (BoM), Meteorological Service of Canada (CMC), Centro de Previsao Tempo e Estudos Climaticos (CPTEC), Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA), Météo France, MetOffice (UKMO), National Centers for Environmental Prediction (NCEP), and National Climatic Data Center (NCDC) are all data providers. Three different transfer protocols are used within the system: Local Data Manager (LDM, a Unidata software package), File Transfer Protocol (FTP), and Hypertext Transfer Protocol (HTTP).

Development began in FY2006 and now largely runs in an operational mode receiving 3.6 TB per week. The data access options include direct file downloads, parameter selection, temporal and spatial subsetting, and regridding of the diverse native model grids to a user-selectable uniform grid. Output data format can be either GRIB2, which is the native format, or Climate Forecast-compliant netCDF.

The high-volume NWP forecast data are augmented with derived ensemble tropical cyclone data from each provider. The cyclone track data product is low-volume and available in an easy-to-use XML format. The TIGGE portal now also allows users to request observational data to match spatial and temporal requests for any selected model. Thus, the same data used to initialize NCEP operational model analyses are used to promote model verification and validation research in TIGGE. Precipitation datasets will be added to the verification suite in the coming year.

The TIGGE project supports CISL's computing imperative for data curation by developing and curating research data sets and maintaining user-centered online access to this archive. Further, this work fulfills CISL's strategic action item to increase both the size and the value of the THORPEX Interactive Grand Global Ensemble for U.S. university weather research. Core funding and one more year from a grant support TIGGE maintenance and development within CISL.

‹ Research Data Archive

CISL data infrastructure enhances IPCC AR5 ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
      - Research Data Archive
      - THORPEX Interactive Grand Global Ensemble
      - CISL data infrastructure enhances IPCC AR5
      - Science gateway services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

CISL data infrastructure enhances IPCC AR5

In FY2011 climate scientists using CCSM and CESM intensified their program of extremely ambitious climate change simulations for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). This work follows the experimental design of the Fifth Coupled Model Intercomparison Project (CMIP5). CMIP5 describes a set of coordinated climate model experiments designed to address questions about climate change that arose from the IPCC's previous assessment report (AR4). CMIP5 is a five-year experimental design, but CISL's data infrastructure improved the efficiency of the workflows for these critical simulations and reduced their time to completion. Further, algorithms developed in CISL were used to assimilate the observed global temperature and ocean salinity as initial conditions for the IPCC's ensemble decadal predictions. Developing this capability with the Data Assimilation Research Testbed (DART) required use of CISL's Climate Simulation Lab (CSL) resources to complete the long-term simulations in time for AR5.

CISL recently deployed the Globally Accessible Data Environment (GLADE) that makes data workflows more efficient and simplifies data access and usage. Researchers can now structure their workflows to use stored data directly without first needing to copy it to and from systems for supercomputing and data analysis and visualization (DAV). GLADE's centralized high-performance file systems span supercomputing, data post-processing, DAV, and HPC-based data transfer services. This data architecture increases the efficiency of modeling workflows and significantly improves the speed at which researchers can run, analyze, and visualize their simulations. CISL's data infrastructure improved the productivity of CMIP5 climate modeling experiments, allowing them to be completed in time for inclusion in IPCC AR5.

IPCC simulations rely on data delivered via the Earth System Grid (ESG), a science gateway to climate data collections that are hosted at eight sites around the globe including NCAR. This federated system forms the primary data access facility for the challenging petascale CMIP5 activity. The Earth System Grid Center for Enabling Technologies (ESG-CET) is a long-term initiative that develops a globally distributed petascale data management environment for CMIP5/IPCC-AR5 and U.S. climate science. CISL leads this gateway development effort and focused FY2011 ESG development on data management priorities for the CMIP5 IPCC work. To expand ESG support for CMIP5 metadata, CISL's ESG developers delivered enhanced security, federation, data versioning, and replication capabilities, along with more sophisticated and scalable services for data analysis and data products.

In FY2011, CMIP5 experiments created more than 1 PB of data. In addition to making CISL's HPSS archival system available to store this data, CISL dedicated 500 TB of GLADE disk to ESG, and 400 TB of that was consumed by CMIP5 efforts. As this data was created and stored at NCAR, the GLADE architecture expedited its archival, analysis, visualization, and distribution around the world via ESG. CISL equipment was also used to perform reanalysis and transformation operations on CMIP5 data before it was served to the community. Finally, CISL provided increased allocations and user support to the CMIP5 IPCC efforts. CISL continues its community leadership role to develop data services that can address the future challenges of data growth, preservation, and management. CISL's disk and tape storage systems provide an efficient, safe, reliable environment for hosting datasets, and CISL's data services continue to be further streamlined, improved, and expanded through the new data-centric design facilitated by GLADE.

CISL staff working on the many aspects of this intensive computational campaign are primarily supported by NSF Core funds. GLADE equipment is supported by NSF Core funds including CSL funding. ESG-CET is funded by the U.S. Department of Energy (DOE) SciDAC-2 program and co-sponsored by NSF.

‹ THORPEX Interactive Grand Global Ensemble

Science gateway services ›

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2011 CISL Annual Report

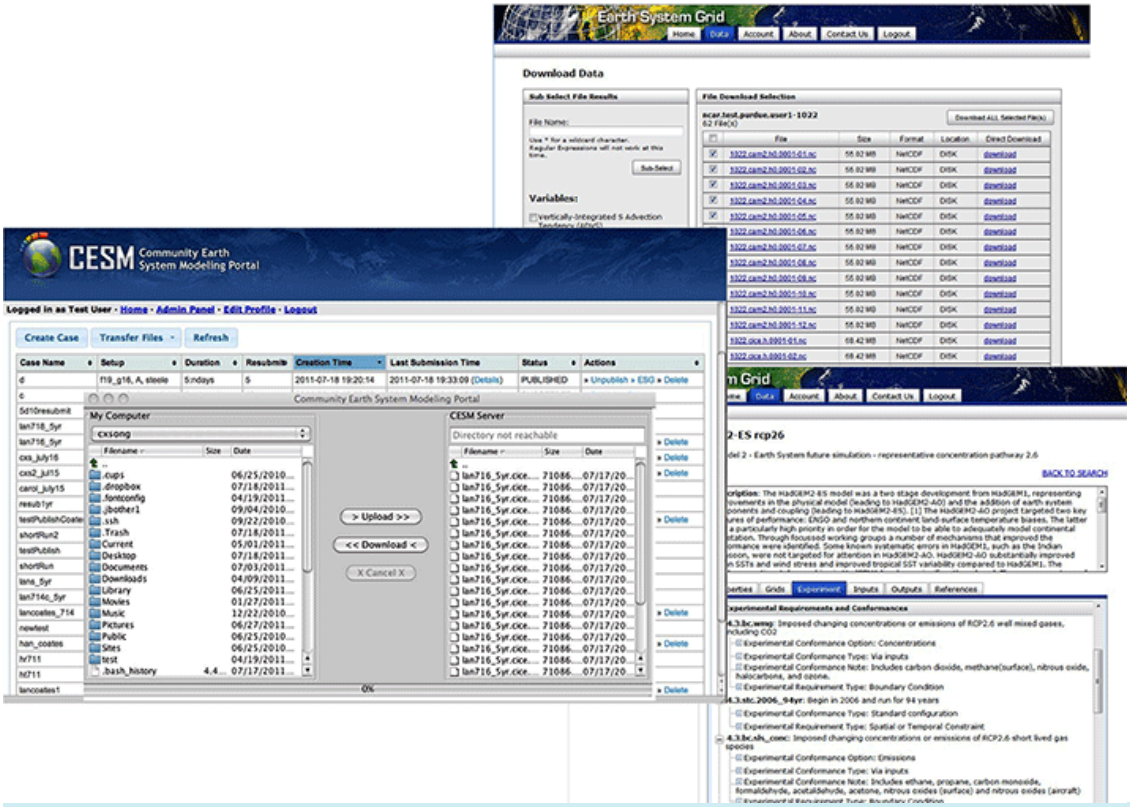
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
      - Research Data Archive
      - THORPEX Interactive Grand Global Ensemble
      - CISL data infrastructure enhances IPCC AR5
      - Science gateway services
    - CISL software cyberinfrastructure
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Science gateway services

CISL develops science gateways and other Grid-based technologies that support the development of virtual organizations. Our projects and initiatives share cyberinfrastructure and span climate science, regional climate change, Arctic science, solar science, digital preservation, and international efforts to develop metadata and knowledge infrastructure. Many efforts are tied to major interagency, national, and international initiatives, including, for example, the World Meteorological Organization (WMO), the Intergovernmental Panel on Climate Change (IPCC), the International Polar Year (IPY), the World Climate Research Program (WCRP), and the Library of Congress' National Digital Information and Infrastructure Preservation Program (NDIIPP). Most of these projects use open source, web portal infrastructure called the Science Gateway Framework (SGF). CISL's work on all of the projects in this suite of science gateway services is supported through NSF Core funding and augmented by special funding as noted below.



This image shows an integrated climate model workflow built on shared science gateway cyberinfrastructure. The CESM portal workflow interface, coupled with SGF-based gateway services, allows users to configure model runs, then publish model output data and related model metadata via a single interface. This integration work demonstrates higher-level capabilities spanning TeraGrid-XSEDE, ESG-CET, and Curator projects via an end-to-end science gateway workflow.

Our contributions to science gateways support CISL's computing imperative for software cyberinfrastructure by developing software specific to the simulation, analysis, and forecasting needs of the atmospheric and related sciences. They also address CISL's computing frontier for center virtualization by developing science gateways and other Grid-based technologies that provide critical cyberinfrastructure (CI) to broad communities. Finally, work accomplished in ESG-CET, CADIS, WMO, and other collaborations address CISL's strategic action item to address the challenges posed by large and heterogeneous environmental data, and to establish metadata standards for diverse collections of data and models.

Science Gateway Framework

The SGF is shared cyberinfrastructure that was developed to support many of our portal activities in providing scientific data access and services to a broad community of users. In FY2011 we continued significant development

of the SGF-based gateway services with a vigorous release schedule focused heavily on the operational, production needs of the IPCC AR5/CMIP5 data management system. We also continued to develop and operate the NCAR CDP, ESG, and CADIS gateways and the NCAR Chronopolis node. These production-level gateway services represent over 25,000 registered users and over 10 million managed files. The NCAR ESG gateway alone provides access to over 1 PB of managed holdings and monthly delivers over 25 TB of scientific data to the community. In the sections that follow, we provide a brief summary for each of the related science gateway initiatives.

The SGF effort is supported through NSF Core funding, augmented by special projects including ESG-CET, NOAA GIP, CADIS, OPERA/ACADIS, and TeraGrid.

Earth System Grid Center for Enabling Technologies (ESG-CET)

This long-term, DOE-funded initiative develops a globally distributed petascale data management environment for CMIP5/IPCC-AR5 and U.S. climate science. The ESG-CET, or simply ESG, is a gateway to scientific data collections that are hosted at eight sites around the globe including NCAR. The ESG gateway is a complex software package with many stakeholders and must be easily deployable at sites around the world. NCAR/CISL leads the gateway development effort, and ESG was built using SGF components.

Early in FY2011 we began development efforts in support of CMIP5 data management priorities. We released three beta versions and three release candidates and reached a significant milestone in February, 2011, the 1.2.0 CMIP5 baseline release. This release included significant improvements to the installation of the SGF ESG Gateway application, enhanced documentation, security updates as well as basic data replication support. The 1.2 version significantly reduced the maintenance burden of the gateway application. Version 1.3.0 was released in June 2011 under the Apache2 open source software license and included a Spring framework upgrade, REST-based services, and security workflow enhancements. Version 1.3.2 was released in August 2011. A notable feature of this version is METAFOR Conceptual Information Model (CIM) model metadata ingestion and display. This work area was done in the context of the Earth System Curator project (with NOAA GIP support) and involved significant collaboration across ESG-CET and the EU-based METAFOR project. Version 1.3.2 is the most recent software release and is in production use at CMIP5 collaborator sites worldwide serving thousands of IPCC AR5 researchers. During Q3 and Q4 we collaborated closely with Argonne National Laboratory to develop a new data access feature integrating the GlobusOnline service within the SGF gateway. A significant reimplementation of the SGF search infrastructure was accomplished during this period based primarily on end user feedback from the CMIP5 community. This new search capability is available as a 2.0 Beta release, and it provides a more flexible platform to address current and future search needs which include support for metadata handling of observational data. Lastly, NCL-based product services were integrated within the SGF/ESG Gateway utilizing NOAA's Live Access Server (LAS). The NCL LAS product services integration with GlobusOnline service, and the gateway 2.0 version search capabilities will be delivered to the community early in FY2012.

ESG-CET has been supported through NSF Core funds as well as DOE's SciDAC-2 program. DOE funding for ESG-CET ended in September 2011, and NSF Core funds will support the operational ESG data management system in the future. We continue to pursue additional funding sources to operate this petascale system, a critical community resource for CCSM, CESM, and CMIP5/IPCC.

Global Organization for Earth System Science Portals (GO-ESSP) and Earth System Grid Federation (ESGF)

This is an international collaboration building federated data systems for CMIP5/IPCC-AR5. NCAR is a founding member and contributes SGF technology to this project. In FY2011 CISL staff served on the GO-ESSP Steering Committee, co-organized the May 2011 GO-ESSP workshop in Asheville, North Carolina, participated in the ESGF/CMIP5 planning/technical meeting, and presented two talks at the workshop on the SGF and CADIS projects.

CISL's contributions to GO-ESSP this year were supported by a combination of NSF Core funds and ESG-CET support.

Cooperative Arctic Data and Information Service (CADIS)

CADIS is an NSF project to manage data from over 30 Arctic Observing Network (AON) programs to support the IPY. The CADIS gateway is a collaboration between CISL and NCAR's Earth Observing Laboratory, the National Snow and Ice Data Center, and Unidata. CADIS provides an end-to-end service where AON projects upload and publish their data, publish and manage their metadata, and users discover and access data in near-real time. Accomplishments in FY2011 include integration of automated, real-time FTP upload services, search enhancements, user interface improvements, dedicated community support, and a pilot Chronopolis-based data preservation service.

The follow-on Advanced Cooperative Arctic Data and Information Service (ACADIS) project started in July 2011 and will continue this work. CADIS project funding ended in August 2011. In both cases, this community data service is supported by NSF Core and NSF Special funds.

Earth System Curator (ESC)

This project extends the ESG gateways to integrate modeling, data, and knowledge. We continued to develop and extend the model "trackback" capability, which provides a connection between datasets and the models that created them. One of the highlights of this year's progress was highly collaborative work that spanned CIRES/NOAA, the EU-based METAFOR project, ESG-CET, and NCAR/CISL. The focus was on ingesting and handling the output of the METAFOR Conceptual Information Model (CIM), which is being produced by the METAFOR CMIP5 Questionnaire. In February 2011 SGF version 1.3.0 was released which included a number of ESC project-related features and

enhancements, including a CIM Atom feed client for ingest of CIM documents, RDF triple store lookup performance improvements, and user interface updates based on user feedback. We also explored technical options for managing CIM document interface changes and kept the CIM harvesting and Trackback UI up-to-date as the CIM evolved. SGF Version 1.3.2 was released in August 2011 including METAFOR Conceptual Information Model (CIM) model metadata ingestion and trackback display in a production-ready form. This work area involved significant collaboration across ESG-CET and the EU-based METAFOR project, and it is in use in the eight ESG federation gateways worldwide.

This work is supported by NOAA/GIP via the Earth System Curator project.

Community Data Portal (CDP)

The CDP offers a broad range of scientific data collections that includes observations, climate, atmospheric chemistry, space weather, field programs, models, analyses, and more. Many programs and projects at NCAR, UCAR, and UCAR Community Programs (UCP) are represented in the portal. CDP provides a self-publishing model that offers data management tools directly to projects and PIs. By automatically sharing these metadata with other portals and international centers, data discovery is enhanced worldwide. Roughly 2,000 registered CDP users are discovering, accessing, and using 8,000 collections. In FY2011 we prioritized support of the AR5/CMIP5 activity during a critical high-use phase and provided basic operational and critical bug fix support for CDP.

CDP is supported by NSF Core funding.

WMO Information System (WMO-WIS)

CISL is a major contributor to the development of the World Meteorological Organization (WMO) Information System (WIS). Under the auspices of the United Nations, the World Meteorological Organization (WMO) is designing, developing, and deploying WIS as a next-generation globally federated information system for weather, climate, hydrology, oceanography, and many other disciplines. CISL plays a strong role in the management and technical direction of WIS and has contributed ideas, strategies, and services developed through our work with CDP, ESG, CADIS, and other efforts. CISL staff serve on many WIS committees, including the driving Intercommission Coordination Group (ICG-WIS), the Expert Team on GISC and DCPC Demonstration Program (ET-GDDP), the ICG-WIS subcommittee on WIS Center Identification, and the Inter-Programme Expert Team on Metadata and Data Interoperability (IPET-MDI). Beyond our committee participation, in FY2011 CISL was an active member of the IPET-MDI expert team and collaborated to produce the WMO Core Metadata Profile Version 1.2.

WMO-WIS is supported by NSF Core funding.

North American Regional Climate Change Assessment Program (NARCCAP)

This project shares regional climate simulation data via the SGF and the ESG data network. NARCCAP is an international program that supports regional climate assessments for the U.S. and Canada, and is served through the ESG-CET. The assets are nine high-resolution regional model outputs forced by various global models and provided by multiple PIs. The core software CI is now mature, and the archive continues to grow as experimental runs are completed and published via the portal. More than doubling in FY2011, NARCCAP-published data volume grew from 8 TB to 18 TB in managed holdings. CISL contributed by supporting operations, data publication, and user interface bug fixes and improvements.

CISL's contributions to NARCCAP are supported by NSF Special funds, and the project will complete in the first quarter of FY2012.

TeraGrid Science Gateways: Prototyping an Environmental Science Gateway

This project is a collaborative effort across Purdue University, CU/CIRES/NOAA, and NCAR/CISL aimed at prototyping an end-to-end modeling and data management capability that incorporates distributed workflows. The strategy is to develop the new capability by building on Purdue's CCSM/CESM modeling portal, the ESG Gateway, and new metadata capabilities developed in the Earth System Curator project. In FY2011, REST-based services and automated end-to-end data publication workflow from the Purdue CESM portal to an ESG Gateway was demonstrated for the TeraGrid Science Gateways project. This highly collaborative work was presented as a paper at this year's TeraGrid Forum in Salt Lake City, and garnered the best paper award in the Science Gateways track.

This science gateway prototyping effort is supported by NSF's TeraGrid project via a GIG award.

Chronopolis: Federated Digital Preservation over Space and Time

There is a critical and growing need to organize, preserve, and make accessible the increasing number of digital holdings that represent vital intellectual capital, much of which is precious and irreplaceable. Chronopolis is a strategic collaboration among the San Diego Supercomputing Center (SDSC, lead organization), NCAR/CISL, the University of California Library System, and the University of Maryland; it is aimed at developing national-scale digital preservation infrastructure that has the potential to broadly serve any community with digital assets for science, engineering, humanities, and more. In addition to community collections, Chronopolis CI is being used to provide pilot digital preservation services for the NCAR Library and the CADIS project.

In FY2011 Chronopolis expanded its production-ready capabilities. Managed holdings more than tripled from 10 TB to a total of 32 TB. The NCAR Chronopolis node was upgraded to new server hardware and usable storage of 100 TB. The underlying data transfer infrastructure was upgraded to iRODS from SRB, and the entire repository was refreshed in the new infrastructure. A pilot Chronopolis-based data preservation service was demonstrated in collaboration with the CADIS project. Lastly, a TRAC audit to certify Chronopolis as a trusted Digital Repository was

undertaken, and is near completion at end-FY2011.

This gateway data preservation service is supported by the Chronopolis project.

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CISL software cyberinfrastructure ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
    - CISL software cyberinfrastructure
      - Data Assimilation Research Testbed software
      - Community data analysis and visualization software
      - VAPOR visualization software for very large datasets
      - Science Gateway Framework
      - Managing complex heterogeneous data
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

CISL software cyberinfrastructure

CISL develops and supports software infrastructure (SI) specific to the simulation, analysis, and forecasting needs of the atmospheric and related sciences. This software infrastructure includes data assimilation frameworks; data analysis and visualization software for climate, weather, and turbulence applications; and software for accessing, comparing, and exploring data through science gateways. In general, CISL balances its use of core funds to ensure the stability and long-term support of existing SI with opportunities to further expand and develop these capabilities via grants. The prioritization criteria used in maintaining this balance of funding sources includes the SI's importance to NCAR's ongoing mission, dependencies of other SI on its continuation, and, in the case of capabilities under development, the proposed SI's relevance to CISL's and NCAR's strategic plans.

Significant new developments in CISL's software portfolio have occurred in FY2011:

- NCL has released a 64-bit version of its visualization software, which allows it to work on array sizes greater than 2 GB.
- The Science Gateway Framework (SGF) package had been released to collaborators under an Apache 2.0 license, and has been deployed at eight sites internationally for WCRP/CMIP5.
- The VAPOR project has begun an international collaboration with Korea Institute of Science and Technology Information (KISTI) to develop ocean data support for the VAPOR 3D visualization tool.
- CISL has partnered with ANL to create an NCL-based package that will have parallel data and computational capabilities to accelerate the analysis of extremely large climate datasets.

To better serve the community and project stakeholders, CISL has also been working to improve the quality and efficiency of its software engineering processes. For example, the NCL and SGF efforts are now managed using the Atlassian software engineering environment, which aids in issue tracking, prioritization, and release coordination. Over the past year, we have also moved to an Agile process for the SGF development work. This has radically improved the frequency and quality of software releases, while also elevating our responsiveness to stakeholders.

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Data Assimilation Research Testbed software ›

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Log in

2011 CISL Annual Report

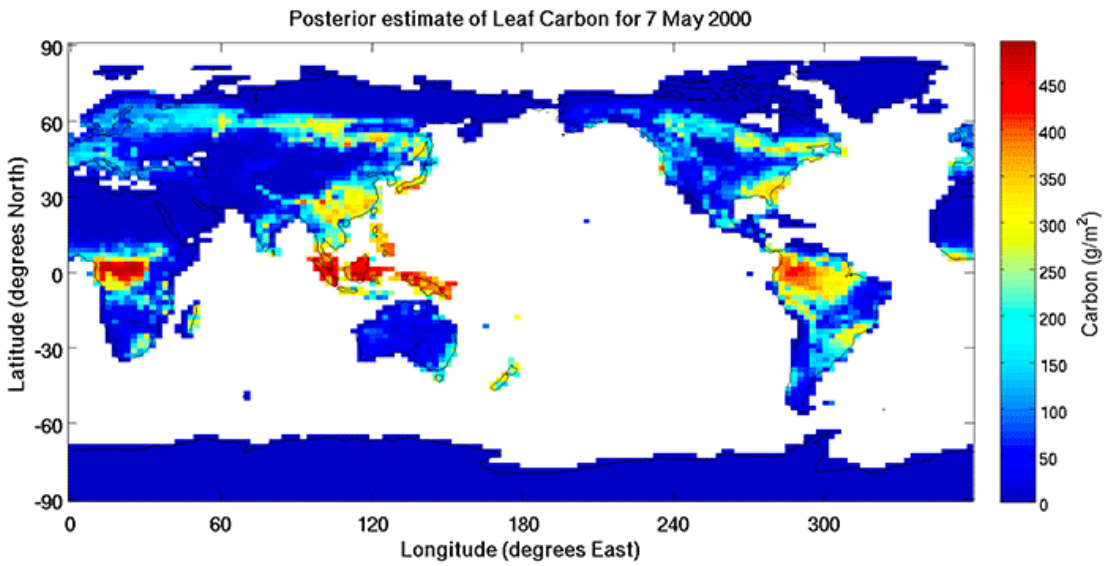
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
    - CISL software cyberinfrastructure
      - **Data Assimilation Research Testbed software**
      - Community data analysis and visualization software
      - VAPOR visualization software for very large datasets
      - Science Gateway Framework
      - Managing complex heterogeneous data
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Data Assimilation Research Testbed software

Data assimilation is providing rapid advances in geophysical studies. The Data Assimilation Research Section (DAReS) of IMAGe develops and maintains the Data Assimilation Research Testbed (DART), a software facility for ensemble data assimilation. DAReS also provides support to a growing community of NCAR, university, and government laboratory partners who are interested in applying ensemble data assimilation methods with DART.



Analyzed estimate of leaf carbon from an idealized assimilation using the Community Land Model (CLM) with DART. In this experiment, synthetic observations of leaf carbon were generated by adding draws from a normal distribution simulating observational error to the leaf carbon from a long CLM forecast. These "observations" were then assimilated with a 40-member ensemble of CLM forced by 40 members of a DART reanalysis with the Community Atmosphere Model for the first week of May 2000. These results demonstrate that the DART/CLM system is ready to be used in assimilation of actual leaf carbon observations.

The DART software is continually upgraded and improved. During FY2011, DAReS supported the incorporation of several large geophysical models: the Community Land Model component of the Community Earth System Model, and the University of Michigan's Global Ionosphere Thermosphere Model. In addition, implementation for the atmospheric component of the Model for Prediction Across Scales (MPAS) was begun, and external efforts began to incorporate the ROMS regional ocean model.

An initial implementation of a capability to assimilate satellite radiance observations was completed in collaboration with MMM. This involves a novel software engineering approach in which forward operators are computed by software from the WRF variational assimilation system and bias corrections to radiances are obtained from operational numerical weather prediction centers.

Further progress on developing a generalized framework for coupled data assimilation with CESM models was completed in collaboration with CGD. DART assimilations for POP and CLM are now done using tools from the CESM coupler, and CAM will soon be tested in the same framework.

The Kodiak release of DART was made available to the public in July 2011. The release includes new filter options like a nongaussian filter, support for a number of new models and observation types, improved performance for the rate-limiting data transposes to increase DART speed for large applications, and new diagnostic and data-handling utilities.

The interface between DART and GPS radio occultation observations was improved to increase the accuracy of GPS assimilations. Improved methods for assimilating observations of hurricane vortex position developed by university collaborators were included in DART.

Significant improvements were made to the interfaces between DART and WRF along with scripting improvements

that increase the flexibility of DART with all large models. DART was also ported to CISL's Cray (Lynx) platform.

A number of new tools for evaluating ensemble analyses and predictions were completed. Most important is a common observation subsetting tool that allows fair comparisons to be made between assimilation experiments that may reject different subsets of observations.

Localizing the impact of observations on model state variables is a fundamental part of ensemble data assimilation algorithms. A new capability to localize using scale height as a vertical coordinate was incorporated. This has improved assimilations near the top of tropospheric models like WRF and was essential for good performance in space weather models like TIEGCM and GITM.

CISL's data assimilation research supports CISL's computing imperative for software cyberinfrastructure. Further, developing and supporting the capabilities of the DART facility is specified as a strategic action item in the CISL Strategic Plan. Data assimilation research in IMAGe is supported by NSF Core funding, NASA Grant NNX08A23G, National Oceanographic Partnership Program Grant G0776112, and NSF Grant CNS1035250

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Community data analysis and visualization software ›

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Log in

2011 CISL Annual Report

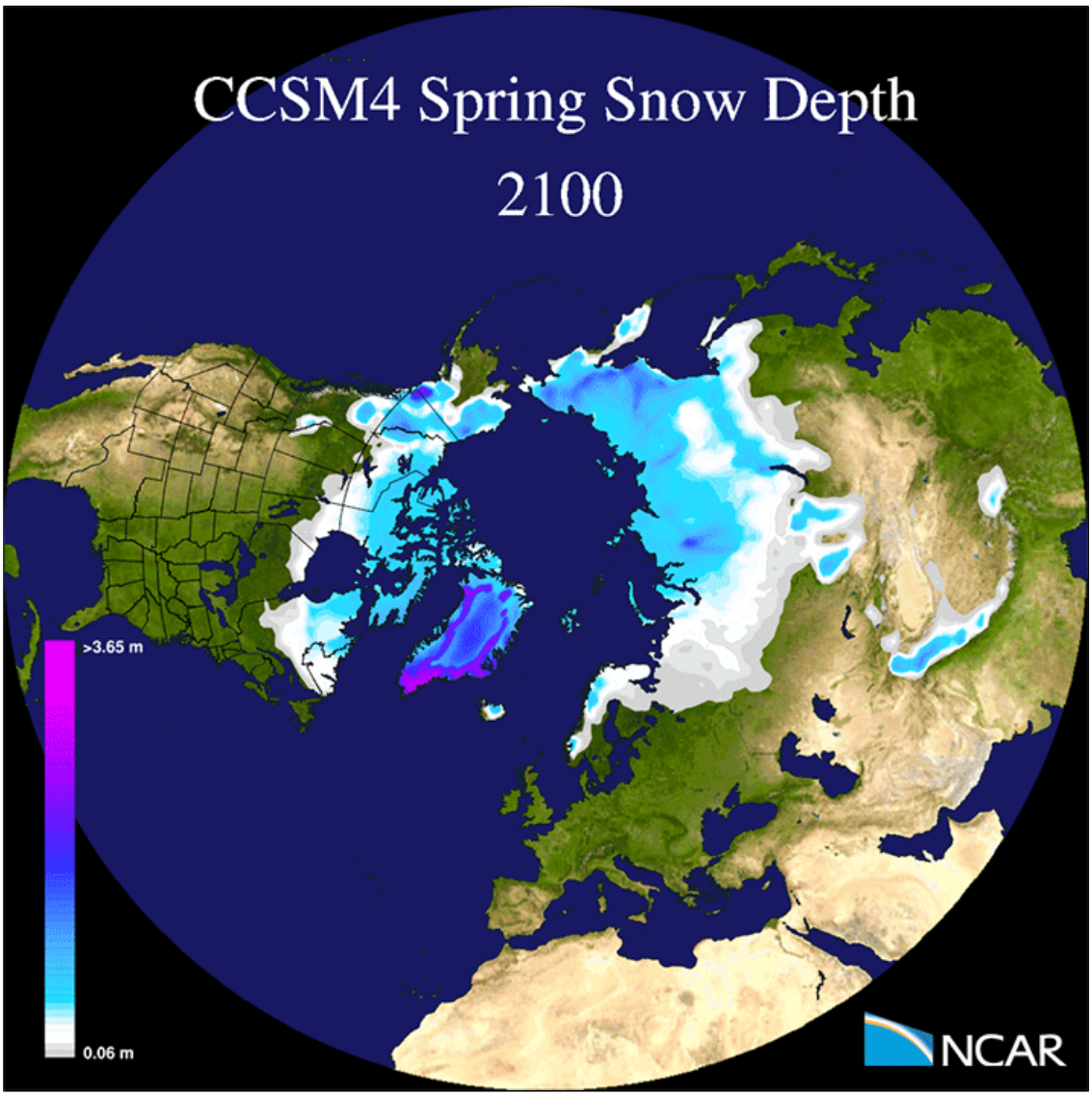
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
    - CISL software cyberinfrastructure
      - Data Assimilation Research Testbed software
      - **Community data analysis and visualization software**
      - VAPOR visualization software for very large datasets
      - Science Gateway Framework
      - Managing complex heterogeneous data
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Community data analysis and visualization software

The NCAR Command Language (NCL) is a data analysis and visualization environment developed primarily at CISL in deep collaboration with a number of core scientific groups. NCL enables scientists to easily and effectively read, analyze, and visualize their geoscientific data on platforms ranging from personal laptops to high performance computers. PyNIO and PyNGL are Python modules based on NCL's file input/output and visualization capabilities, thereby offering NCL's software components to a wider and more mainstream user base. The NCL and Python tools have been embraced broadly across the international Earth System sciences community spanning research, education, operational, military, government, and commercial organizations including the Bureau of Meteorology in Melbourne, Australia, IPMet in Brazil, Eurasia Institute of Earth Sciences in Turkey, Max-Planck-Institut für Meteorologie in Hamburg, and MeteoSwiss in Zürich.



NSF-funded research by NCAR scientist Synte Peacock suggests that Wolverine habitat is likely to warm dramatically if society continues to emit large amounts of greenhouse gases. This image shows the decreased extent of spring snow depth by the end of this century, a change that is likely to imperil the wolverine. NCL was used to read and process the data, to regenerate the NASA terrain map over a polar stereographic projection, then to overlay the snow depth contours. NCL provides important

resources and tools to scientists, enabling them to graphically communicate the results of their research to a diverse audience that includes students, researchers, and the general public.

NCL, PyNIO, and PYNGL are used for data analysis and display in many graduate-level courses to generate publication-quality visualizations for journals, for post-processing and comparing data from a wide range of Earth System models, for real-time data access and display at operational centers, and by hundreds of graduate students as the primary tool for their research. Critical to the importance of these tools is that they are free, well supported, easy to install, and run across a wide variety of UNIX systems, allowing students and scientists to continue their research uninterrupted as they change organizations.

In FY2011 we completed and released new versions of NCL, PyNGL, and PyNIO, allowing support for reading, writing, and analyzing large (>2 GB) arrays. These releases constituted major overhauls of the software and are a critical first step toward supporting the next generation of ultra-large climate datasets. We are also working collaboratively with DOE and UCD on the ParVis project, where we are developing new, scalable parallel NCL capabilities. The new versions of NCL and PyNIO also contained alpha support for an HDF5 reader, an overhaul of missing values and data types (preparing us for full support of NetCDF4 and HDF5), a more robust replacement of our highly popular date functions, and a new suite of string manipulation functions. Since these releases, we have added almost full support for NetCDF4, including preliminary capabilities to read NetCDF files in parallel. We continued to add numerous scripting examples to our websites -- including ones contributed by users - to address questions we receive through our email lists.

There were 20,823 downloads of NCL, PyNGL, and PyNIO software in FY2011 by 5,794 unique users. Of these downloads, 7,606 were of the new software by 1,279 unique users. Our email lists had 3,136 total postings in FY2011 on 1,100 unique subjects.

This work advances one of NCAR's goals to support, enhance, and extend the capabilities of the university community and the broader scientific community both nationally and internationally. It also addresses CISL's strategic imperative for software cyberinfrastructure through developing and supporting software specific to the simulation, analysis, and forecasting needs of the atmospheric and related sciences. Specifically, this effort fulfills CISL's strategic action item to continue the support and development of community data analysis and visualization software. These community tools are primarily supported by NSF Core funding.

‹ Data Assimilation Research Testbed software

VAPOR visualization software for very large datasets ›

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Log in

2011 CISL Annual Report

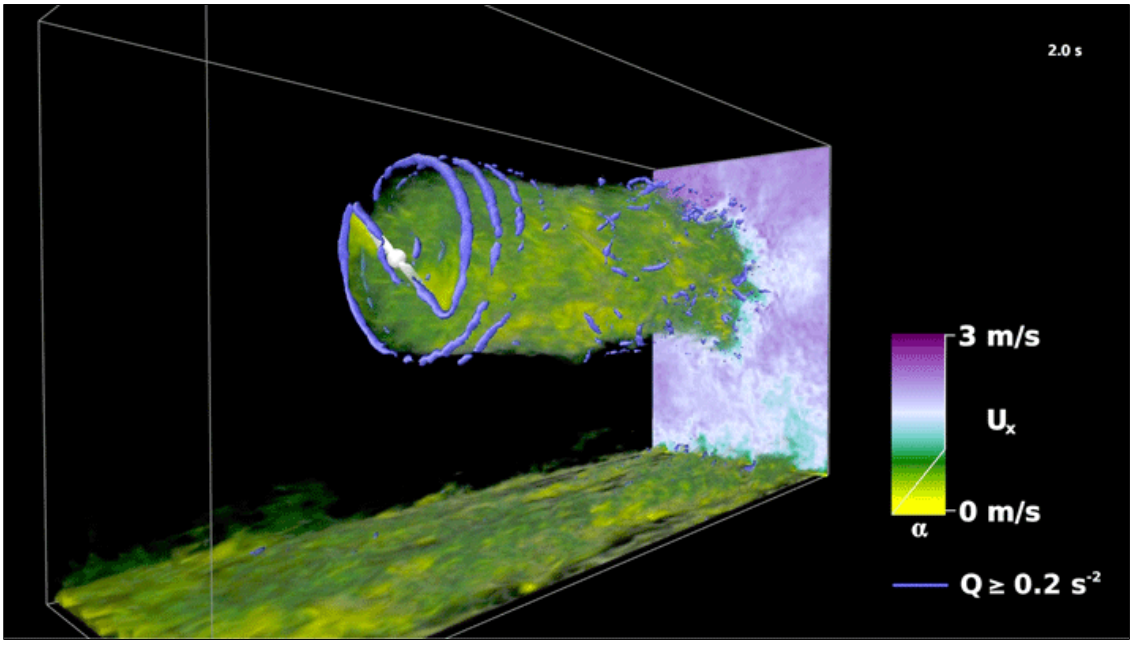
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
    - CISL software cyberinfrastructure
      - Data Assimilation Research Testbed software
      - Community data analysis and visualization software
      - **VAPOR visualization software for very large datasets**
      - Science Gateway Framework
      - Managing complex heterogeneous data
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

VAPOR visualization software for very large datasets

The VAPOR project is an open source software development effort aimed at improving the ability of researchers in the Earth System sciences to analyze and interpret results from some of the largest numerical simulation outputs. The genesis of this work was an NSF-ITR research grant that supported CISL as well as collaborators at the University of California at Davis and the Ohio State University. VAPOR has transitioned into production from a research project, and it has become a strategic priority for CISL. Though VAPOR's origins are strongly rooted in geophysical turbulence, recent work on VAPOR has focused on expanding its capabilities to support the needs of the broader Earth System sciences community. Development of VAPOR is closely guided by a steering committee comprised of Earth scientists from around the world that sets development priorities, dictates software requirements, and serves as friendly users for testing and evaluating new software features. VAPOR's unique features include its use of a multi-resolution model that permits exploration of some of the largest simulation outputs using only desktop computing resources; a feature set and user interface that is focused on the needs of the Earth System sciences community; and a strong emphasis on supporting quantitative data analysis.



This visualization was generated from a simulation of the turbulent wake behind a windmill. Included in the image is a correctly registered 3D model of the windmill turbine itself. The visualization and the capability to include 3D geometry (windmill turbine) are the results of efforts at the DOE's National Renewable Energy Lab, and stem from the re-factoring of VAPOR's architecture to facilitate third-party extensions to the code.

The goals of the VAPOR project are strongly aligned with the cyberinfractructure components of CISL's strategic plan in the areas of:

- Developing and supporting software infrastructure specific to the simulation, analysis, and forecasting needs of the atmospheric and related sciences.
- Preparing for petascale computing by developing visualization and analysis capabilities in support of extremely large data sets.

For a second year, VAPOR efforts were largely focused on meeting contractual obligations of two external funding sources (NSF-09-06379 and a TeraGrid GIG award), as well as on developing and enhancing core capabilities. The second of three phases to re-factor VAPOR's internal architecture to facilitate third-party development was completed. Collaborators at the DOE's National Renewable Energy Lab (NREL) took advantage of these changes to contribute a module for displaying 3D graphics model files within a VAPOR scene (see image above). Also completed, with support from a TeraGrid GIG award, was the development of a Fortran-callable, MPI-based API that enables numerical modelers to directly output data to VAPOR's progressive-access data format. In addition to these major

milestones numerous new capabilities and features were added to the VAPOR package, such as “hedgehog” plots, built-in geo-referenced images, and numerous usability improvements. A release candidate for VAPOR’s next major version (2.1) has been made available to VAPOR steering committee members and other friendly users, with an anticipated December release of the production code.

The VAPOR team was also successful in winning a grant from the Korean Institute of Science and Information Technology (KISTI). The one-year award, with a possible extension of up to three years, will fund VAPOR enhancements to support the global ocean circulation modeling community. Work on this award officially began in September 2011.

This project is supported by NSF Core funds, NSF-09-06379, TeraGrid GIG PY6 award, and a grant from KISTI.

‹ Community data analysis and visualization software

Science Gateway Framework ›

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Log in

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2011 CISL Annual Report

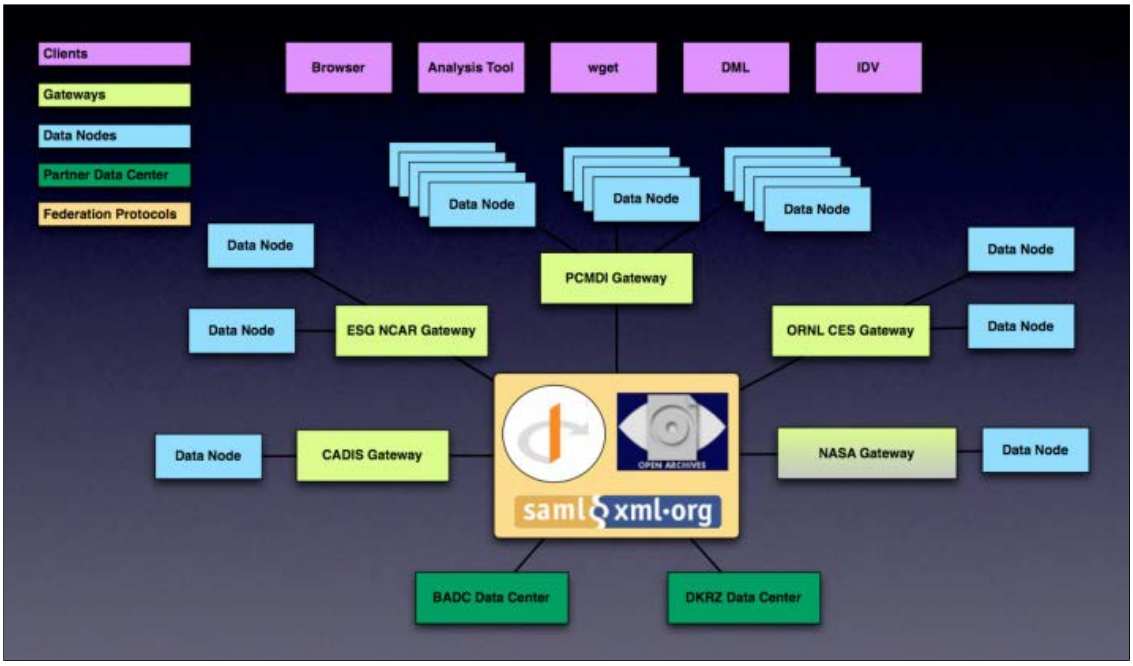
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
    - CISL software cyberinfrastructure
      - Data Assimilation Research Testbed software
      - Community data analysis and visualization software
      - VAPOR visualization software for very large datasets
      - Science Gateway Framework
      - Managing complex heterogeneous data
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Science Gateway Framework

Science gateways now facilitate scientific communities' access to shared cyberinfrastructure. A science gateway typically provides a specific community with some level of integrated, web-based data and knowledge management, secure data access, simulation capability, and analysis/visualization capabilities. NCAR/CISL is engaged in a number of efforts in this area, and is now developing the Science Gateway Framework (SGF) as shared software cyberinfrastructure to support a range of community activities. The SGF serves as a foundation for ESG-CET, Curator (NOAA/GIP), CADIS, CDP, NARCCAP, WMO-WIS, and TeraGrid science gateways. The SGF underpins data services that support national and international science efforts such as the World Climate Research Programme Coupled Model Intercomparison Project (WCRP CMIP) effort, the IPCC AR5 process, the CESM, and more.



This image shows the concept of globally federated science gateways built on shared cyberinfrastructure. The Science Gateway Framework (SGF) serves as the foundation for the gateway components in the figure.

Development of the SGF supports CISL's strategic imperative for software cyberinfrastructure through developing and supporting software specific to the simulation, analysis, and forecasting needs of the atmospheric and related sciences. Specifically, this effort fulfills CISL's strategic action item to refactor existing Earth System Grid and Community Data Portal infrastructure into a Science Gateway Framework. This project also advances CISL's strategic frontier for center virtualization by developing science gateways and other Grid-based technologies to support and enhance the development of virtual organizations. Finally, by developing new methods and tools to extract information from large and heterogeneous data sets, this work supports CISL's science frontier for understanding large and heterogeneous data sets.

In FY2011 we continued significant development of the SGF with a vigorous release schedule. This was made possible, in part, by a continued migration to Agile software engineering practices that the development team has adopted. The SGF capabilities were extended during this period primarily in support of the demanding requirements of the operational Earth System Grid Federation (ESGF) IPCC AR5/CMIP5 data management system funded by the ESG-CET project. In February 2011 we released SGF version 1.2.0, which provided baseline capabilities for CMIP5 data management including full support of the CMIP5 Data Reference Syntax (DRS) metadata specification. This release included significant improvements related to the installation and configuration of the SGF Gateway application, documentation, security updates, and basic data replication support. The SGF version 1.3.0 was released in June 2011 under the Apache2 open source software license. SGF Version 1.3.2, released in August 2011, is the most recent software release and is in production use at eight sites worldwide. New software features completed and

deployed during FY2011 include METAFOR Conceptual Information Model (CIM) model metadata ingestion and display. This work was done in the context of the Earth System Curator project (NOAA GIP support) and involved significant collaboration across ESG-CET and the EU-based METAFOR project.

Software enhancements accomplished during the reporting period include streamlined software installation and update, user interface refinement, expanded CMIP5 metadata support, dataset replication support, a centralized gateway registry, and security updates. New REST-based web services were developed to support an end-to-end climate model publication workflow (TeraGrid.) An automated data upload service was integrated and pilot data preservation capabilities were demonstrated with support from the CADIS project. We collaborated significantly with ANL to develop a new data access feature integrating the GlobusOnline service within the SGF gateway. A reimplementation of the SGF search infrastructure was accomplished during this period based primarily on end user feedback from the CMIP5 community. This new search capability is available as a 2.0 Beta release, and provides a more flexible platform to address current and future search needs which include support for metadata handling of observation data. NCL-based product services have been integrated with ESG and NOAA's Live Access Server (LAS) and will be delivered to the community early in FY2012.

The SGF-based ESGF Gateway is currently running at NCAR, LLNL/PCMDI, ORNL, NASA/JPL, LBNL/NERSC, BADC (UK), DKRZ (DE), and NCI (AUS) in support of the CMIP5 activity and other projects.

This project is supported through NSF Core funding, augmented by special projects including ESG-CET, NOAA GIP, CADIS, OPERA/ACADIS, and TeraGrid.

‹ VAPOR visualization software for very large datasets

Managing complex heterogeneous data ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
    - CISL facilities
    - CISL computing services
    - CISL data services
    - CISL software cyberinfrastructure
      - Data Assimilation Research Testbed software
      - Community data analysis and visualization software
      - VAPOR visualization software for very large datasets
      - Science Gateway Framework
      - **Managing complex heterogeneous data**
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Managing complex heterogeneous data

The Parallel Analysis Tools and New Visualization Techniques for Ultra-Large Climate Data Sets (ParVis) project completed its first year in FY2011. ParVis is a 3-year joint project with Argonne National Laboratory and several other organizations to parallelize components of NCL for analyzing ultra-large climate datasets. Focused on the needs of supercomputer users in the climate simulation community, ParVis will:

- Address increasing data complexity by incorporating components of MOAB and Gridspec
- Parallelize highly utilized NCL file I/O and computational functions
- Speed up the execution of time-intensive NCL scripts via the use of Swift
- Research the integration of NCL with a large-scale 3D visualization package called ICAV

We are well underway in converting the CESM atmospheric and ocean diagnostic scripts to NCL for testing the file I/O and computational part of this work. To support project objectives in both NCL and ParVis, we sponsored two projects in CISL's SIParCS internship program:

- An exploratory project to determine if OpenCL could be leveraged to improve the speed of selected NCL functions through parallel processing performed on commodity-level GPUs and multicore CPUs
- A project to integrate Earth System Modeling Framework (ESMF) regridding capabilities into NCL, allowing users to regrid to and from various topographically rectangular and unstructured grids

The regridding functionality is a highly requested user feature, and it is critical in the IPCC AR5 for comparing model runs generated on large, complex, and dissimilar grids. The ESMF work is being integrated into the next release of NCL. NCL has been implemented as a backend service for the Live Access Server (LAS) to perform simple visualizations and analysis computations. This work has been deployed on NCAR's production release of the Earth System Grid (ESG) gateway, as well as on a publicly visible prototyping machine.

Support for parVis comes from core NSF funding and a grant from DOE's Office of Biological and Environmental Research (BER).

‹ Science Gateway Framework CISL Science ›

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Log in

2011 CISL Annual Report

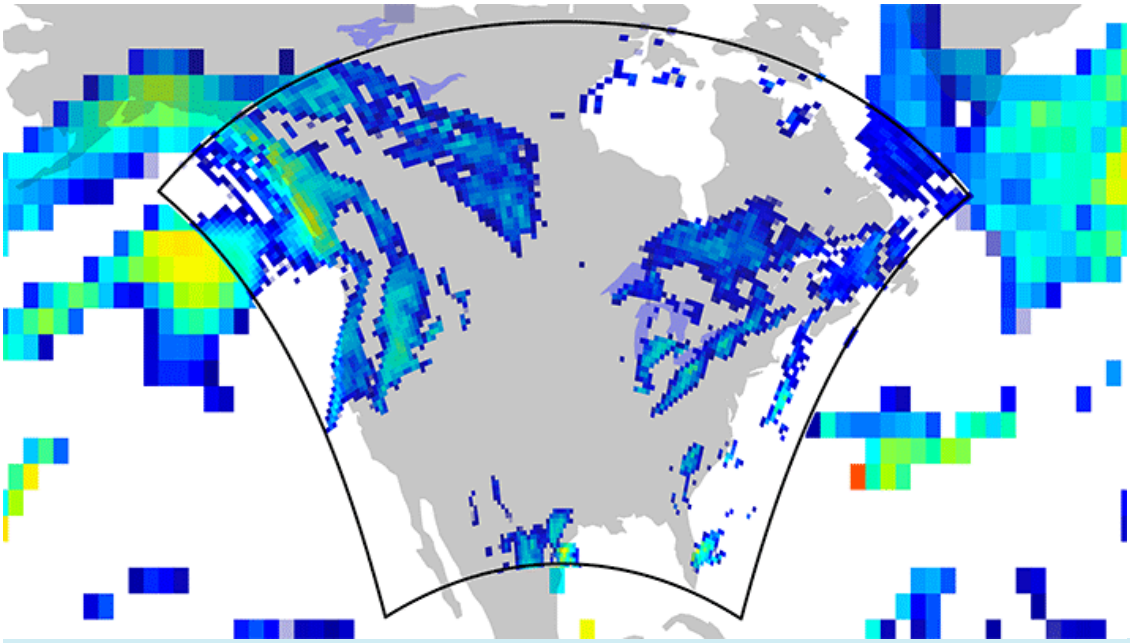
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - Scalable algorithms for massively parallel computers
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

CISL Science

CISL research activities support scientific computation, numerical methods, geophysical modeling, and the analysis of geophysical data and model experiments. These activities are chosen to lead the geophysics community in adopting new computational methods and mathematical tools to improve research. Diverse scientific disciplines often share common tools and numerical methods. The kind of mathematical, computational, and physical sciences housed in CISL focus on general mathematical tools, models, and algorithms that have broad application across NCAR. Hallmarks of this research are innovative and standout contributions that not only have relevance for the overall NCAR scientific program, but are also significant in their specific area of mathematical, physical, or computational science.



This three-hour snapshot of a regional climate simulation illustrates many of the issues addressed by CISL research. Depicted is the surface precipitation field over a three-hour interval from the coarse global forcing (NCEP reanalysis observations for 6 January 2000 at 6:00 UTC) and the higher resolution that is produced by a regional climate model developed by the Experimental Climate Prediction Center (ECPC). The downscaling by the ECPC model uses the coarse global information within the domain and at its boundaries but does not use the surface precipitation directly. This output is taken from the extensive series of simulations of the North American Regional Climate Change and Assessment Program (NARCCAP).

The simulation of regional climate, as illustrated by the figure above, is both an important numerical problem and touches on the grand challenge of modeling and interpreting the multiscale response of the Earth System. Although the current regional climate simulations typically couple two different models, the goal is to develop a single model with an adaptive resolution that allows for high-resolution modeling in parts of the domain and coarser resolution in areas of lower interest. CISL research is focused on developing both the numerical methods and the computational infrastructure for these next-generation models. These high-resolution regional simulations also pose problems in interpreting simulation results and comparing models to observed climate. This is pursued in CISL with research on statistical methods and also through an innovative application for data assimilation. Part of the challenge in climate analysis is to quantify the uncertainty in the simulation results in a way that is useful for resource managers and planners to make balanced decisions. Thus there are also research activities to translate the results of numerical experiments such as NARCCAP into useful information outside of climate science.

The NARCCAP figure is also a marker for the highly collaborative nature of CISL research. NARCCAP is accomplished through many teams: it involves six regional and three global modeling groups outside NCAR and would not be possible without this coordinated effort. Most of the projects described in the following sections reflect this style of modern interdisciplinary science -- complex problems are attacked by diverse groups of experts that combine their skills. One distinction of CISL research is that even with a focus on the computational and mathematical sciences, there is often substantial involvement of geoscientists to stay relevant to the NCAR scientific mission.

The activities outlined in this report advance the imperatives and frontiers of CISL's research strategy. The breadth of this research aligns with CISL's strategic imperative of scientific excellence. For CISL's interactions with the scientific community, a robust visitor program and a popular summer internship program provide numerous strategic benefits. Another scientific imperative addressed by CISL research is meeting the challenges of Earth System modeling as it moves to the petascale and exascale. Thus, research is pursued on adaptive numerical methods and multiscale models, both areas addressing the need for higher-resolution geophysical simulations. A companion to this effort is work in computational science for taking advantage of massively parallel supercomputers and new kinds of processors. Set against these computational goals is the creation of new analysis tools to interpret complex multifactor geophysical simulations and heterogeneous observational data. These are addressed in CISL research by the focus on the impacts of regional climate change and data assimilation.

‹ Managing complex heterogeneous data

Interdisciplinary contributions ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
      - Data assimilation research
      - Multiscale modeling of geophysical and astrophysical turbulence
      - Statistics for geophysical data and model experiments
      - Integrated regional climate science
      - GTP: Facilitating studies in interdiscplinary turbulence
    - Scalable algorithms for massively parallel computers
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Interdisciplinary contributions

One strategy to support sustained progress in the computational geosciences is to bring in new ideas from other scientific disciplines to anticipate emerging technology trends and the evolving NCAR scientific mission. Because of its expertise in computer science, applied mathematics, and statistics uniquely juxtaposed with the geosciences, CISL has been successful as an interdisciplinary computational science laboratory.

The interdisciplinary research within CISL serves several purposes. Besides a direct contribution to NCAR science programs, it also engages the larger computational science and mathematics communities to focus on problems from the geosciences. In this way the research capacity in CISL provides an interface between NCAR and other NSF communities. Moreover, many scientists in CISL leverage their work through collaboration with other external groups at universities and national laboratories. Apart from the specific research by CISL groups, interdisciplinary science is also supported by CISL workshops, the IMAGe Theme-of-the-Year, and SIParCS interns. This outreach would be difficult without CISL's in-house scientific activities described below.

An important accomplishment for 2011 was completing a complementary reanalysis for the atmosphere and ocean over the period 1997-2006 and a coupled reanalysis for selected years. This unique data product uses model components from CESM, the technology in DART, and supports the decadal climate prediction experiments for the next IPCC report. The application of DART to this project is an example of the power and flexibility of ensemble-based data assimilation when developed in a geophysical context.

Progress was also made in FY2011 on the analysis and curation of the NARCCAP experiments. Statistical methods were created to distinguish between contributions of the global model and regional downscaling to a climate simulation, and a detailed process study has clarified model differences in simulating seasonal rainfall in the U.S. Southwest. The modeling of multiscale processes is a scientific effort that depends on innovative use of high performance computing. The research in FY2011 focused on rotating frames of reference and turbulence for charged flows in magnetic fields. Using a TeraGrid allocation of 22 million CPU hours, novel numerical simulations were successfully completed on grids of up to $3{,}072^3$ spatial points.

Funding for these activities is indicated at the end on each of the following subsections.

‹ CISL Science

Data assimilation research ›

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Log in

2011 CISL Annual Report

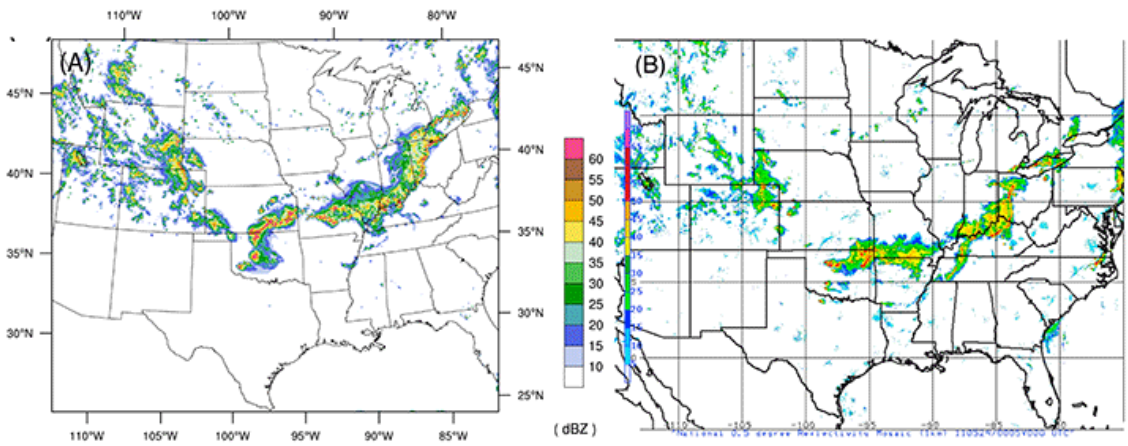
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
      - Data assimilation research
      - Multiscale modeling of geophysical and astrophysical turbulence
      - Statistics for geophysical data and model experiments
      - Integrated regional climate science
      - GTP: Facilitating studies in interdiscplinary turbulence
    - Scalable algorithms for massively parallel computers
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Data assimilation research

Data assimilation is the process of merging data from observations with computer models. It can transform diverse and incomplete observations to gridded estimates that can easily be used and interpreted. The assimilation process also produces quantitative information on model error, forecast skill, and observational errors, all of which allows us to improve models.



During Spring 2011, WRF-DART was run in real-time as a cycled analysis system in support of the NSSL/SPC Hazardous Weather Testbed over a 45-day period. On the left, (A) shows a 24-hour forecast of composite radar reflectivity; on the right, (B) shows verifying observed reflectivity valid on 24 May 2011 at 00 UTC. Large-scale aspects of the precipitating weather system are accurate in the forecast. Results from the experiment were used to improve the WRF model, and the forecast skill of revised WRF-DART mesoscale analyses are now comparable with the skill of NCEP operational analysis systems.

Data assimilation is providing rapid advances in geophysical studies. The Data Assimilation Research Section (DAReS) of IMAGe performs fundamental research on ensemble data assimilation methodologies for application across a wide range of geophysical problems. DAReS develops and maintains the Data Assimilation Research Testbed (DART), a software facility for ensemble data assimilation. DAReS also provides support to a growing community of NCAR, university, and government laboratory partners who are interested in applying ensemble data assimilation methods.

A broad range of NCAR projects was advanced by DART during FY2011:

- A DART/CAM4 ensemble reanalysis from 1998-2010 has been completed, and a corresponding POP ocean ensemble reanalysis is complete to 2006. Individual year-long atmosphere and ocean analyses have also been completed for 1974, 1979, 1984, 1989, and 1994. The ocean ensemble analyses are being used as initial conditions for ensemble decadal predictions that are part of the next IPCC assessment.
- DART was used with WRF to generate real-time analyses to initialize WRF mesoscale predictions of severe convective weather as part of the National Severe Storm Lab's Spring Forecast Experiment. A number of additional retrospective assimilations and forecasts have been made to evaluate the impact of changes in the WRF model physical parameterizations on forecast quality for convective weather.
- An efficient ensemble-based technique is under development for estimating and correcting systematic errors in observations during an assimilation. Initial tests in low-order models have been able to detect and correct specified biases. A bias correction method is essential for effective assimilation of satellite radiance observaions.
- A novel method is under development for estimating and adapting to model forecast systematic errors by using ensemble covariances. Tests in low-order models have demonstrated a robust ability to correct for certain kinds of model errors during an assimilation. Combining this capability with the observation systematic error correction will be a major research focus in the coming year.
- A systematic kinetic energy backscatter scheme (SKEBS) was tested in assimilations with CAM and WRF in collaboration with NESL. The SKEBS scheme parameterizes the transfer of energy from unresolved to resolved model scales. By adding more diversity to ensembles forecasts, it is expected to reduce the lack of variance that is common to ensemble predictions.

- The sampling error correction algorithm developed in previous years was applied to a large number of hurricane assimilation and prediction cases in the Pacific and Atlantic. Important and significant improvements in uncertainty estimates were found in all cases.
- Ensemble analyses with and without rapid scan cloud track wind observations and CIMMS AIRS temperature and moisture retrievals were performed for several tropical cyclone cases. The use of either of the additional observation sets resulted in improved forecasts of storm track and intensification.

CISL's data assimilation research advances CISL's strategic imperative to produce scientific excellence. Specifically, this work leads the mathematics and geophysical communities in ways that accentuate the contributions of mathematical methods and models to scientific progress in the geosciences. Further, DAReS research advances CISL's science frontier for understanding large and heterogeneous data sets by assimilating strategic, heterogeneous, and nonlinear observations into Earth System models. Data assimilation research in IMAGe is supported by NSF Core funding, NASA Grant NNX09AJ05G, National Oceanographic Partnership Program Grant G076112, and NSF Grant CNS1035250.

‹ Interdisciplinary contributions

Multiscale modeling of geophysical and astrophysical turbulence ›

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Log in

2011 CISL Annual Report

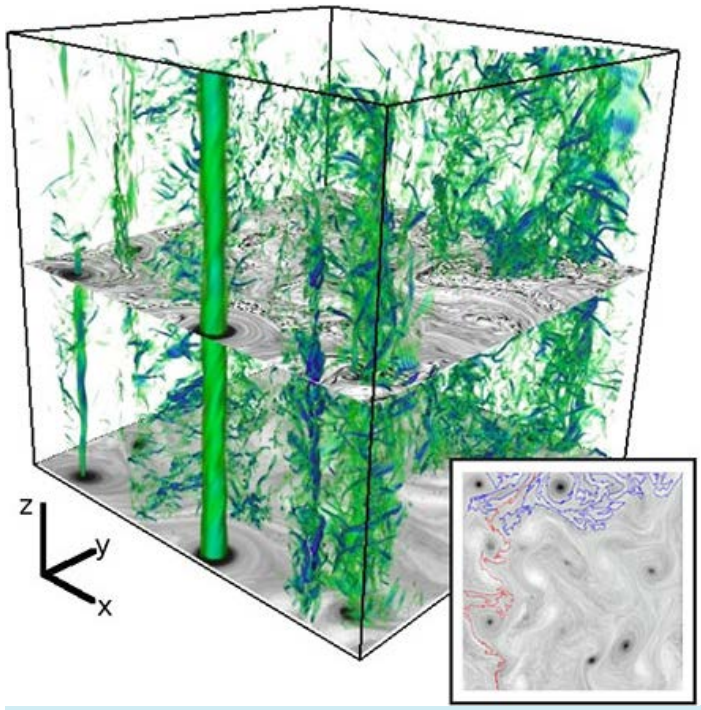
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
      - Data assimilation research
      - **Multiscale modeling of geophysical and astrophysical turbulence**
      - Statistics for geophysical data and model experiments
      - Integrated regional climate science
      - GTP: Facilitating studies in interdiscplinary turbulence
    - Scalable algorithms for massively parallel computers
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Multiscale modeling of geophysical and astrophysical turbulence

The Turbulence Numerics Team (TNT) complements the Geophysical Turbulence Program (GTP) and is focused on accurately simulating and understanding turbulence for fluids such as those in the atmosphere and the oceans, and for charged flows in the presence of magnetic fields as in space weather and in the solar atmosphere and corona. TNT studies simplified physical systems that still reproduce the complexity and multiscale properties associated with such flows. Such fundamental, long-term research on multiscale phenomena is appropriate for a national center. These activities support CISL's strategic goals and have educational and outreach components since state-of-the-art computations are performed and the data is publicly available and used by students, postdocs, engineers, and scientists.



Perspective volume rendering of vorticity intensity in a snapshot of a $1{,}536^3$ rotating turbulent helical flow. The slice in the middle of the box shows a cross-sectional cut of vorticity while the slice at the bottom shows the average of all such cross-sectional cuts. Statistical analysis of contour lines of zero vertical vorticity such as those in the inset utilizes the fact that the rapid rotation has reduced the structure in the flow to 2D planes, and imposes an additional type of symmetry upon the flow. The research has exploited this symmetry property for the first time in a 3D turbulent fluid system to apply a type of statistical classification that also encompasses non-fluid physical systems, and thereby links with other areas of physics.

In FY2011 TNT focused on two broad areas: turbulence related to rotating frames of reference and MHD turbulence. High resolution direct numerical simulations (DNS) were performed to examine the return to isotropy in the small scales of rotating turbulent flows. These simulations were carried out with a TeraGrid allocation of 22 million CPU-hours on grids of up to $3{,}072^3$ spatial points. Parameters were chosen to add energy and helicity at low wavenumber (so there is minimal inverse cascade), with a small Rossby number, Ro=0.07, and high Reynolds number, Re=27,000. In these simulations, the Zeman wavenumber -- at which the inertial and eddy turnover times are equal -- is well resolved. Spectra show that a helical wave-modulated inertial law is obtained for the energy and helicity down to the Zeman scale, and at smaller scales they show Kolmogorov behavior, indicative of a recovery of three-dimensionality in the small scales. Columnar structures found in earlier work are seen to persist as well, but with features that indicate less domination by rotation.

Inspired by the two-dimensionalization process seen in rapidly rotating turbulent flows, we undertook two studies that consider the conformal invariance properties of 2D and 3D flows. The first was an experimental flow using a soap film that represented 2D Navier-Stokes turbulence, and the second considered a two-dimensional representation of a 3D DNS of forced rotating turbulence. The determination of conformal invariance in the numerical simulation was the first such identification of this property in the direct cascade region of a 3D flow. Such a classification may elucidate properties of these 3D flows by comparison with aspects of other physical systems that have little other apparent connection to fluid systems. The figure above illustrates how the 3D flow was two-dimensionalized to investigate the fractality of the 0-field isolines, and thereby determine conformal invariance of the two-dimensionalized flow.

Consideration of the two-dimensionalization of the forced rotating 3D flows and the subsequent cascade of energy to large scales, together with what appear to be inverse cascades in experimentally decaying 2D flows led us to examine ensembles of 2D hydrodynamic runs with random initial conditions. Ensemble- and time-averaging of the data demonstrated inverse cascade behavior in the large scales, even in the absence of external forcing. The source

of energy for this ergodic behavior is the energy in the energy-containing scale at t=0, and such behavior helps reveal the connections between decaying and forced turbulence in experimental systems. Finally, we examined the ideal (no dissipation) dynamics of a variety of 3D flows. In all these cases, the results agree with isotropic predictions stemming from statistical mechanics of truncated systems. Long- and intermediate-time behavior of strongly rotating systems as well as of 2D and 3D, and MHD flows in different geometries were also considered in this context. Numerical simulations of rotating turbulence provides additional information and references on these results.

Several projects were also carried out in the context of MHD at high Reynolds number. The first, conducted in collaboration with Eric Blackman (Rochester) and Jonathan Pietarila-Graham (LANL), examined the dynamics of helical MHD flows and the changes due to different fractional values of kinetic helicity on the large-scale dynamo threshold. DNS was used to show that the minimum fractional kinetic helicty to drive large scale magnetic field growth decreases strongly as the ratio of the forcing to large scale wavenumber increases. A second project considered high Reynolds number regimes up to equivalent resolutions of $6{,}000^3$ grid points in the absence of forcing and with no imposed uniform magnetic field to encapsulate results that reflect dynamics of a globally isotropic MHD flow with local anisotropies due to a strong large-scale magnetic field. Finally, we carried out research on highly turbulent MHD flows that obey the Taylor-Green symmetries to examine the development of singular (small-scale) structures. A 15-million CPU-hour DOE INCITE allocation grant was awarded to carry out these symmetric simulations at equivalent resolutions of $6{,}144^3$ spatial grid points. This project also led to the development of additional software capabilities for the GHOST and TYGRES DNS codes.

Research and service activities of TNT are supported by NSF Core funding, and by additional funding from NSF-CMG Grant 1025188. We also gratefully acknowledge DOE INCITE award TUR020, and NSF TeraGrid/XSEDE grant TG-PHY10029.

‹ Data assimilation research

Statistics for geophysical data and model experiments ›

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Log in

2011 CISL Annual Report

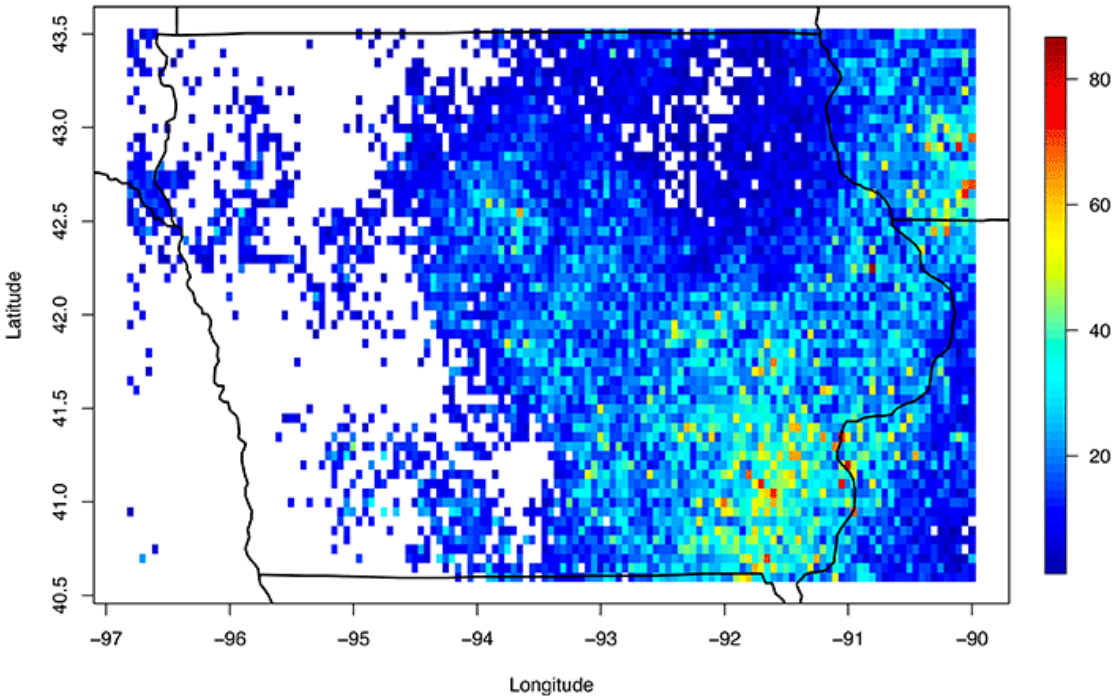
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
      - Data assimilation research
      - Multiscale modeling of geophysical and astrophysical turbulence
      - **Statistics for geophysical data and model experiments**
      - Integrated regional climate science
      - GTP: Facilitating studies in interdiscplinary turbulence
    - Scalable algorithms for massively parallel computers
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Statistics for geophysical data and model experiments

From our unique position within CISL and IMAGe, the Geophysical Statistics Project (GSP) has been a leader in training and research emphasizing the synergy between the geosciences and the statistical sciences. In addition to basic methodological and theoretical statistical research aimed at problems arising from NCAR science, GSP has a strong interdisciplinary training component supporting graduate students and postdoctoral visiting scientists. These young researchers are immersed in research activities that not only focus their skills as applied statisticians but also expose them to important geophysical applications.



Based on a spatial-temporal statistical model trained on observations from a set of 22 meteorology stations in Iowa, this figure displays a simulation of daily precipitation (mm) for 1 January. This new technique for constructing a weather-generator allows spatially consistent simulations of precipitation anywhere across a domain of interest (almost all current methods only simulate at locations with observations) while accurately representing the local behavior and the intermittency of precipitation. Informed by information from high-resolution climate models, these weather-generators can simulate daily weather under future climate change scenarios, and, for example, aid agricultural researchers in better understanding the impacts of climate change.

In addition to these core activities, GSP also has an active visitor program providing research opportunities for visiting faculty members from across the nation and abroad. Our goal is to foster collaboration between graduate students, postdocs, the permanent and visiting statistical staff, and NCAR scientists. These programs -- as well as the research and training aspects of GSP that emphasize the interaction between statistics and the geosciences -- embody the tenets of integration, innovation, and community building within the CISL Strategic Plan. This program advances CISL's strategic imperative to produce scientific excellence by leading the scientific community in adopting new computational methods and mathematical tools that enhance scientific research. More specifically, GSP supports CISL's science frontier of developing innovative statistical design and analysis techniques to improve the efficiency and accuracy of model development and testing.

During FY2011, GSP researchers have been involved in numerous important projects, including:

- Design and analysis of computer experiments, in particular focusing on regional climate models and models of the upper atmosphere and the magnetosphere
- Developing methodology for analyzing extremes of weather and climate
- Developing stochastic weather-generators
- Modeling uncertainty in climate reconstruction

- Impacts of climate and climate change on public health

In addition, GSP continues to develop theory and methodology for analyzing spatial data, including large datasets, nonstationary covariance models, models for spatial lattice data, multivariate spatial observations, spatial-temporal models, and general methodology for computational statistics and Bayesian hierarchical models.

This project is made possible through NSF Core funding, as well as grants through NSF's Division of Mathematical Sciences, NSF's Division of Atmospheric Sciences, NSF's Collaboration in Mathematical Geosciences, the Environmental Protection Agency (EPA), and the National Aeronautics and Space Administration (NASA).

‹ Multiscale modeling of geophysical and astrophysical turbulence

Integrated regional climate science ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
      - Data assimilation research
      - Multiscale modeling of geophysical and astrophysical turbulence
      - Statistics for geophysical data and model experiments
      - **Integrated regional climate science**
      - GTP: Facilitating studies in interdiscplinary turbulence
    - Scalable algorithms for massively parallel computers
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Integrated regional climate science

In collaboration with a broad range of public and private laboratories and universities, the mission of the Regional Integrated Science Collective (RISC) is to generate high-quality regional-scale scenarios of projected climate change, then develop tools and methods for analyzing impacts, vulnerability, and adaptation options. RISC's placement in IMAGe shows the close ties between evaluating climate models and quantifying uncertainty using statistics. RISC also reaches out to the broader decision-making and policy communities by integrating mathematical analyses into a more immediate and pragmatic realm. RISC has responsibility for serving large and multifaceted numerical experiments, so it is well aligned with CISL's mission of data support to the climate science community.

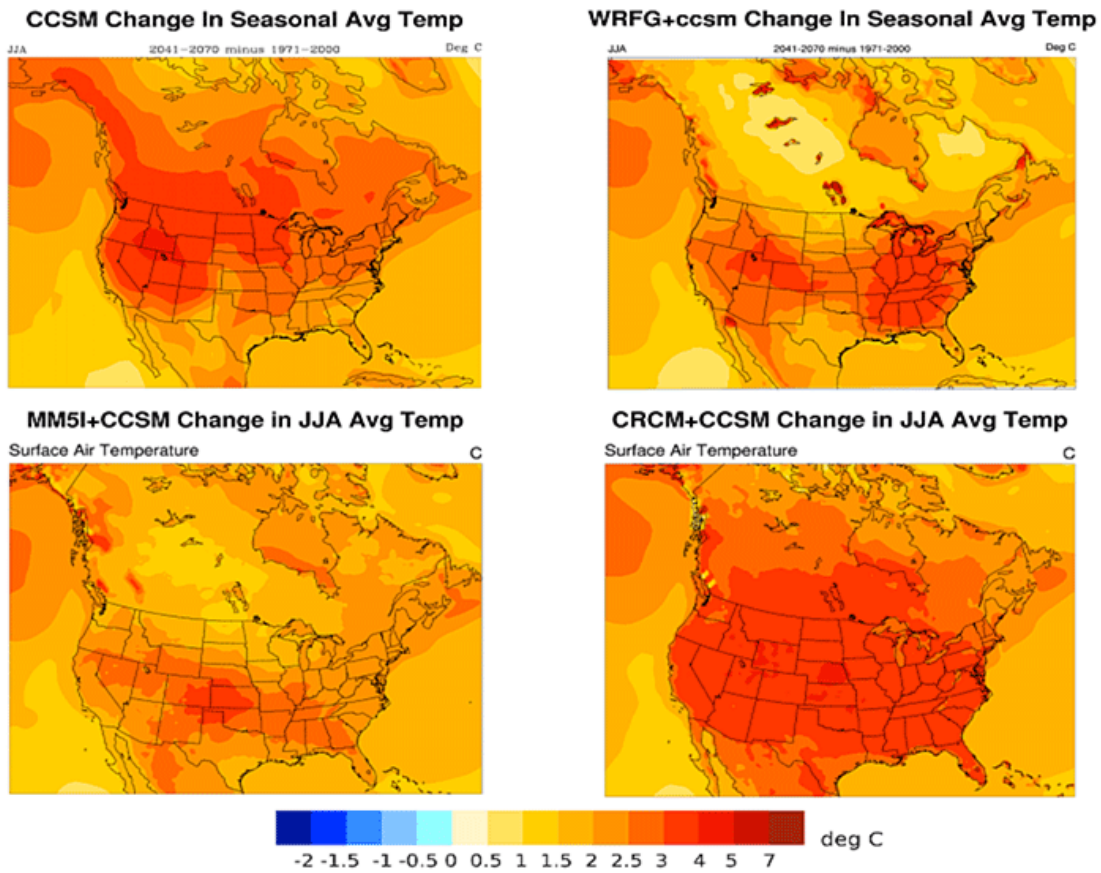

Illustration of NARCCAP projections of regional climate change for several regional climate models (RCMs) demonstrating the uncertainty in the projections at regional scales. Change in summer temperature in °C for 2041-2070 minus 1971-2000 for the NCAR CCSM3 run under the A2 emissions/concentration scenario (upper left panel), and the same change in summer temperature from simulations with three RCMs all driven by the CCSM3, upper right MM5, bottom left WRF, bottom right the Canadian CRCM. Note the very different patterns of change in all four figures. The Canadian RCM amplifies the changes in the CCSM3 in the eastern U.S., while the MM5 and WRF models diminish the warming in the Canadian prairies.

A centerpiece of RISC's activity is its leadership of the North American Regional Climate Change Assessment Program (NARCCAP). NARCCAP is systematically investigating the uncertainties in regional-scale projections of future climate. It is unique in its balanced design that allows for isolating the influence of individual regional and global models on the resultant climate simulations. The overall goal of NARCCAP is to produce high-resolution (50 km) climate change scenarios using six regional climate models (RCMs) nested within four atmosphere ocean general circulation models (AOGCMs) forced with the A2 SRES emission scenario, over a domain covering the conterminous U.S., northern Mexico, and most of Canada. The project also includes an evaluation arm whereby the participating RCMs are forced by reanalysis data sets. The resulting regional climate model runs and time slices form the basis for multiple high-resolution climate scenarios that can be used in climate change impacts assessments in the U.S. and Canada.

In FY2011, substantial progress was made in completing the climate change simulations. Three new simulations of current and future climate were completed driving the WRF model with the CGCM3, the MM5 model with the HadCM3, and the ECPC RSM with the GFDL. We now have two complete sets of three different RCMs driven with the same AOGCM (see figure above). In addition, more of the upper-air data from the GCM-driven runs was made available. Detailed analyses of the reanalysis-driven runs were performed, including analysis of domain-wide temperature and precipitation biases and reproduction of temperature trends compared to observations. An overview paper of Phase I results was submitted to Bulletin of the American Meteorological Society and has been accepted pending revisions. Another paper on temperature trends is about to be submitted. Further progress has been made on analyzing the climate change results and quantifying uncertainties. The NARCCAP website has been further developed to facilitate use by the now 500 NARCCAP users.

RISC also maintains and develops the Weather and Climate Impacts Assessment Science Program (WCIASP). WCIASP has three primary thrusts: investigating uncertainty in climate change research, studying extreme weather and climate events, and the Climate and Health Workshop series. The fourth biannual Climate and Health Colloquium, on Climate and Infectious Diseases, was held during summer 2011.

The Regional Integrated Science Collective (RISC) is supported by NSF Core funding as well as interagency support for NARCCAP from NSF, EPA, DOE, NOAA, and NASA.

‹ Statistics for geophysical data and model experiments

GTP: Facilitating studies in interdiscplinary turbulence ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
      - Data assimilation research
      - Multiscale modeling of geophysical and astrophysical turbulence
      - Statistics for geophysical data and model experiments
      - Integrated regional climate science
      - **GTP: Facilitating studies in interdiscplinary turbulence**
    - Scalable algorithms for massively parallel computers
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

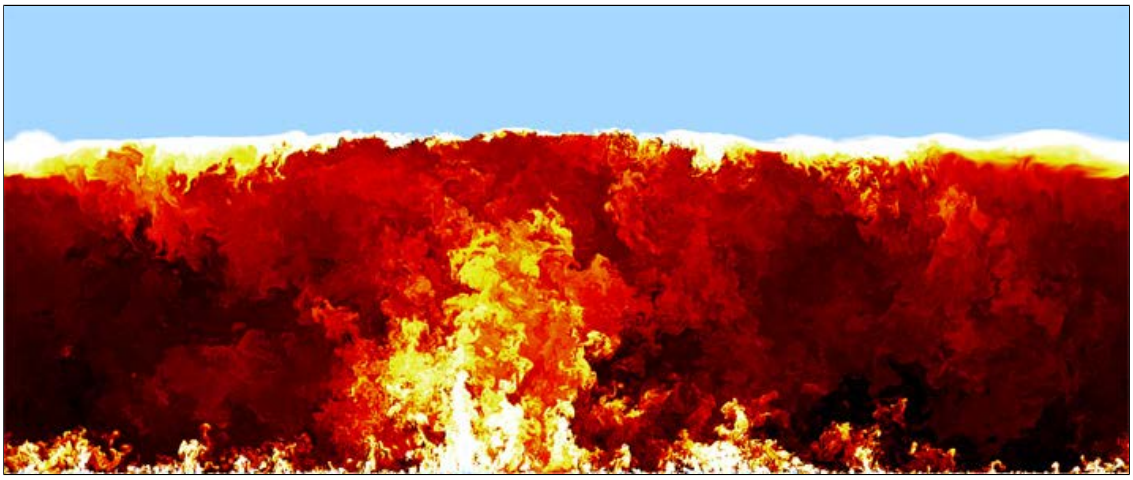
2009-2014 Strategic Plan »

Search

GTP: Facilitating studies in interdiscplinary turbulence

Research on turbulence has been a significant part of the NCAR scientific program since its beginning in the early 1960s. The original scientific leaders of NCAR recognized that to understand the dynamics of the atmosphere, the oceans, the climate, the sun, and solar-terrestrial interactions, understanding relevant turbulent processes would be essential. A number of scientific appointments in the first 10-15 years of NCAR's existence reflected this view and provided an in-house base from which to productively interact and collaborate with the world turbulence community. From these beginnings, a sustained emphasis on geophysical turbulence at NCAR has emerged in research, visitors, seminars, and workshops that continues to this day. Most of this emphasis manifests itself currently in the Geophysical Turbulence Program (GTP).

By design, GTP is an interdiscplinary group of about 40 members that spans many divisions and laboratories at NCAR with a few external affiliates. GTP encompasses research at NCAR on multi-scale nonlinear processes with an array of applications in a broad variety of areas. GTP is also the outreach arm of this research, and is complementary to the Turbulence Numerics Team.



A vertical x-z cross-section of the temperature field from a direct numerical simulation of a convective boundary layer with a strong capping inversion. The image depicts a wide range of scales in the boundary layer, which results from the high Reynolds number of the simulation, and the intermittent entrainment of warmer fluid at the top of the boundary layer.

In FY2011, GTP hosted 12 visitors, six from the U.S. and six from Europe, for stays between one week and one month or more (the longer stay was made possible through substantial support from NCAR's Advanced Study Program for a fellowship). The average stay was 26 days in FY2011, and most visitors gave a talk. We also had a visitor from the University of Colorado for the whole year. Our seminar series, with 11 talks given, saw topics ranging from petascale computing and modeling to mixing, zonal flows, particle-laden flows, shear flows and anisotropy, and finally convection and dynamos.

Research topics included:

- Land-surface response to shallow cumulus
- Development of a shallow spectrum in quasi-geostrophic turbulence due to the influence of the induced ageostrophic flow
- A nonhydrostatic unstructured-mesh soundproof model for simulation of internal gravity waves
- High resolution prediction of alpine weather
- Solar and stellar convection with LES codes
- Multiscale simulations of droplet-laden turbulent flows and their application to cloud physics
- Toward petascale simulation of atmospheric circulations
- Petascale direct simulations to determine the growth-rate law of convective boundary layers

In the final case on boundary layers (see figure), simulations were conducted within a European "Extreme Computing Initiative" framework; the largest simulations, which ran on the Juelich BlueGene supercomputer, used 3,0723 grid points and employed 32,768 cores. These simulations shed light on why different laboratory experiments with

different setups produced different growth-rate laws for convective atmospheric boundary layers, gaining insight into how the Reynolds/Peclet number combination influences the resulting growth-rate and entrainment-law behavior. The small boundary layers near the lower wall and near the inversion turned out to be pivotal in this respect.

GTP funding for these activities was either partial or total, with particular support from ASP, HAO, and MMM.

GTP did not hold a workshop in FY2011 because FY2012 is going to be rather full (see below). GTP proposed and obtained funding for a Theme of the Year (TOY) in FY2012 on rotating stratified turbulence under the direction of Baylor Fox-Kemper (CIRES, CU), in collaboration with Keith Julien (CU), Leslie Smith (U. Wisconsin), and Susan Kurien (LANL). Planned for calendar year 2012 are three workshops to be held at NCAR; these are funded or co-sponsored by GTP. In May a workshop on “Connections between Rotating, Stratified Turbulence and Climate: Theory, Observations, Experiments, and Models” will be held in the framework of the TOY 2012.

In August, the GTP workshop will be on particle-laden flows, organized by Peter Lian-Ping (University of Delaware) and several GTP members in MMM. In December 2012, a workshop on “Modeling the Earth System” will be sponsored by Journal of Computational Physics and organized locally by Piotr Smolarkiewicz (MMM and IMAGe) and Annick Pouquet.

Finally, a team of GTP scientists from MMM and CGD submitted a collaborative proposal to DOE/SciDAC (Scientific Discovery through Advanced Computing) with the goal to develop, implement, and evaluate an overall improved parameterization of the atmospheric planetary boundary layer (PBL) in the NCAR Community Earth System Model (CESM). The initial target is the parameterization of the heterogeneous Arctic stable boundary layer (SBL) in the presence of open-water leads. Funding for this effort was not awarded, but the effort will be pursued.

GTP activities are mainly supported by NSF Core funding. Some of the collaborations with the university community also receive funds from NSF and can be co-sponsored by NCAR funds from its laboratories and programs.

‹ Integrated regional climate science

Scalable algorithms for massively parallel computers ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - **Scalable algorithms for massively parallel computers**
      - Discontinuous Galerkin HOMME
      - Adaptive methods for geoscience modeling
      - Scaling Earth System models
      - Highly scalable codes for turbulent flows
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Scalable algorithms for massively parallel computers

The Earth System and solar physics models at NCAR motivate CISL's scientific research on algorithms, numerical methods, and computational performance. A priority in geophysical modeling is to increase resolution to resolve important processes and uncover unexpected interactions within the physical system. This goal must be pursued within the context of massively parallel computational resources. Given these two elements, CISL research has focused on areas to increase model resolution through methods that scale to large numbers of processing cores. It is well understood that to take advantage of the unique characteristics of large systems, improvements in simulation speed depend on better numerical algorithms and innovative computer science.

A FY2011 research highlight in numerical methods is the successful test of a discontinuous Galerkin (DG) method in the atmospheric dynamical core of the Community Atmosphere Model that is high-order, conservative, and highly scalable. Another significant numerical result is the demonstration that radial basis function (RBF) methods have comparable or better performance to the more complex DG methods currently in development; RBFs may be an alternative for some kinds of geophysical problems. In computer science a milestone for FY2011 is the completion of a 155-year simulation of the NCAR climate system model that couples high-resolution atmosphere, ocean, and sea ice components. The length of this high-resolution experiment is unprecedented, and many performance issues had to be solved to achieve this rate of simulation. Also in FY2011, a highlight in CISL turbulence research is that the Geophysical High-Order Suite for Turbulence (GHOST) and TaYlor-GREen Symmetrical (TYGRES) codes were evaluated in a large, multi-core environment suggesting that hybridization approaches lead to faster codes.

Funding for this research is detailed in the individual reports below.

‹ GTP: Facilitating studies in interdiscplinary turbulence Discontinuous Galerkin HOMME ›

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Log in

2011 CISL Annual Report

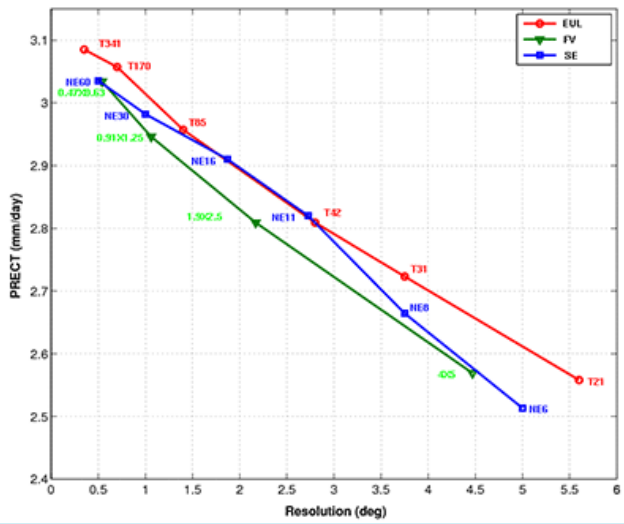
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - Scalable algorithms for massively parallel computers
      - **Discontinuous Galerkin HOMME**
      - Adaptive methods for geoscience modeling
      - Scaling Earth System models
      - Highly scalable codes for turbulent flows
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

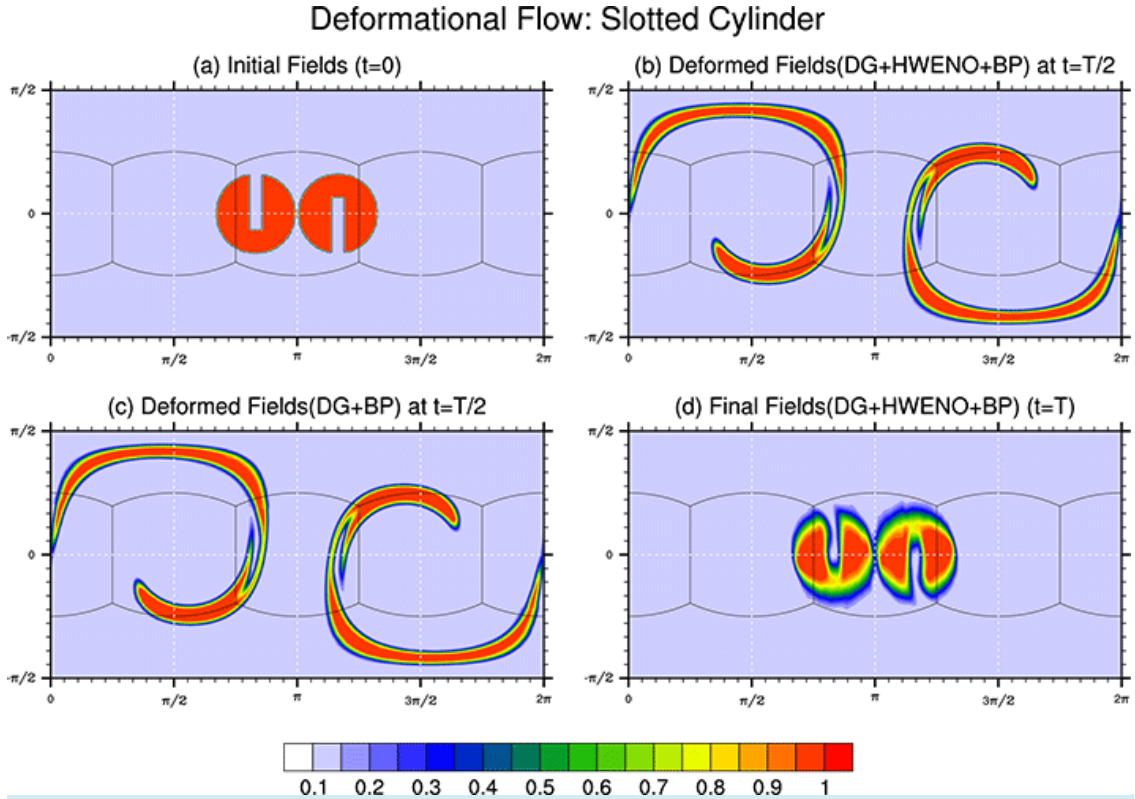
Discontinuous Galerkin HOMME

The High-Order Method Modeling Environment (HOMME) is a framework to investigate using high-order element-based methods to build conservative and accurate dynamical cores. Currently, HOMME employs the Spectral Element (SE) and Discontinuous Galerkin (DG) methods on a cubed-sphere tiled with quadrilateral elements. HOMME can be configured to solve the shallow water or the dry/moist primitive equations, and has been shown to efficiently scale to nearly 170,000 processors on a supercomputer. The objective of this project is to extend HOMME to a framework capable of providing the atmospheric science community with a new generation of atmospheric general circulation models (AGCMs) for the CESM (Community Earth System Model).



This figure shows how the HOMME dynamical core compares with the Eulerian (EUL) and Finite-Volume (FV) dynamical cores for the Community Atmospheric Model version 5 (CAM5) framework set to an aqua-planet configuration. The plots show the time mean global average precipitation versus horizontal resolution for EUL (red), FV (green), and HOMME (blue). In low latitudes, HOMME performance at coarser resolutions is generally equivalent to the performance of EUL and FV at finer resolutions.

HOMME is based on high-order numerical methods on the cubed-sphere that efficiently scale to hundreds of thousands of processors, achieve scientifically useful integration rates, provide monotonic and mass-conserving transport of multiple species, and easily couple to community physics packages such as Community Atmosphere Model (CAM) physics. Achieving these objectives will allow climate scientists to take full advantage of the petascale computing capabilities being deployed by NSF, and will lead to dramatic increases in climate science productivity.



This figure illustrates a deformational flow simulation using the new non-oscillatory DG scheme on the cubed-sphere. Initial non-smooth field (twin slotted cylinder) shown in panel (a) deforms into thin filaments and moves along the zonal direction during the simulation. Panels (b) and (c) show the numerical solutions with the DG transport scheme at half-time (when the deformation is most severe) using the limiter and bound-preserving filter options. Panel (d) shows the final solution when the deformed field returns to its original shape. The new non-oscillatory DG scheme does not produce spurious wiggles or negative values, qualifying it for the requirements of atmospheric tracer transport models.

In FY2011, a performance comparison of the SE version of the HOMME dynamical core with other established dynamical cores in the Community Atmospheric Model (CAM) was carried out. The latest version of the CAM framework (CAM5) set to an aqua-planet configuration was used for that purpose. CAM5 currently offers three dynamical cores – Eulerian (EUL), Finite Volume (FV), and HOMME/SE with a wide (0.35° to 5.5°) range of horizontal resolutions for climate study. It is desirable to understand the equivalence in resolutions across the dynamical cores. The equivalence is judged on the basis of precipitation because of its importance to the Earth's climate system. For this, global average precipitation and its distribution in horizontal, vertical, and temporal dimensions are analyzed.

For accurate simulation of global mean precipitation, FV needs finer resolutions to be equivalent with EUL. At moderate resolutions (between 1.5° and 3°) HOMME and EUL have the same equivalent resolutions. But at low (below 3°) and high (above 1.5°) resolutions, HOMME needs finer resolution to be equivalent with EUL. To be equivalent with EUL in the tropical latitudes, HOMME usually needs relatively coarser resolutions, but in the polar latitudes, just the opposite happens. FV and EUL generally perform similarly. Note that for a given equatorial grid spacing, the latitude-longitude grid system needs more (~30%) grid points than the cubed-sphere grid system, hence HOMME is more economical than EUL, even though they have the same equivalent resolutions at the global scale.

The DG version of HOMME employs an arbitrary high-order spatial discretization. With explicit time-stepping as used in HOMME, however, a fourth or higher-order DG scheme has a more restrictive CFL stability constraint than the SE version. Reducing the order-accuracy has some benefits. It significantly improves CFL stability and allows one to implement limiting algorithms based on those designed for FV methods. A lower-order DG scheme is particularly desirable for non-hydrostatic model development where the time step restriction is more severe due to vertically propagating acoustic waves. To meet these requirements, a new third-order DG scheme has been developed. The non-oscillatory and positivity-preserving properties for the DG transport scheme are achieved by applying the H-WENO (Hermite weighted essentially non-oscillatory) limiter and a bound-preserving (BP) filter, respectively. The figure above shows a challenging deformational flow simulation with the new third-order DG scheme on the cubed-sphere, in which a non-smooth initial distribution deforms and successfully returns to its original shape without spurious oscillations or negative values. This demonstrates its usefulness for models that simulate the transport of atmospheric tracers.

This work supports CISL's science imperative to develop mathematical research codes that improve modeling. Specifically, it fulfills the strategic action item to further develop the High Order Method Modeling Environment (HOMME) dynamical core.

Primary support for HOMME is provided by NSF Core funding. The validation of the HOMME dynamical core and HOMME/DG development are supported by the U.S. Department of Energy under grants DE-F402-07ER64464,

DOE/BER program DE-SC0001658, and DOE BER SciDAC 06-13194.

‹ Scalable algorithms for massively parallel computers

Adaptive methods for geoscience modeling ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - Scalable algorithms for massively parallel computers
      - Discontinuous Galerkin HOMME
      - **Adaptive methods for geoscience modeling**
      - Scaling Earth System models
      - Highly scalable codes for turbulent flows
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

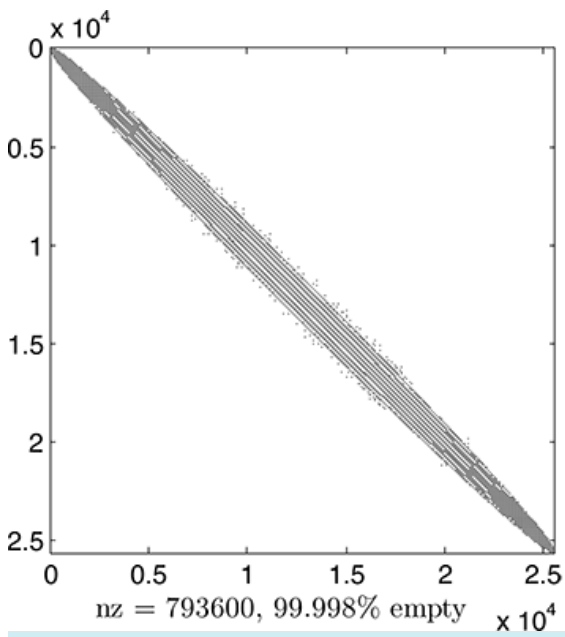
Search

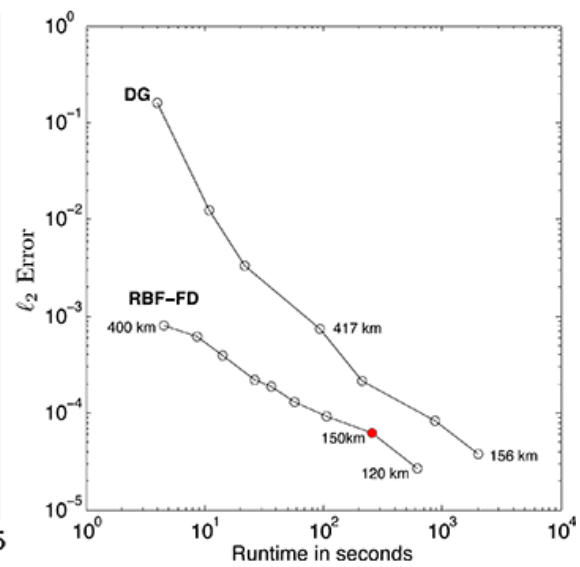
Adaptive methods for geoscience modeling

While computer technology has advanced rapidly in recent years, numerical schemes currently used for geoscience modeling fall short of scientists' expectations. Radial basis functions (RBFs) offer a novel numerical approach for solving partial differential equations (PDEs) to high accuracy. Compared to other methods, such as spherical harmonics, spectral/finite elements, or finite differences, relatively coarse discretizations suffice for obtaining matching accuracies. Further, RBFs boast stability for large time steps. Being a mesh-less method, RBFs excel in solving problems that require geometric flexibility, local refinement for small features, and they require little increase in programming complexity when extended to higher dimensional spaces.

Building on the accomplishments of FY2010, the IMAGe Computational Mathematics Group together with Boise State University, University of Colorado, University of Minnesota, University of California at Davis, and Uppsala University in Sweden continue research in the developing area of RBFs for geoscience modeling.

In FY2011, RBF methodology was further improved to become more computationally cost-effective in terms of scalability, memory, and runtime. A promising horizon is the development of RBF-generated finite difference stencils (RBF-FD) for approximating the derivatives in PDEs. The local character of this novel concept will allow for much sparser matrices (requiring less memory and computation) while still giving high-order accuracy and geometric flexibility. RBF-FD are currently being explored on a variety of geoscience testbeds. The plots below show one example.





The left plot shows the sparsity of RBF-FD matrices necessary to compute shallow water flow over a cone mountain on Earth's surface at 150-km resolution. Each row approximates the derivative at a node on a sphere having 25,000 nodes. Also for the flow over the cone mountain test case, the chart on the right shows the RBF-FD error as a function of runtime (defined by wallclock time) when compared to a high-order Discontinuous Galerkin (DG) method. Simulations were run on the same computer with the same hardware configurations enabled. The red marker corresponds to the error at 150-km resolution obtained by a discretization whose matrix structure is given in the left plot.

This work advances CISL's scientific efforts to develop scalable algorithms for massively parallel computers. This development effort at NCAR is supported by NSF grants ATM-0620100, DMS-0934317, and OCI-0904599.

‹ Discontinuous Galerkin HOMME

Scaling Earth System models ›

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Log in

2011 CISL Annual Report

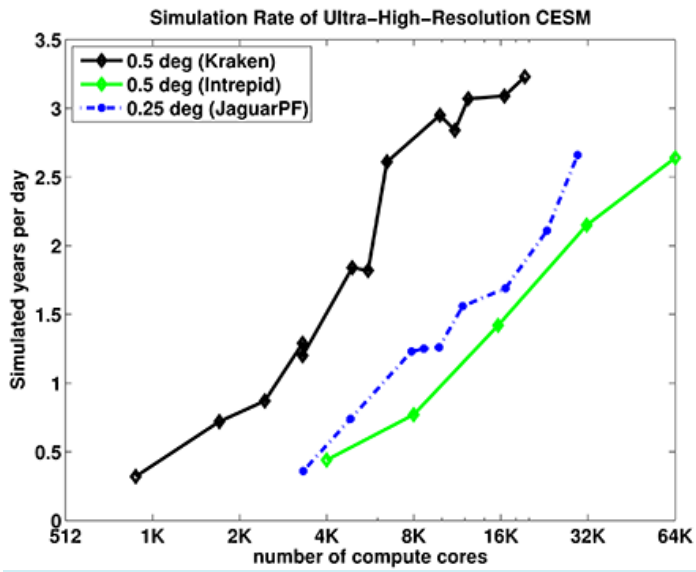
- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - Scalable algorithms for massively parallel computers
      - Discontinuous Galerkin HOMME
      - Adaptive methods for geoscience modeling
      - Scaling Earth System models
      - Highly scalable codes for turbulent flows
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Scaling Earth System models

Over the last several years CISL staff and collaborators have been improving the scalability of the various components of the Community Earth System Model (CESM). Significant improvements have been made to the efficiency of the Parallel Ocean Program (POP) and the Community Ice CodE (CICE) at 0.1° on large processor counts. This work focused on improving the simulation rate and reducing the computational cost to simulate ultra-high-resolution climate.



This chart shows the simulation rates achieved in three runs of a fully coupled CESM configuration with 0.1° POP and CICE using: 0.5° CAM and CLM on Kraken (Cray XT5, black line), 0.5° CAM and CLM on Intrepid (IBM Blue Gene/P, green), and 0.25° CAM and CLM on JaguarPF (Cray XT5, blue). This image illustrates that it is now possible to utilize very-large-scale parallelism to achieve climatologically relevant simulation rates to explore the impact of ultra-high-resolution on the fidelity of climate simulations.

All of these improvements, along with a new scalable dynamical core for the Community Atmosphere Model (CAM) based on the High Order Method Modeling Environment (HOMME), have been made available through the official release of CESM. This scalability improvement has also enabled the completion of a 155-year control run that couples a 0.1° POP and CICE to a 0.5° CAM and LND on Kraken, a Cray XT5 system located at the National Institute for Computational Sciences (NICS). This 155-year control run is part of the NSF-funded PetaApps project to investigate the impact of weather noise within the coupled climate system.

These advances are significant because it is now possible to simulate the Earth System on currently available supercomputing resources at resolutions that are 30 times as computationally demanding as the current production CESM simulation. This work enables the climate simulation community to explore the impact of ultra-high-resolution. Our work demonstrates that we are prepared to use the upcoming NSF petascale system to finally resolve many of the important physical processes with the Earth System that previously had to be parameterized.

This work advances CISL's strategic imperative to produce scientific excellence, and it prepares a foundation for petascale and exascale computing. This work is supported by NSF Core funds and NSF PetaApps grant OCI-0749206. Additional funding is provided through the Department of Energy's CCPP program grant DE-FC03-97ER62402.

‹ Adaptive methods for geoscience modeling Highly scalable codes for turbulent flows ›

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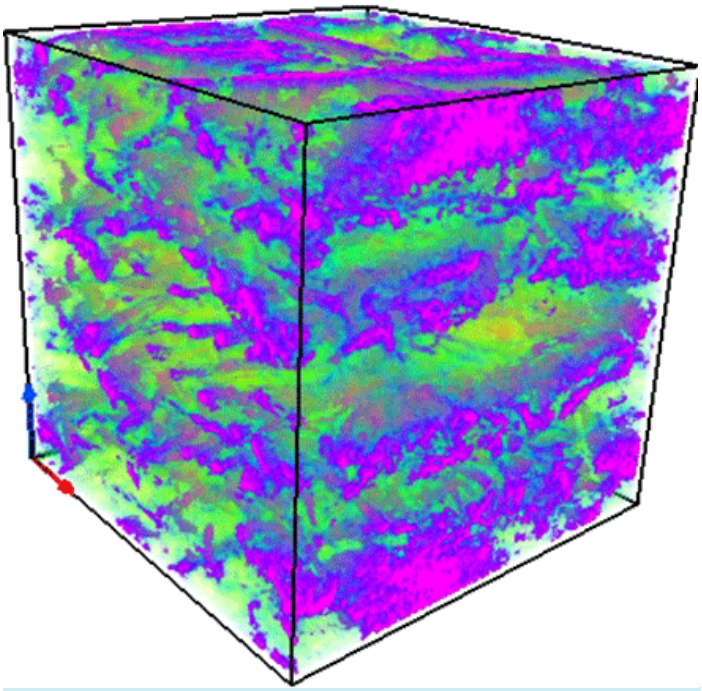
Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - Scalable algorithms for massively parallel computers
      - Discontinuous Galerkin HOMME
      - Adaptive methods for geoscience modeling
      - Scaling Earth System models
      - **Highly scalable codes for turbulent flows**
    - Computational research and development
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Highly scalable codes for turbulent flows



Perspective volume rendering of density for a turbulent and strongly stratified Boussinesq run at 256^3 resolution. The figure clearly shows both turbulent fluctuations and stratification in a decay flow, and this helps validate the new Boussinesq solver in the GHOST code.

The Turbulence Numerics Team (TNT) generally focuses on simplified physical fluid systems that retain the full multiscale properties and complexity of geophysical and astrophysical systems in an effort to understand the detailed scale interactions that characterize turbulence in them. Accurate numerical methods are required when examining the small-scale statistical properties of such complex flows. Pseudo-spectral codes thus retain a great usefulness, both for examining high-Reynolds-number flows and for testing numerous modeling parameterizations in detail. In this spirit, the Geophysical High-Order Suite for Turbulence (GHOST) code was developed originally by P. Mininni in collaboration with D. Gómez (U. Buenos Aires). GHOST has since been extended to include several methods for parametrization (a regularization procedure, and a helical spectral model for both eddy viscosity and eddy noise) as well as adding a variety of new PDE solvers, including those for rotation, magnetohydrodynamics (MHD), and Hall MHD. Considerable work was invested in recent years to hybridize the parallelization of GHOST using MPI and OpenMP, and to test the scaling and characterize in detail the behavior of the code on large-core-count multiprocessor systems. New and continuing efforts in these areas are described below. This code is available to the community upon request.

The TaYlor-GREen Symmetrical (TYGRES) code was developed originally by M. Brachet and extended recently to MHD. MPI parallelization of the code, implemented in FY2009-10, follows the methodology developed for GHOST. TYGRES enforces the four-fold symmetry of the Taylor-Green (TG) flow, leading to a factor of 32 savings in CPU and memory at a given Reynolds number Re compared to GHOST. It thus makes possible (1) detailed examination of potential singularity development in ideal Euler and MHD, and of the equilibria that follow once thermalization of the modes occur; (2) consideration of the link to the nonlinear properties of such flows in the dissipative case, substantially cheaper in CPU and memory, allowing for longer evolutionary times in the ideal case and higher Re in the dissipative case. TYGRES enforces the TG symmetries within the periodic cube of length 2π, corresponding to the von Kármán flow between two counter-rotating cylinders. This has been performed in several laboratory experiments including those using liquid metals to study the generation of magnetic fields. Below we discuss accomplishments related to TYGRES development in FY2011.

GASpAR (Geophysics-Astrophysics Spectral element Adaptive Refinement) has been developed over several years at NCAR as a high-order adaptive mesh framework for the solution of PDEs. This code uses spectral elements at variable order to achieve scalable spectral accuracy. Solvers exist for generalized advection-diffusion, Navier Stokes, and MHD. The code has functioned mainly in two dimensions, but recently we added adaptivity in 3D as well and began testing it with the advection-diffusion solver. Work planned for the GASpAR project was postponed to FY2012 due to personnel losses and the fact that remaining staff were reassigned to support codes for the GHOST and TYGRES projects to fulfill grant requirements.

This year, we completed additional performance characterization of GHOST on the NICS Kraken system in which we were able to shed light on the behavior of both GHOST and TYGRES in large multicore environments. First, we demonstrated that cache contention is inherent in the threaded (hybrid) mode in multicore, multisocket environments. We were also able to separate communication and computation costs to definitively show that MPI

wait times -- that arise in the asynchronous all-to-all communication from the multidimensional Fourier transform -- increase with the number of MPI tasks that are used per node. This suggests that using GHOST and TYGRES in hybrid mode offers a potential reduction in these costs that pure MPI techniques cannot provide.

Both the GHOST and TYGRES codes were functionally enhanced in several ways in FY2011. We developed a truncation capability for GHOST that enables us to reduce the resolution of a dataset spectrally. This "spectral downsizing" is useful, for example, when conducting a parameter study with a subgrid-scale model, using data generated from a direct numerical simulation. We also developed the opposite capability for both GHOST and TYGRES: bootstrapping spectrally a lower-resolution dataset to higher resolution. The utilities for both of these capabilities provide for byte-swapping (changing "endianness") on either input or output, so we can use these features for datasets computed on different platforms. The utilities were tested at high resolution and reproduced the correct spectra to an accuracy within machine roundoff. Additional detail is provided in Developments on the spectral codes GHOST, TYGRES, and GASpAR.

In FY2011 we also developed and systematized a series of interfaces ("bindings") to the CUDA runtime library (RTL) that enable GHOST to carry out a variety of tasks on a GPGPU device. These interfaces enabled us to develop a multidimensional FFT kernel that operates currently in 2D. Preliminary timings indicate a single-device gain of a few, which seems to be limited by data movement to and from the GPGPU. To assess the feasibility of extending this work to the 3D FFT kernel, we received a development grant that will enable us to test this design at high resolution on a multi-GPU system at NCSA.

For GHOST, we developed and tested a new solver for the Boussinesq equations to prepare for anticipated large stratification runs in FY2012. The equations for momentum and temperature (density) are parameterized by the viscosity, the Brunt-Väisälä frequency (quantifying the degree of stratification), and the thermal diffusivity. The solver has had some preliminary testing against published works in the literature that consider significant stratification and turbulence. Ongoing work is characterizing the performance of this solver.

Research and service activities of TNT are supported by NSF Core funding, and by additional funding from NSF-CMG Grant 1025188. We also gratefully acknowledge DOE INCITE award TUR020, and NSF TeraGrid/XSEDE grant TG-PHY10029.

‹ Scaling Earth System models

Computational research and development ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - Scalable algorithms for massively parallel computers
    - **Computational research and development**
      - Evaluating many-core and accelerator-based architectures
      - Accelerating data analysis
      - Accelerate applications algorithmically
      - Scientific data compression and visualizing large datasets
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Computational research and development

Meeting the grand challenges in simulating the Earth System will require more than just migrating standard algorithms to larger computational platforms. New hardware, parallel computational approaches, and more efficient algorithms will all be needed to reach the resolution and complexity levels needed to support scientific breakthroughs in modeling. The research in this section focuses on CISL's mission to anticipate new computational technologies and determine their fit for geoscience applications. These activities also adapt software tools and numerical methods to emerging technologies.

CISL research activities support scientific computation, numerical methods, geophysical modeling, and the analysis of geophysical data and model experiments to improve research through new computational methods and mathematical tools. Diverse scientific disciplines often share common tools and numerical methods. The types of mathematical, computational, and physical sciences housed in CISL focus on general mathematical tools, models, and algorithms that have broad application across NCAR and are also significant in their specific area of mathematical, physical, or computational science. The activities outlined in this section reflect the breadth and quality of this scientific research.

CISL derives its research priorities from the computational science challenges in the NCAR strategic plan with emphasis on innovation and collaboration. Based on these priorities, CISL focuses its applied scientific research and development activities in these areas:

Evaluating many-core and accelerator-based architectures. CISL designed, implemented, and evaluated the performance of a model accelerated with the use of compiler support instead of using device language directly. TDD also continues to evaluate the evolution of new cluster architectures that are built with one or more GPUs per node.

Accelerating data analysis. CISL also conducted follow-on research to develop technologies for a data-intensive system intended to provide computation support for data analysis and processing. Named Polynya, this experimental system environment facilitates an end-to-end data post-processing pipeline that orchestrates data transfer from TeraGrid supercomputers to NCAR, performs the analysis, and transfers the data to the tape archive system, all without writing any data to spinning disks. This work advances CISL's science by preparing the foundation for petascale and exascale computing.

Accelerating applications algorithmically. The goal for the next generation of global atmospheric models is to resolve dynamics on the order of a few kilometers. In response, the numerical methods in the HOMME dynamical core are being adapted to efficiently handle the equations underlying these new ultra-high-resolution models.

Scientific data compression and visualizing large datasets. CISL is exploring a variety of hardware- and software-based approaches for addressing the challenges of the visualization and analysis of large data sets. Large data visualization is a central component in preparing for petascale computing and enabling the understanding of large and heterogeneous data sets. Hundreds of diagnostic and derived variables were compared to quantify the sensitivity of these data to information loss in the context of numerous well-known analyses. CISL developed the VAPOR Data Collection (VDC) model and integrated it into IMAGe's turbulence modeling code, GHOST.

This work is supported by NSF Core funding, with supplemental funding supplied by other sources as noted in the following reports.

‹ Highly scalable codes for turbulent flows

Evaluating many-core and accelerator-based architectures ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - Scalable algorithms for massively parallel computers
    - Computational research and development
      - Evaluating many-core and accelerator-based architectures
      - Accelerating data analysis
      - Accelerate applications algorithmically
      - Scientific data compression and visualizing large datasets
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Evaluating many-core and accelerator-based architectures

CISL's Technology Development Division (TDD) continues to track the evolution of accelerator technology and its applicability to NCAR's main applications. Two main areas have been the focus of its work: the feasibility of using compiler-based directives and compiler-based translation to generate code for graphics cards, and the implementation and execution of larger experiments with accelerated software in a cluster with one or more GPU per node.

During summer 2011, with the participation of a SIParCS intern, TDD worked on the design, implementation, and evaluation of the performance of the CRM model, this time accelerated with the use of compiler support instead of using device language directly. Specifically building on the success of the kernels implemented in CUDA during 2010, TDD intended to determine if the code generated for the same kernel with the help of pragmas and a compiler could perform at acceptable levels when compared to code written manually. This effort is helping guide CISL by allowing researchers to understand the productivity and performance attained when different strategies are used to port complex codes to new computer systems.

TDD also continues to evaluate the evolution of new cluster architectures that are built with one or more GPUs per node. As research institutions continue to evolve and adapt existing applications to a single GPU, it will soon be necessary to port such applications to environments where the system is composed of multiple nodes that each have multiple cores and one or more GPU card for each node. The complexity of such systems is presenting new challenges to application developers as it is now necessary to write software that explicitly exploits the multiple layers of parallelism: MPI among nodes, OpenMP among cores, and CUDA and/or OpenCL in each of the GPUs.

‹ Computational research and development Accelerating data analysis ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - Scalable algorithms for massively parallel computers
    - Computational research and development
      - Evaluating many-core and accelerator-based architectures
      - Accelerating data analysis
      - Accelerate applications algorithmically
      - Scientific data compression and visualizing large datasets
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

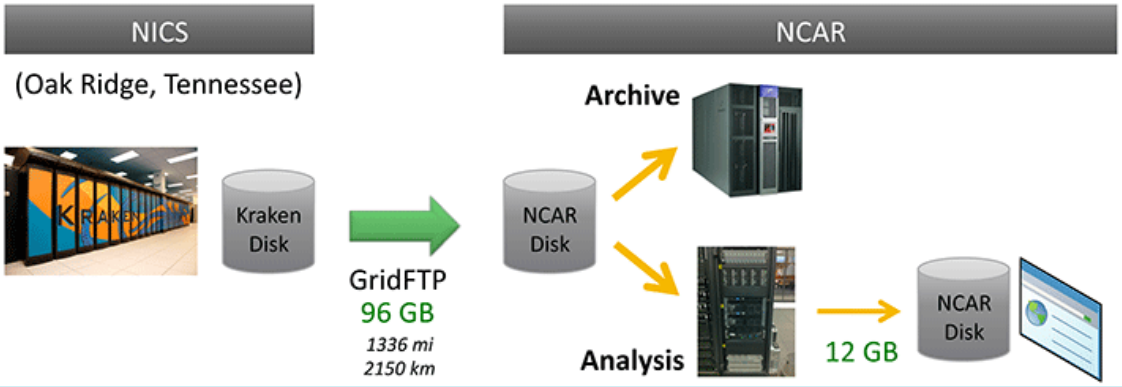
2009-2014 Strategic Plan »

Accelerating data analysis

Recent advances in the computational capabilities of the Community Earth System Model (CESM) have increased -- by an order of magnitude -- the rate at which output data is generated. A single ongoing high-resolution climate simulation performed by the NICS Kraken system can generate as much as 1 TB of data in one day of processing -- data that must be promptly transferred to NCAR for analysis and archiving. Moreover, such high data volumes may become commonplace in the near future as more researchers exploit new computational systems (such as the upcoming system at NWSC) and explore increased-resolution simulations.

SIParCS interns Dmitry Duplyakin (left) and Allan Espinosa (right) present the results of their work on system development and automation software for data-intensive workflows at the SIParCS internship colloquium. Their complementary projects helped evaluate and establish technologies and techniques for reducing the time and manual intervention required to process large volumes of climate data.

As an Earth System model runs, the output data must be analyzed -- a process that is typically performed separately on specialized computer systems. In FY2010, with the assistance of a SIParCS intern, CISL developed a prototype parallel version of the computational portion of the Atmospheric Model Working Group (AMWG) diagnostic package using the Swift programming language. This process reduced the time required to analyze the CESM's atmospheric data output. In addition to performance improvements obtained through parallelization, this work demonstrated that analyzing the data on a RAM-based file system, rather than a spinning-disk parallel file system, significantly decreases analysis time.



This diagram shows the end-to-end prototype workflow supporting the automated transfer of data generated at the National Institute for Computational Sciences (NICS) to NCAR for analysis and archival. Each of the main steps in the workflow -- generation, data transfer, data storage, analysis, and archiving -- have typically been performed manually. The automated workflow simplifies the execution of several of these steps, and it also takes advantage of an FY2010 SIParCS project in parallel data analysis that used parallel processing to reduce analysis time.

In FY2011, CISL conducted follow-on research to develop technologies for a data-intensive system intended to provide computation support for data analysis and processing. Named Polynya, this experimental system environment was reconfigured to provide shared RAM-based storage using the Lustre parallel file system and to mediate access to that storage using the system's resource manager. The result is an end-to-end data post-processing pipeline that orchestrates data transfer from TeraGrid supercomputers to NCAR, performs the analysis, and transfers the data to the tape archive system, all without placing any data on spinning disks.

This work advances CISL's science by preparing the foundation for petascale and exascale computing. The results described here were prototyped and implemented by three students in NCAR's SIParCS program over two years, demonstrating that multiple SIParCS projects in a single year can be effectively coordinated to support a divisional objective, and that SIParCS projects staged across multiple years can make meaningful contributions to CISL capabilities. SIParCS supports CISL's education imperative to integrate research and education. This work is supported by NSF Core funding and NSF Grant OCI-0749206.

‹ Evaluating many-core and accelerator-based architectures

Accelerate applications algorithmically ›

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Log in

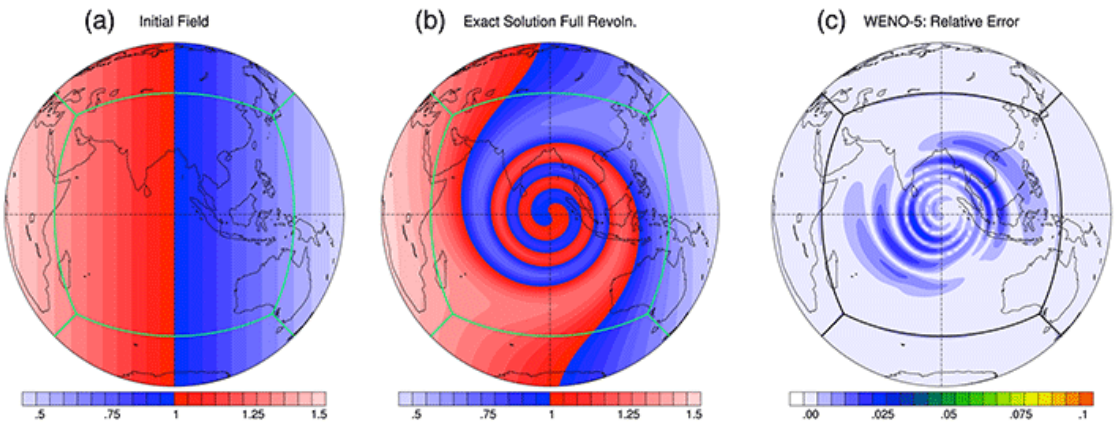
2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - Scalable algorithms for massively parallel computers
    - Computational research and development
      - Evaluating many-core and accelerator-based architectures
      - Accelerating data analysis
      - **Accelerate applications algorithmically**
      - Scientific data compression and visualizing large datasets
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

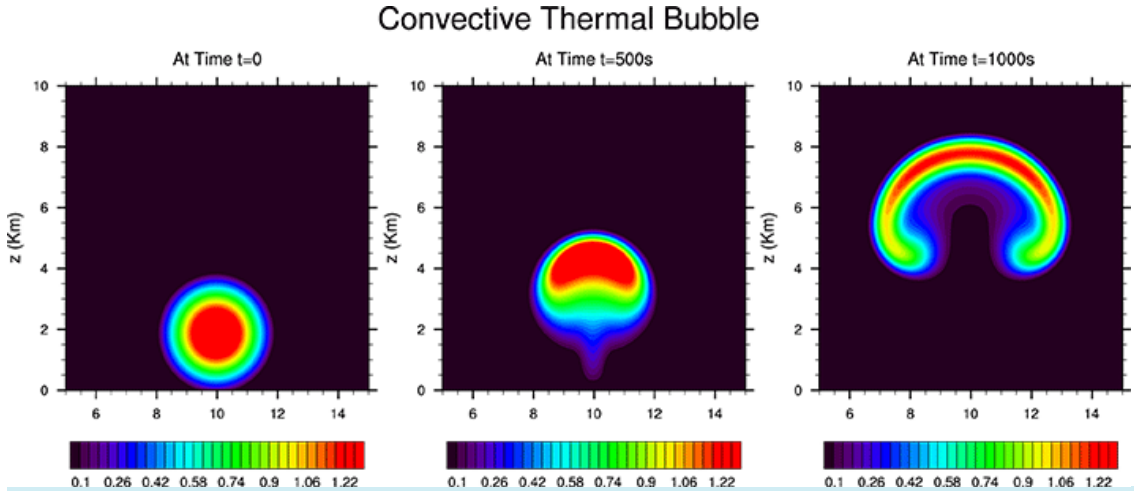
Accelerate applications algorithmically

With the increased amount of computing resources available to modelers, it is now possible to develop global models with resolution on the order of a few kilometers. However, this opens up another challenge – switching the governing equations from the hydrostatic to the non-hydrostatic regime. The equation set generally used in traditional global climate models (hydrostatic equations of motion) is not adequate at the non-hydrostatic scale. In the very high-resolution regime, viable options for the governing equations of motion are the compressible (or quasi-compressible) Euler equations or Navier-Stokes equations. Also, it is highly desirable that the underlying model equations follow the physical laws of conservation for integral invariants such as mass, energy, etc. To comply with these constraints and address new computational challenges, the next generation of atmospheric models should be based on robust numerical methods. HOMME is designed for hydrostatic models, and extending it to a non-hydrostatic framework requires significant changes in vertical discretization. An alternative approach for the discretization may be based on compact finite-volume methods. A class of new central finite-volume (C-FV) schemes has been developed for 2D horizontal transport (cubed-sphere) and 2D compressible (non-hydrostatic) Euler equations in (x,z)-plane. The results are very promising.



Simulation of a moving vortex in a non-divergent flow on the cubed-sphere using a central finite-volume (C-FV) scheme. Panel (a) shows the initial field, which ranges from values 0.5 to 1.5. Panel (b) shows the simulated field after a full rotation along the north-east direction. Panel (c) is the difference field, exact minus numerical solution, after a full rotation. The advection scheme is based on an inherently conservative and non-oscillatory fifth-order central WENO (weighted essentially non-oscillatory) scheme.

The C-FV schemes are inherently conservative and non-oscillatory, and they have lenient CFL stability restriction even with high-order accuracy. A fifth-order C-FV scheme based on WENO discretization employs a two-cell-wide halo in each coordinate direction, with a CFL limit of approximately 1. The C-FV schemes do not require a staggered grid or expensive Riemann solvers, and they are local methods amenable to both CPU and GPU architectures. The C-FV scheme will be further extended for HOMME non-hydrostatic model development, and this research will also pave a way to include high-order finite-volume-based model development in the HOMME framework.



This sequence shows frames from an animation of convection in a neutral atmosphere simulated by the C-FV Euler solver employing a fifth-order WENO scheme. The 2D convective thermal uses a hydrostatic balance based on a constant potential temperature with zero initial wind, and the bubble is triggered by perturbing the potential temperature. Initial potential temperature perturbation (θ') in K is shown in the left panel. The middle and right panels show the convective bubble after 500 and 1,000 seconds of simulation. The model domain is [0,20] km × [0,10] km, grid spacing is uniformly set to $\Delta x = \Delta z =$ 50m, and an explicit third-order Runge-Kutta time integrator is used for the model.

This work advances CISL's science frontier in algorithmic acceleration by developing new algorithms and computational approaches to produce simulations capable of addressing grand challenges. Specifically, it fulfills a strategic action item to accelerate applications algorithmically by developing new numerical methods, AMR, new solvers, and new time integration schemes. This work is supported by NSF Core funding.

‹ Accelerating data analysis

Scientific data compression and visualizing large datasets ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
    - Interdisciplinary contributions
    - Scalable algorithms for massively parallel computers
    - Computational research and development
      - Evaluating many-core and accelerator-based architectures
      - Accelerating data analysis
      - Accelerate applications algorithmically
      - **Scientific data compression and visualizing large datasets**
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

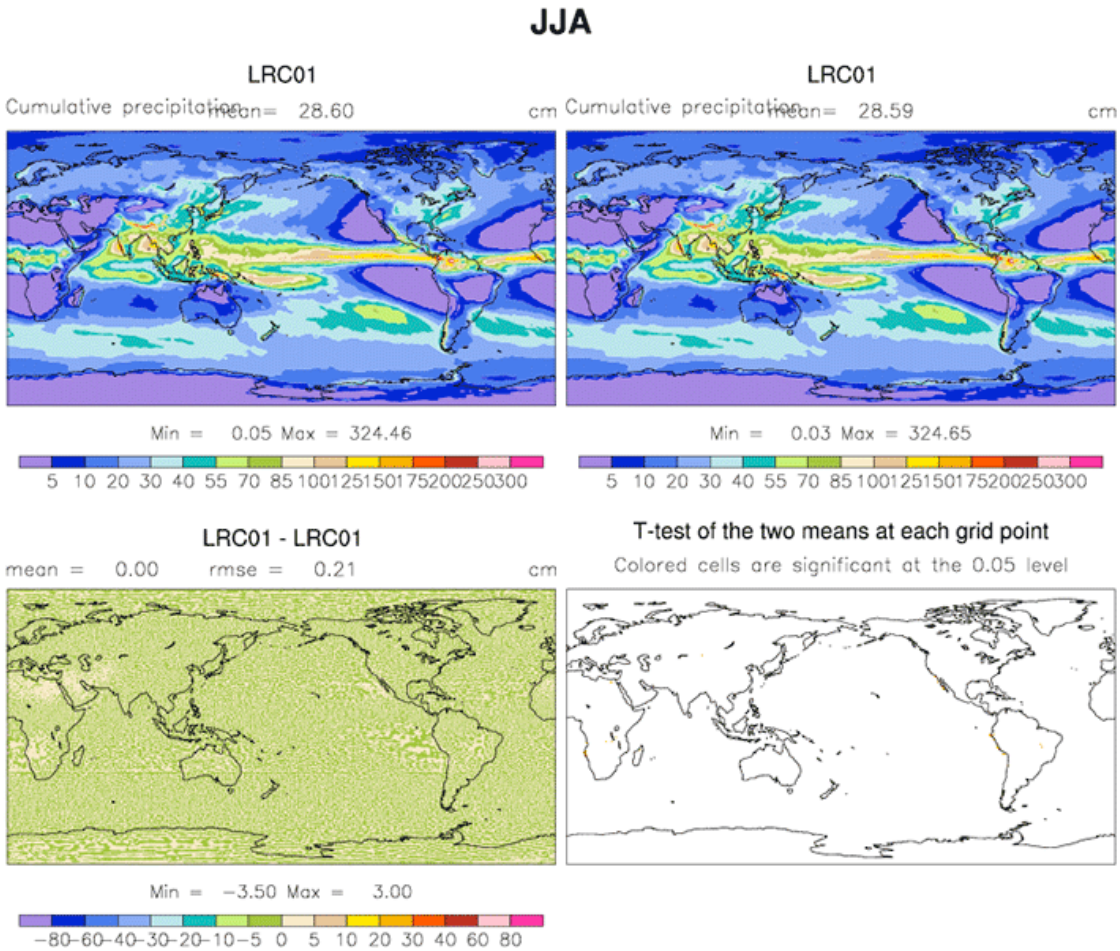
2009-2014 Strategic Plan »

Search

Scientific data compression and visualizing large datasets

CISL is exploring a variety of hardware- and software-based approaches for addressing the challenges of the visualization and analysis of large data sets. A major software thrust in this area has been the research, development, and experimentation with wavelet-based progressive-access data models for structured scientific data sets. Wavelets are the basis for numerous, ubiquitous multimedia compression technologies such as the JPEG 2000 image compression standard. However, unlike the "lossy" compression strategies employed in consumer entertainment, our efforts are focused on level-of-detail techniques that offer perfect reconstruction of the original data, while allowing the user to make speed/quality tradeoffs when performing interactive work. The goals of this work are to:

- Determine whether, and to what degree, scientific data sets can tolerate information loss.
- Investigate a variety of compression methods and their suitability for geoscience data.
- Develop user tools for data compression and improved, more general, progressive data access.



Imagery generated from the CCSM Atmospheric Model Working Group diagnostic package comparing original data (top left) with compressed data (top right). Shown at bottom left is the difference between the two data sets, and shown at bottom right is a T-test comparison at the 0.05 significance level. This research aims to develop multimedia compression technologies that allow perfect reconstruction of the original data.

Exponential growth in transistor density is producing ongoing increases in computer processing power. These increases enable computational scientists to create numerical simulations of physical phenomena at unprecedented scales, thus generating extraordinary amounts of data. Yet while microprocessor performance continues to advance in accordance with Moore's Law, other computing technologies are improving at much more modest rates. In particular, storage and networking bandwidths have lagged behind. As a result, the challenge of storing, analyzing,

managing, and sharing large simulation data sets is becoming ever more problematic. Moreover, large data visualization is a central component in preparing for petascale computing and enabling the understanding of large and heterogeneous data sets: this is a science frontier specified in CISL's strategic plan. The CISL strategic plan specifies these tasks:

- Deploy and investigate parallel visualization clusters.
- Partner with peer institutions and combine efforts to develop and enable large visualization of large data.

In FY2011 we began experimenting with compressed outputs from NCAR's CAM global atmospheric circulation model in an attempt to quantify the sensitivity of these data to information loss in the context of numerous well-known analyses. In particular, compressed and original data were compared using the AMWG model diagnostic package, the basis of which is the Student T-test. Hundreds of diagnostic and derived variables were compared. While the results were encouraging -- and were presented at an invited Joint Statistical Meetings conference talk -- the experiments also exposed the fragile nature of some of the AMWG operators in the face of even modest data perturbations.

In late FY2011 we completed the development of a Fortran-callable, parallel API for transforming and writing data into a wavelet-based, progressive access data model: the VAPOR Data Collection (VDC). The API, which is built on CISL's community PIO library, has been integrated into IMAGe's turbulence modeling code, GHOST. Evaluation of the new GHOST capability is underway. Our earlier work in wavelet-based progressive data access models served as the basis for an invited book chapter edited by W. Bethel, H. Childs, and C. Hansen.

Lastly, in the area of hardware, CISL's RFP specification for NWSC included the procurement of a production, GPU-enabled, 16-node visualization cluster. The new cluster will allow CISL to offer parallel visualization tools, such as VisIt and ParaView, to our user community for the first time.

This data compression and visualization research is supported by NSF Core funds, and the development of the parallel VDC API is supported by NSF Core funds and NSF Grant NSF-09-06379.

‹ Accelerate applications algorithmically

CISL Education ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
    - Integrating research and education
    - Workforce training and development
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

CISL Education

CISL designs education programs to integrate research and education and teach the technical skills that students and faculty need to make effective use of advanced cyberinfrastructure. These programs also promote diversity, enhance a culture of teaching and mentorship within CISL, and provide opportunities for collaboration with the university community. These objectives are accomplished through visitor, internship, workshop, and training programs.

A supercomputing laboratory in a national research center is a unique place to help integrate research and education between disciplines. CISL focuses on the computational and atmospheric sciences, and has a math institute dedicated to education and advancing research using applied mathematics and statistics. CISL's educational efforts are designed to complement and supplement programs at universities and other centers.

CISL manages two principal training thrusts: for HPC systems and for CISL-developed data analysis and visualization tools. NCAR and CISL also provide cyberinfrastructure resources and user support for community workshops, tutorials, and summer schools in the atmospheric and related sciences.

This work is supported by NSF Core funding, with supplemental funding supplied by other sources as noted in the following reports.

‹ Scientific data compression and visualizing large datasets Integrating research and education ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
    - Integrating research and education
      - Summer Internships in Parallel Computational Science
      - IMAGe Theme Of the Year
      - Research and Supercomputing Visitor Program
      - Visualization Laboratory (Vislab) Outreach
    - Workforce training and development
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Integrating research and education

SIParCS intern Dmitry Duplyakin stands with his summer project: Polynya is a prototype data-intensive computer developed by the Computer Science Section of CISL's Technology Development Division. Using Lustre-based parallel file systems configured in system memory rather than disk, this system can achieve dramatic speed-ups on climate modeling workflows. This type of project brings hands-on education and research together to benefit individual students and advance technology.

As a supercomputing laboratory embedded in a national center focused on the atmospheric and related sciences, CISL is in a unique position to help integrate research and education between the disciplines of the computational and atmospheric sciences. CISL's educational efforts are therefore designed to serve this function in a way that complements and supplements programs at universities and other centers.

CISL's Summer Internships in Parallel Computational Science (SIParCS) program offers graduate and undergraduate students significant hands-on opportunities in computational science, applied mathematics, and geostatistics in an effort to build a workforce that can exploit petascale computers. CISL's Research and Supercomputing Visitor Program (RSVP) allows prolonged engagement and collaboration between our staff, the university community, and researchers at peer centers around the world. IMAGe's Theme-of-the-Year (TOY) is a series of year-long programs, each focused on a specific aspect of mathematics applied to the geosciences; it is designed to advance research, education, and collaboration between the mathematical and geosciences communities.

Topics such as multiscale modeling, data assimilation, and turbulence offer hands-on experience to young researchers. CISL budgets to support a core group of 10 SIParCS interns each year and actively recruits for diversity. The RSVP program is visitor-driven and generally operates on a first-come, first-served basis. CISL now supplies RSVP travel support to CISL training classes for attendees from EPSCoR states and minority-serving institutions. TOY establishes collaborations around potentially rewarding research activities and encourages contributions from talented young investigators in a variety of disciplines.

CISL's education imperative for integrating research and education is primarily supported by NSF Core funding, with supplemental funding supplied by other sources as noted in the following reports.

‹ CISL Education

Summer Internships in Parallel Computational Science ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
    - Integrating research and education
      - **Summer Internships in Parallel Computational Science**
      - IMAGe Theme Of the Year
      - Research and Supercomputing Visitor Program
      - Visualization Laboratory (Vislab) Outreach
    - Workforce training and development
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Summer Internships in Parallel Computational Science

The Summer Internships in Parallel Computational Science (SIParCS) program seeks to develop students with a background in computational science, applied mathematics, computer science, or the computational geosciences. The 10-week internships provide opportunities for exceptional students to gain practical experience with a wide variety of parallel computational science problems by working with the HPC systems and applications related to NCAR's Earth System science mission. The ultimate goal of SIParCS is to address shortages of trained scientists and engineers capable of using and maintaining these high-end systems to achieve the goals of 21st-century computational geoscience research. SIParCS supports NCAR's and CISL's core missions in education. CISL's contribution is to teach the mathematical and computational science concepts and skills that students will need to make effective use of advanced cyberinfrastructure.

The SIParCS and NWSC Engineering intern class of 2011 brought 17 students from 14 colleges and universities across the country to work on computational science and engineering projects. Adding Engineering interns to work on technical aspects of the state-of-the-art NWSC facility was an innovation in 2011.

The application process for the Summer 2011 SIParCS program ran from November 2010 to March 2011. Most student interns arrived by June 1st, and their 10-week visit wrapped up at the end of July. Each student gave a project presentation during the last week of July. The fifth annual SIParCS program included 15 students from 12 U.S. colleges and universities. Student research topics in 2011 covered diverse problems in applied mathematics, geostatistics, numerical algorithms, software engineering, HPC system administration, and computer science. For the first time, the SIParCS program was extended to include two NCAR-Wyoming Supercomputing Center (NWSC) Engineering interns, bringing the internship count to 17.

Adding Engineering Interns was inspired by repeated inquiries about the program from engineering students during a January 2011 outreach visit to a university. The program director then arranged two new positions with the NWSC engineering team. Selected from a separate pool of 16 applicants, these two interns worked on engineering projects related to the petascale NWSC facility in Cheyenne, Wyoming. Those projects involved defining the metrics for a visitor center display of the facility's overall energy efficiency and working with computational fluid dynamics software to analyze the airflow around different petascale supercomputer designs on the NWSC machine room floor.

Collectively, SIParCS and NWSC Engineering interns were drawn from a pool of approximately 99 applicants, for an

applicant-to-intern ratio of 5.53. This is up from 2.75 in 2010, indicating that the internship program is becoming significantly more competitive.

One intern came from a Minority Serving Institution; four were from EPSCoR state institutions; a total of four were from under-represented groups; and nine (the majority) came from outside the Front Range region. Of the 17 total positions, 10 were funded by CISL core funds (either one-time or recurring), four were funded by partner organizations or grants, two were funded by NWSC funds, and one was funded by NCAR diversity funds. SIParCS external partners in 2011 included NOAA, the University of Wyoming, and the Colorado School of Mines.

Support for intern enrichment activities, such as paying for related conference attendance registration and travel or publication costs is a key feature of the SIParCS program. In June 2011, two SIParCS interns attended the EXADAPT 2011 conference in San Jose California: the travel costs for one student to this conference was funded by the SIParCS program. EXADAPT is a conference devoted to adaptive self-tuning for exascale computing systems. This workshop provided the students with experience relevant to their SIParCS projects in machine learning, which were titled Machine Learning for Application Optimization with cTuning, and Source-source Translators with Respect to Climate Models.

The development of the SIParCS program can be credited to a comprehensive aggressive outreach strategy. A significant number of university faculty across the country now serve as points of contact for the program, and an extensive network of email and career center postings ensure the supply of high-quality applicants.

SIParCS internships are supported by NSF core funding, with some funding provided by partner institutions and outside grants. For instance, six interns in 2010 were funded by partner organizations or grants. We plan to continue with a similar amount of outside support each year.

‹ Integrating research and education

IMAGe Theme Of the Year ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
    - Integrating research and education
      - Summer Internships in Parallel Computational Science
      - IMAGe Theme Of the Year
      - Research and Supercomputing Visitor Program
      - Visualization Laboratory (Vislab) Outreach
    - Workforce training and development
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

IMAGe Theme Of the Year

The Theme Of the Year (TOY) is a series of activities that explores the opportunity to enrich both applied mathematics and the geosciences through a common scientific topic. TOY is designed to advance research and education between the mathematical and geosciences communities; it involves targeted projects for building interdisciplinary communities. The topics are selected by the IMAGe external advisory panel and coordinated by one or more visiting co-directors. The yearly TOY programs support CISL's education imperative to integrate research and education, sparking collaborations between the mathematics community and Earth System scientists.

William Kleiber (standing), an IMAGe statistics postdoc, helping students work on a spatial data analysis exercise during an afternoon practicum.

The theme for TOY 2011 was "Hierarchical statistical models for the geosciences." This theme highlighted an important statistical methodology that when harnessed with computational resources is changing how statistical analysis is done for complex geophysical data sets. The main principle is to separate the scientific data analysis problem into a three-level hierarchy: a data model that gives the connection between the observations given the process of interest, a process model (or state equation) that can incorporate the dynamics of the process, and a level that has prior assumptions on parameters in the data and process models. With this formulation, Bayes theorem is used to compute the distribution of the process given the data. Here the range of this distribution provides a natural measure of uncertainty in estimating the process of interest from data. Bayesian hierarchical models have been successful in analyzing spatial and space-time geophysical data, and the intent of this program was to focus attention on two important areas of climate that pose difficult data problems: multi-model regional climate experiments and reconstructing paleo-climate from climate proxies.

Mathematical Science of Understanding and Predicting Regional Climate: A School and Workshop (28 February – 11 March 2011) was pursued in partnership with the Institute of Mathematical Sciences (IMS) at the National University of Singapore (NUS). This program increased IMAGe/CISL/NCAR visibility in a dynamic and new community (Singapore) and included 50 participants drawn from Southeast Asia and around the world. The program successfully brought together internationally recognized climate scientists and statisticians at NUS and engaged the local faculty

and scientists. Throughout the week-long workshop there was substantial discussion that often dealt with interdisciplinary issues. One measure of the impact from the workshop was the quality and insight in the final discussion session.

The short course brought students with a diverse range of backgrounds and statistical skills to the point of interpreting spatial climate data and using the R statistical language. They worked alone and in small groups to analyze regional climate model output and data. One important outcome of this short course was an integrated set of lectures and supporting R software that can be used for giving versions of this course again. In this way this program yielded some very useful educational and training products.

The program also helped to raise the level of awareness for statistical methods in regional climate by bringing in several of the leading statisticians working on this topic. This also will help the NUS Statistics Department and IMS in capturing the interest of geophysical and hydrological research groups at the university as the case is made for more deliberate uncertainty quantification of regional climate studies.

Bayesian Hierarchical Models for High-Resolution Climate Reconstructions, March 24–25 brought together a working group of approximately 30 paleo-climate scientists and statisticians concerned with reconstructing climate over the past 1,000 years. The workshop followed up on some statistical topics that were developed in the Statistics and Applied Mathematical Sciences Institute (SAMSI), an NSF Mathematics Institute program. By reconvening the participants from the program and adding some relevant climate scientists, this workshop helped maintain the collaborations initiated at SAMSI. The last session, synthesizing new research directions, was useful in directing statistical research to the relevant paleo-climate problems.

One tangible result is that Suz Tolwinski-Ward, an applied math Ph.D. student at the University Arizona began a collaboration with IMAGe staff on a new way to use tree ring data for inferring both precipitation and temperature together. (Past work has only treated these separately.)

Outreach activities of the Theme of the Year are supported by NSF Core funding, the Institute of Mathematical Sciences, the National University of Singapore, and NSF CMG Collaborative Grant 0724828.

‹ Summer Internships in Parallel Computational Science

Research and Supercomputing Visitor Program ›

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Log in

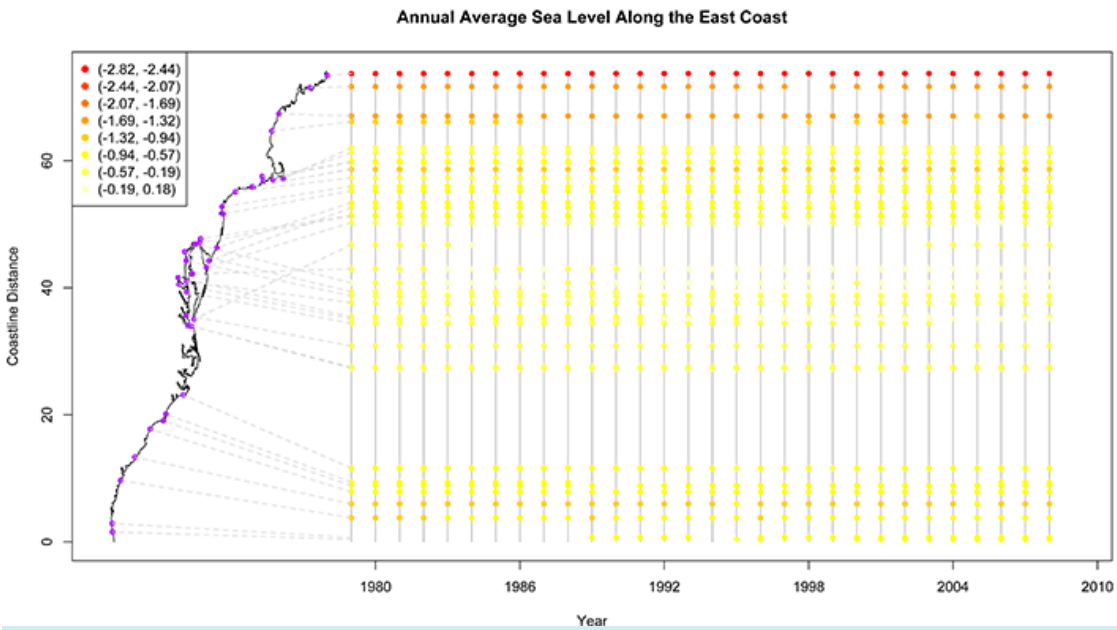
2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
    - Integrating research and education
      - Summer Internships in Parallel Computational Science
      - IMAGe Theme Of the Year
      - **Research and Supercomputing Visitor Program**
      - Visualization Laboratory (Vislab) Outreach
    - Workforce training and development
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Research and Supercomputing Visitor Program

RSVP is a visitor program designed to bring university faculty, researchers, and students to NCAR to foster collaboration with CISL staff and to provide training opportunities for underrepresented groups. The program pays for travel and living expenses for stays of up to three months. These extended visits help establish stronger relationships that lead to long-term collaborations. For many visitors, this program represents a unique opportunity to interact with CISL and NCAR scientists and staff on topics ranging from high-performance computing and Earth System modeling to applied mathematics and statistics.



This plot shows the differences between the annual average water level and the mean high water level for 38 stations along the East Coast of the United States. With each row of colored dots representing a particular monitoring location and each column a year, this plot is a visualization of a spatial-temporal statistical model for assessing sea level rise that is being developed by 2011 RSVP visitor Candace Berrett (Asst. Professor, Department of Statistics, Brigham Young University, Provo, UT) and scientists in CISL's Institute of Mathematics Applied to Geosicences (IMAGe). These statistical models will allow prediction of sea level rise at locations along the coast where there are no monitoring stations, and allow researchers to further examine sea level rise and its impacts on storm surge.

This program supports CISL's education imperatives of integrating research and education and broadening participation by being a key, integrative component of CISL's education, outreach, and training (EOT) program.

RSVP has sponsored graduate students, junior faculty, senior faculty, and scientist visitors from the U.S. and across the world. The focus of visits in FY2011 included improving access to new datasets available through NCAR, uncertainty quantification and the analysis of climate model ensembles, constructing new computational algorithms for systems of differential equations, and improved computer codes for representing atmospheric turbulence. The program has also partially sponsors sabbatical stays for senior researchers in statistics and computational mathematics.

This program is made possible through NSF Core funding.

‹ IMAGe Theme Of the Year

Visualization Laboratory (Vislab) Outreach ›

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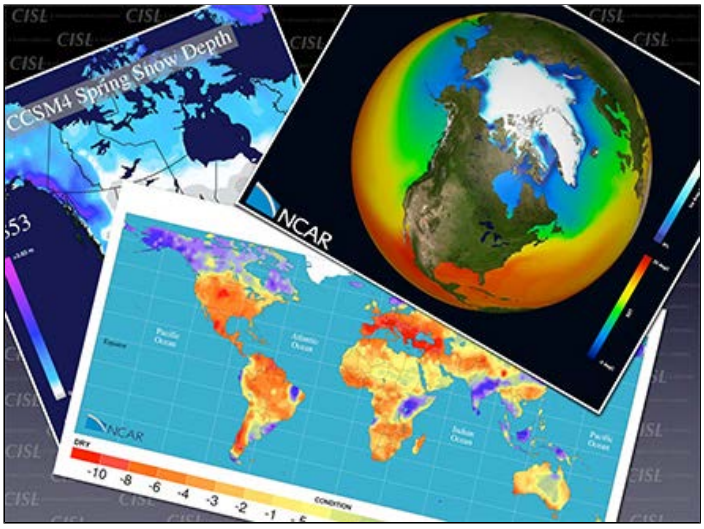
Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
    - Integrating research and education
      - Summer Internships in Parallel Computational Science
      - IMAGe Theme Of the Year
      - Research and Supercomputing Visitor Program
      - Visualization Laboratory (Vislab) Outreach
    - Workforce training and development
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Visualization Laboratory (Vislab) Outreach



Vislab staff work closely with NCAR scientists to create a wide range of geoscience visualizations. These visualizations are used for publication, education, and outreach to student, scientific, government, and corporate visitors to help increase scientific understanding and communicate the results and benefits of NCAR's research.

CISL's Visualization and Enabling Technologies Section (VETS) operates the Vislab, a visual computing center that is used to conduct many of CISL's education, outreach, and collaboration efforts. The 1,000-square-foot facility supports video conferencing technologies, data analysis and visualization, and theater-style presentations in a widescreen, high-resolution, 3D format. The facility is equipped with a collaborative touch-screen interface, a high definition 3D 1920×1080-resolution active stereo projector, and a 12×7-foot screen. This system displays imagery and presentation materials simultaneously from multiple sources including user laptops, digital media systems, and high definition video conferencing platforms.

The Vislab serves as an important resource for CISL's education and outreach efforts, fulfilling the strategic action item for CISL to tell NCAR's story to the world. Vislab activities serve thousands of staff and visitors each year and include support for advanced collaboration environments that foster geographically distributed research and communication. The Vislab operates a sizable outreach program that provides 3D presentations to a wide range of student, governmental, and scientific visitors. The Vislab's implementation and support of collaborative technologies help enhance communication while minimizing the need for travel between geographically distributed teams collaborating on cross-institutional projects. The Vislab is also routinely used as an important presentation venue by UCAR staff for general meetings, conferences, and classes.

The Vislab continued its productive relationship with the UCAR Public Visitor Program and partnered with them on a successful UCAR MESA to Mesa Diversity Project proposal to help expose under-served math, engineering, and science student populations to the scientific tools and processes for modeling and visualizing scientific data. The Vislab provided 3D geoscience visualization presentations to 18 schools and 662 students (65% were of non-white ethnicity). The Vislab also supported over 190 meetings and demos to more than 2,700 visitors and users in FY2011, an increase of over 20% from FY2010. Additionally, 500 remote users were served through the use of the Vislab's video and teleconferencing systems. The Vislab supported classroom activities including a week-long CISL HPC training course that taught essential knowledge and skills for working with supercomputers to interns and visiting researchers. The Vislab also continued to collaborate with researchers to develop new and engaging visualizations of CCSM4 spring snow depth, projected drought severity in the 21st century, and CCSM4 sea ice cover. These products were used in collaboration with UCAR Communications to develop material for communicating science on emerging research topics and are routinely posted to YouTube, UCAR news sites, and used by international news publishers. Technology enhancements for this year included the installation of a collaborative SmartBoard system, integration of a new HD videoconferencing camera, and experimentation with a 3D video capture camera. The VisLab also coordinated a technical team that developed requirements and evaluated vendor proposals for the audio/visual and remote communication needs at the NCAR-Wyoming Supercomputing Center.

This project is supported by NSF Core funds with supplemental resources provided by the UCAR Diversity Fund for Vislab support of the MESA to Mesa Diversity Project.

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
    - Integrating research and education
    - Workforce training and development
      - Training interns in computing at NCAR
      - Training in geoscientific tools
      - Support for community workshops, tutorials, and summer schools
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Workforce training and development

CISL prepares for the coming petascale computing era by training young researchers to answer questions in the atmospheric and related sciences using high performance cyberinfrastructure. CISL delivers educational content synchronously through workshops and training classes, and asynchronously through web content.

CISL's two principal synchronous workforce development activities include training in high performance computing including MPI, OpenMP, Fortran, and other HPC technologies performed by the Consulting Services Group, and in scientific data analysis and visualization conducted by the NCL developers.

CISL's education imperative for workforce training and development is primarily supported by NSF Core funding, with supplemental funding supplied by other sources as noted in the following reports.

Students and instructors attending the class "Introduction to Scientific Computing on GPUs." This was one of a series of 12 classes for interns in computational sciences and math presented by CISL's Consulting Services Group in June. Providing CISL's interns with opportunities to participate in training classes like this helps them develop important skills, enriches their summer work experience, and ultimately improves research outcomes.

‹ Visualization Laboratory (Vislab) Outreach

Training interns in computing at NCAR ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
    - Integrating research and education
    - Workforce training and development
      - Training interns in computing at NCAR
      - Training in geoscientific tools
      - Support for community workshops, tutorials, and summer schools
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Training interns in computing at NCAR

Education is a core mission of NCAR. CISL's contribution is to teach the concepts and skills in computing, mathematics, and computational science that students need to make effective use of advanced cyberinfrastructure. In addition, CISL's work to advance the goals of 21st-century computational Earth System science research can only succeed if CISL attracts and retains a diverse and talented staff. Therefore CISL must also encourage students to embark on careers in supercomputing and the computational sciences. This work supports two education imperatives defined in CISL's Strategic Plan: Integration of research and education and Workforce training and development.

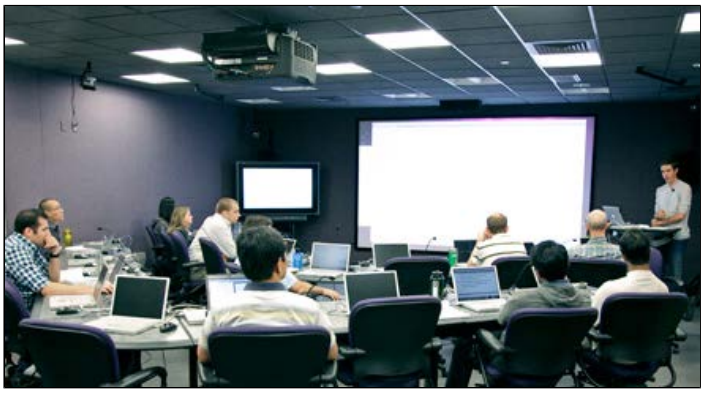
Increasing interest in these courses, particularly from students at universities around the country, prompted CSG's February 2011 decision to stream videos of the courses online in real time with the help of UCAR Multimedia Services. Student response was enthusiastic, so the summer program was webcast using Adobe Connect. All of these sessions were recorded and are available for viewing on demand. There were about 19 classes conducted in two programs with 152 total participants, mostly students from U.S. universities.

This year CSG offered an enhanced array of course material. CSG added Tutorial Introduction to GPU and some data analysis tutorials including introductions to NCL, IDL, and Matlab. The GPU computing courses received a strong response from students, research staff members, and software engineers.

CISL takes an active role in mentoring and training student interns, and summer is the busiest time of year. In FY2011, CISL's Consulting Services Group provided the following classes to a total of 659 participants (368 onsite, 291 online), of which 322 were interns, protégés, undergrads, or graduate students, and 128 were from underrepresented groups. (Note that many students took multiple classes, so these totals count some individual participants multiple times.)

- Introduction to Parallel Computing with

MPI, 10/19/2010
- CISL Facilities and Support Overview, 02/14/2011
- Introduction to Unix, 02/14/2011
- Fortran 90 Part I, 02/14/2011
- Fortran 90 Part II, 02/15/2011
- Introduction to Parallel Programming with MPI, 02/15/2011
- Introduction to Parallel Programming with OpenMP, 02/16/2011
- Introduction to Unix, 06/06/2011
- CISL Facilities and Support Overview, 06/06/2011
- Fortran 90 Part I, 06/06/2011
- Fortran 90 Part II, 06/07/2011
- Programmer's Tools, 06/07/2011
- Introduction to Parallel Programming with OpenMP, 06/08/2011
- Introduction to Scientific Computing on GPUs Part I, 06/08/2011
- Introduction to Scientific Computing on GPUs Part II, 06/09/2011
- Introduction to Parallel Programming with MPI, 06/09/2011
- Getting Started with NCL, 06/10/2011
- Getting Started with IDL, 06/10/2011
- Introduction to Matlab, 06/10/2011



Four consultants from CISL's User Services Section and one associate scientist from CISL's math institute IMAGe taught 12 high performance computing courses to SIParCS interns in June 2011. The consultants present more than 20 HPC training classes each year to improve the computing efficiency of new users.

In FY2011, CISL's Consulting Services Group provided training and mentors for one internship program at NCAR: CISL's Summer Internships in Parallel Computational Science (SIParCS). CISL again provided computing mentors to supplement that program's existing collection of specialized science, writing, community, and peer mentors. All SIParCS interns were supported by CISL mentors, and two worked with collaborating mentors: one at NOAA/CIRES and one at NCAR/CGD. The SIParCS program focuses on computational science, applied mathematics, computer science, and the computational geosciences. All the SIParCS interns participated in CSG's summer training workshops.

For FY2012, Consulting Services will continue offering the successful new multi-day Fortran 90 class for students and early-career scientists. Fortran is heavily used in scientific modeling, yet there are very few opportunities for students to obtain advanced training in this language. We plan to continue teaching the course at NCAR, and we will also make the course materials available online via the NCAR Multimedia Services website and possibly via the XSEDE portal.

Intern training is supported entirely by NSF Core funding.

‹ Workforce training and development

Training in geoscientific tools ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
    - Integrating research and education
    - Workforce training and development
      - Training interns in computing at NCAR
      - Training in geoscientific tools
      - Support for community workshops, tutorials, and summer schools
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Training in geoscientific tools

Staff in CISL/VETS and NESL/CGD have collaborated for 11 years to provide a series of training workshops for the NCAR Command Language (NCL) – a free, interpreted language designed specifically for geoscientific data analysis and visualization. To date, a total of 55 local and non-local workshops have been taught to 801 students. These workshops, which are free for students, are four days in length with morning lectures and intensive hands-on labs in the afternoons. These workshops target students' specific needs because they use their own datasets for analysis and visualization rather than canned datasets and examples. The instructors work with students individually during the labs, and by the end of the workshop most students have developed nearly complete NCL programs that produce meaningful results from their data.

CISL/VETS and NESL/CGD taught two NCL workshops in Australia in FY2011: one hosted by Mark Collier of CSIRO at the Bureau of Meteorology Training Centre in Melbourne (above), and one hosted by Jason Evans at the University of New South Wales in Sydney (below). Fifty-five students from various research organizations and universities around Australia attended. Both groups of students had a high focus on drought, fire, and precipitation research, and many were using data from WRF in their research.

A core NCAR value is partnership with the university community. We proactively reach out to U.S. university students by offering at least one free workshop at a U.S. university each year, and by covering all travel expenses for qualified students from EPSCoR universities and minority-serving institutions (MSIs) to attend workshops. (EPSCoR universities are located in states that are deemed to be underserved by federal research and education funding. The goal of the Experimental Program to Stimulate Competitive Research – EPSCoR – is to balance national research and education support by strengthening it in these states.) FY2011 was the fourth year we offered this free workshop, and we provided full funding for nine EPSCoR/MSI students to attend our summer workshops in Boulder and Wyoming.

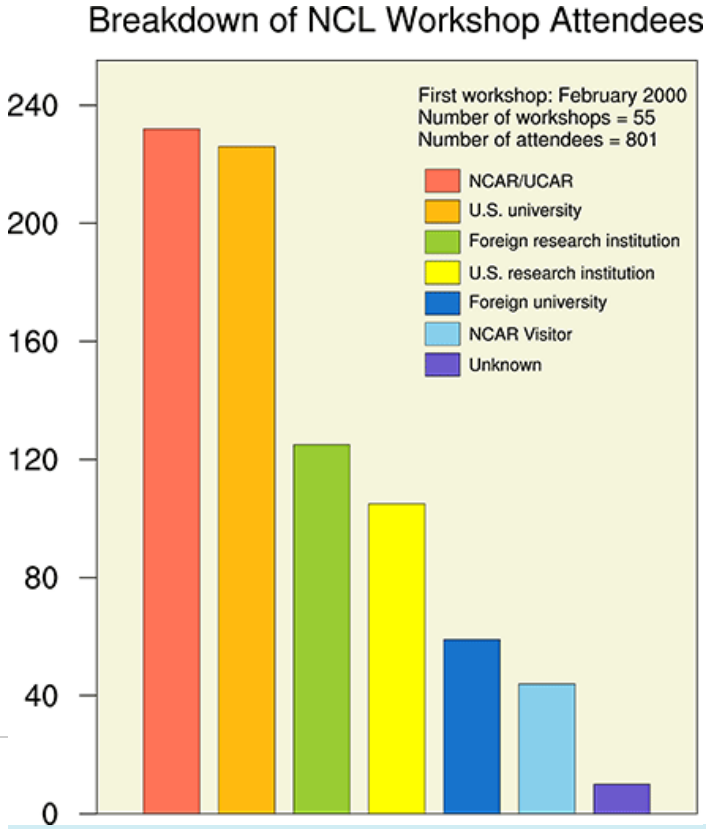
These workshops are a unique community capacity-building resource; they are key to connecting with scientific users and providing them with the knowledge they need to use NCL tools effectively in their research. Most of the participants in the courses we teach at universities are graduate students. The chart summarizes attendee demographics since the first NCL workshop was offered.

In FY2011, we taught five workshops: two in Boulder, one at the Bureau of Meteorology in Melbourne, Australia, one at the University of New South Wales in Sydney, Australia, and one at the University of Wyoming. Our international

efforts support the NCAR strategic goal of engaging a broader and more diverse community.

Two local workshops have been scheduled for FY2012, and we intend to provide at least two NCAR-supported workshops at a U.S. university. Funds will again be made available for EPSCoR/MSI students to attend these workshops. We have been researching ideas for providing these workshops on a wider scale, including offering online short tutorials, and training NCL experts at remote sites to teach their own workshops. The national training workshops are supported by NSF Core funding. The international workshops were financially supported by the recipient organizations.

‹ Training interns in computing at NCAR



Since its inception in February 2000, the NCL workshops have served a variety of scientific users, including international students and professionals. More than one fourth of these participants have been U.S. university students.

Support for community workshops, tutorials, and summer schools ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
    - Integrating research and education
    - Workforce training and development
      - Training interns in computing at NCAR
      - Training in geoscientific tools
      - **Support for community workshops, tutorials, and summer schools**
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Support for community workshops, tutorials, and summer schools

NCAR hosted and provided logistical support for a workshop entitled "Programming Weather, Climate, and Earth System Models on Heterogeneous Multi-core Platforms" on 7-8 September 2011. The workshop was attended by 45 researchers engaged in developing and testing climate, weather, and Earth System application components on many-core architectures such as Nvidia's line of powerful graphics cards. Topics addressed at the workshop included challenges, application development approaches for physics and dynamics, communications, and experiences with tools, compilers, and programming models.

An application development workshop for cluster computing systems was held in Boulder 7-8 September 2011 and attracted 45 international participants who presented the latest results in GPU acceleration of weather and climate codes. This photo shows the organizing committee for this international cross-agency workshop: Front row left to right: Ilene Carpenter (NREL), Chris Kerr (NOAA), and Bill Putman (NASA); Back row left to right: William Sawyer (CSCS), Mark Govett (NOAA), and Rich Loft (NCAR).

‹ Training in geoscientific tools

Broader Impacts ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - **Broader Impacts**
    - Broadening participation
    - CISL leadership in cyberinfrastructure
    - CISL participation in the HPC community
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Broader Impacts

CISL engages in a spectrum of activities designed to broaden the laboratory's impact through outreach, collaboration, and community engagement, and through capacity building at regional, national, and international scales. These activities have two main thrusts. First, CISL does outreach and provides training and education opportunities aimed at broadening participation and encouraging the development of the trained and diverse workforce necessary to continue advancing the scientific use of high performance computing resources. Second, CISL encourages collaboration and exchanges of information and expertise for developing shared cyberinfrastructure and standards that will advance high-performance computing, not only in the atmospheric and related sciences, but also in the general HPC community as well.

Clear examples of how CISL's education efforts broaden the laboratory's impact on the U.S. STEM workforce arise yearly from CISL's internship program SIParCS. Numerous interns have redirected their career plans in response to their positive research experiences in CISL. Taleena Sines, now a senior at Frostburg State University, learned what a career in high-performance computing might look like through SIParCS. "I did not want to commit myself to the Masters program without knowing for sure that this is what I wanted to do. This program definitely helped me to know that high-performance computing is something I could do for the rest of my life," said Sines. Sines' work improved, by an order of magnitude, the performance of the post-processing and data analysis suite associated with an advanced, high-resolution climate model. To fully exploit these advances, Sines and her colleagues used the Swift parallel scripting language to remove the bottlenecks inherent in the existing serial data analysis approach. Says Sines, "I will definitely carry this research forward into a Masters program."

Taleena Sines' SIParCS project improved post-processing times in NCAR's Community Earth System Model (CESM). She also attended a supplemental course on the challenges, techniques, and resources to scale applications for petascale computing systems.

Other members of the future STEM workforce whose career direction was influenced by SIParCS include Ashley Bell (Ithaca College), Chris McKinlay (University of California Los Angeles), Paul Ullrich (University of Michigan), and Hong Zhang (Virginia Polytechnic Institute and State University).

This work is supported by NSF Core funding.

‹ Support for community workshops, tutorials, and summer schools

Broadening participation ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
    - Broadening participation
      - Outreach
      - Training
  - CISL leadership in cyberinfrastructure
  - CISL participation in the HPC community
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Broadening participation

The CISL Strategic Plan elevates education, outreach, and training (EOT) to a core mission of the laboratory, at the same level as providing supercomputing and data services and doing computational science research. A key element of this role is broadening participation, particularly as expressed by the diversity of the organization, as well as attracting members of underrepresented groups to careers in high performance computing and the related scientific and technical disciplines.

CISL continues to aggressively expand and integrate its EOT and diversity efforts. Programs such as the Summer Internships in Parallel Computational Science (SIParCS), the Research and Supercomputing Visitor Program (RSVP), and IMAGe's Theme of the Year (TOY) have grown to become vibrant and inter-supporting elements in CISL's EOT strategy. As described below, CISL has extended unspent NCAR Directorate Diversity funds from FY2010 into FY2011, in support of diversity goals.

A key component of CISL's effort to broaden participation is the use of its Research and Supercomputing Visitor Program (RSVP) and NCAR's Directorate Diversity funds to provide travel support to visitors from minority-serving and EPSCoR-state institutions that attend CISL HPC and data analysis training classes.

CISL has established the practice of supporting at least one mission-appropriate "diversity" conference each year. CISL sent a computational scientist to represent NCAR at the 4-5 November 2010 Colorado Celebration of Women in Computing (CCWIC) at the Colorado School of Mines in Golden, Colorado. CCWIC is a regional conference modeled after the highly successful international Grace Hopper Celebration to encourage the research and career interests of women in computing. CISL also sent two Outreach Group staff to promote careers at NCAR at the 3-5 April 2011 Richard Tapia Celebration of Diversity in Computing Conference in San Francisco, California. CISL staff described NCAR research careers, encouraged faculty members to nominate students for NCAR programs, and distributed printed information about internship opportunities and professional development programs including SOARS and SIParCS. UCAR staff also distributes CISL's internship program materials at diversity-oriented conferences such as the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS). Finally, a CISL Director does outreach through site visits and presentations to universities and tribal colleges as a key strategic element of our recruiting activities.

CISL also participated in the Wyoming State Science Fair, providing student project judges and a science exhibit booth. UCAR staff also distributes CISL EOT materials at diversity conferences such as the Society for the Advancment of Chicanos and Native Americans in Science (SACNAS). CISL does outreach to colleges and universities through on-site presentations about its programs, making contact with students and faculty at educational institutions a key strategic element of our recruiting activities. SIParCS was also cross-listed on TeraGrid's internship website in FY2011, allowing effective cross-marketing to occur. CISL distributes information at the annual Supercomputing Job Fair and at conferences such as Supercomputing, AMS, and AGU.

CISL's education imperative for broadening participation is supported by NSF Core funding, with supplemental funding from other sources as noted above.

‹ Broader Impacts Outreach ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
    - Broadening participation
      - Outreach
      - Training
    - CISL leadership in cyberinfrastructure
    - CISL participation in the HPC community
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Outreach

Outreach is a gateway activity: it is the conduit through which other goals are reached. Examples include integrating education and research, broadening participation, and workforce development. Enhancing these activities offers opportunities to better connect with our user community, students, and future employees at all levels. In general, the goals for enhancing our outreach programs include:

- Reach a larger and broader audience.
- Develop our message to be more impactful and compelling.
- Communicate our accomplishments and the benefits of working in CISL more effectively.

Marc Mueller of NCAR's Education and Outreach Public Visitor Program (center) presented five types of hands-on science demonstrations to students at the Wyoming State Science Fair reception in Laramie. CISL staff also provided information about the NCAR-Wyoming Supercomputing Center (NWSC) in Cheyenne.

Since 1989, CISL has deployed a series of exhibit booths for a variety of scientific and technical conferences. In these booths, CISL staff demonstrates supercomputing capabilities, scientific visualization, and NCAR research in science, computational science, computing technology, and applied mathematics and statistics for the geosciences. CISL also invites NCAR scientists to present their current findings in the CISL exhibit booth. At the height of its conference outreach program, CISL staff provided demonstrations and presentations at many conferences each year, including Supercomputing, the American Meteorological Society, the American Geophysical Union, and others. In recent years, CISL has focused its energy and resources on providing NCAR outreach at the annual Supercomputing and TeraGrid conferences and on local Visualization Laboratory presentations and outreach activities. CISL also hosts and provides planning and logistics support for mission-appropriate conferences and workshops.

CISL's outreach activities at SC10 included 10 science and technology presentations in the exhibit booth. CISL invited two NCAR scientists to give daily science talks in the exhibit booth shown above. Mariana Vertenstein (NESL Senior Scientist) presented the talk "A Scalable, Flexible New Infrastructure for Earth System Modeling." She explained how CESM1 contains totally new infrastructure capabilities designed to address the challenges of Earth System modeling. Peter Gent (NESL Senior Scientist) presented "Community Climate System Model Version 4." He presented CCSM4 results that predict future climate change and described the high-resolution atmosphere and ocean components. Pamela Gillman (CISL Software Engineer) presented "Evolving Scientific Data Workflow." Rory Kelly (CISL Software

Matthew Woitaszek (foreground) and Kristin Mooney (seated at table) describe CISL internship and career opportunities at the SC10 Student Job

Engineer) presented "Designing a Science-Centered Benchmark Suite for NCAR's Next Supercomputer." Anke Kamrath (CISL Operations and Services Director) described progress on the NCAR-Wyoming Supercomputing Center (NWSC). Also at SC10, CISL staffed a table at the Supercomputing Student Job Fair with two computational scientists and the coordinator of SIParCS, CISL's internship program. They provided young people interested in careers in computational science and engineering with information about SIParCS and CISL's employment opportunities.

Fair. At this venue, students can explore research and engineering employment opportunities at major laboratories and manufacturers, and university faculty can learn about CISL's internship program. CISL will continue to promote employment and internship opportunities at future job fairs.

As part of its diversity program, CISL conducts outreach in mission-appropriate diversity-oriented venues. CISL sent a computational scientist to represent NCAR at the 4-5 November 2010 Colorado Celebration of Women in Computing (CCWIC) at the Colorado School of Mines in Golden, Colorado. CCWIC is a regional conference modeled after the highly successful international Grace Hopper Celebration to encourage the research and career interests of women in computing. CISL also sent two Outreach Group staff to promote careers at NCAR at the 3-5 April 2011 Richard Tapia Celebration of Diversity in Computing Conference in San Francisco, California. CISL staff described NCAR research careers, encouraged faculty members to nominate students for NCAR programs, and distributed printed information about internship opportunities and professional development programs including SOARS and SIParCS.

UCAR staff also distributes materials about CISL programs at diversity-oriented conferences such as the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS). CISL does outreach through site visits and presentations to universities and tribal colleges as a key strategic element of our recruiting activities. CISL also distributes information at the Supercomputing Student Job Fair and at conferences such as Supercomputing, AMS, and AGU.

CISL supported the March 2011 Wyoming State Science Fair at the University of Wyoming in Laramie. CISL supplied two scientist volunteers as judges, presented four awards for top junior and senior computational and Earth System science projects, presented atmospheric science demonstrations, and exhibited information about the NWSC facility under construction in Cheyenne. CISL's outreach efforts are part of the NWSC partnership with the State, University, and business community of Wyoming. CISL encourages students to embark on careers in computational science and engineering, and our efforts at this venue demonstrate our long-term commitments to outreach, workforce development, and broadening participation in the sciences.

CISL's Outreach Group is leading the design and construction of the public visitor area at NWSC. This NWSC education exhibit will inform K-12 students and the public how high performance computing supports and advances scientific research and discoveries. In FY2011 CISL established a collaboration for this effort with staff at the University of Wyoming, the Laramie County Library System, and UCAR Education and Outreach. With these collaborators, CISL planned the content of the displays and prepared an RFP for vendors to build the exhibits at the new supercomputing facility in Wyoming. The NWSC Education and Outreach Strategic Plan, which was written in a collaboration between directors of CISL and the University of Wyoming, calls for NWSC education efforts to support diversity and in particular to serve tribal colleges and community colleges throughout the intermountain west.

CISL has provided mentors for UCAR's Significant Opportunities in Atmospheric Research and Science (SOARS) program for 16 years, every year since its inception. CISL's SIParCS program collaborates with SOARS in outreach activities, and has established a reciprocal arrangement for referring candidates between the programs.

CISL's outreach program supports CISL's education imperative for outreach: to actively attract qualified candidates, particularly those from diverse backgrounds. This work fulfills CISL's strategic action item to expand outreach activities at conferences that enable CISL to effectively interact with our user community, students, and potential employees. Conference outreach also contributes to CISL's educational imperatives for workforce training and development, and for broadening participation. These efforts are supported by NSF Core funds, with supplemental funding supplied by other sources as appropriate.

‹ Broadening participation

Training ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
    - Broadening participation
      - Outreach
      - Training
    - CISL leadership in cyberinfrastructure
    - CISL participation in the HPC community
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Training

This photo shows some of the students who attended a "hands-on" NCL workshop at the University of Wyoming in Laramie. NCAR offers this course multiple times each year because NCL is being used in a variety of scientific modeling communities. NCAR supplements this workshop with many online resources including a website that provides an interactive email interface. NCL workshops target students' specific needs because they use their own datasets for analysis and visualization.

CISL is lowering the access barriers to training for students and staff from U.S. minority-serving and EPSCoR-state institutions by providing travel support from its Research and Supercomputing Visitor Program (RSVP) program. The types of classes covered include CISL HPC training such as Fortran 90 and MPI/OpenMP, and its Data Analysis Boot Camps. RSVP also encourages university visitors from diverse backgrounds to visit CISL and NCAR for extended periods.

In FY2011, the RSVP program supported eight visitors (five international and one on extended visits as part of a sabbatical) to collaborate with scientists across CISL. For the second year, RSVP funds were used to provide travel support for attendees of CISL training courses. Specifically, support was targeted to enable attendees originating from institutions in EPSCoR states, or from minority-serving institutions, to participate in these courses. Also in FY2011, RSVP provided support for eight attendees of NCL Data Analysis and Visualization Boot Camps from EPSCoR-state institutions.

To bring training to EPSCoR-state students, CISL held a four-day NCL data analysis and visualization workshop at the University of Wyoming in August 2011 with 24 participants: 18 from Wyoming, and six from other EPSCoR states.

CISL efforts to broaden participation in training activities, such as RSVP are supported by NSF Core funding and NCAR diversity funds.

‹ Outreach

CISL leadership in cyberinfrastructure ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
    - Broadening participation
    - CISL leadership in cyberinfrastructure
      - Regional CI engagement
      - National CI engagement
      - International impacts
      - Interactions with industry
    - CISL participation in the HPC community
  - CISL Profiles in Science

2009-2014 Strategic Plan »

CISL leadership in cyberinfrastructure

CISL participates in a broad portfolio of activities intended to further the development of computing technology and the improvement of regional, national, and international cyberinfrastructure. These activities are consistent with NCAR's leadership role as a national Federally Funded Research and Development Center (FFRDC), and are supported by NSF Core funding.

‹ Training

Regional CI engagement ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
    - Broadening participation
    - CISL leadership in cyberinfrastructure
      - Regional CI engagement
      - National CI engagement
      - International impacts
      - Interactions with industry
    - CISL participation in the HPC community
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Regional CI engagement

CISL has a strong presence in regional CI development, including both the HPC and networking communities. Working with regional entities broadens NCAR's impact by fostering the maturation of regional HPC CI, leverages unique regional resources and partnerships to tackle regional problems, and is a natural and mutually beneficial component of a national center's role.

CISL is a recognized leader and participant in many regional networking projects that are tightly integrated with national networks. CISL's involvement with regional networking consortia includes FRGP, UPoP, BiSON, WRN, EAGLE-Net, CHECO, BRAN, the Colorado Broadband Roundtable for the IT Economic Development and Business Planning group with the Colorado Governor's Office, and the Quilt. These are all designed to provide NCAR/UCAR and other institutions in the region with robust wide area data pathways. CISL designs, plans, engineers, installs, operates, maintains, develops strategy, and performs research for NCAR and UCAR state-of-the-art data networking and telecommunications facilities, providing a vital service to NCAR's research communities by linking scientists at partner institutions throughout the western U.S. to CISL's supercomputing resources. On behalf of UCAR, CISL continues to lead and participate in several important metropolitan, regional, and national networking initiatives. The tangible benefits of such participation include economical, diverse, high-performance networking for UCAR and its member universities. However, the intangible benefits are at least as important: participating in these initiatives reinforces UCAR's public mission of providing services to its members while simultaneously fostering cooperative ventures among these institutions. As a leading participant in such community alliances, CISL's Network Engineering and Telecommunications Section (NETS) contributes to strengthening UCAR's value as an institution and helps UCAR fulfill its leadership obligations for NSF funding.

In the area of regional high-performance computing, CISL has collaborated with the University of Colorado, Boulder and the University of Colorado, Denver on two Major Research Instrumentation (MRI) proposals. The first MRI system secured a 5.7-TFLOPS Blue Gene/L system, Frost, that was operated, maintained, and subsequently expanded to 22.8 TFLOPS by CISL. Frost was used for three purposes: as a TeraGrid resource, as a CU computing resource, and as a resource for atmospheric and computational science researchers interested in its unique architecture. The second MRI system acquired is Janus, a 184-TFLOPS Dell cluster housed at CU that has recently begun operation after acceptance testing. A 9.8% portion of this system is being used by CISL as an important resource for the atmospheric and related science community.

As part of CISL's leadership activities, CISL staff serve on a variety of regional HPC panels, including the allocation and procurement panel of the Golden Energy Computing Organization (GECO) at the Colorado School of Mines, and the Boulder Campus Cyberinfrastructure Board (BCCB). Most recently, CISL is strongly engaged with the University of Wyoming in developing campus CI and EOT activities that will enhance the impact of NWSC to Wyoming and eventually to other EPSCoR states in the region. These regional HPC activities allow CISL to gain hands-on experience in collaborating with campus IT staff through the processes of CI acquisition, deployment, and resource federation.

CISL also participates in the activities of the The Front Range Consortium for Research Computing (FRCRC), an informal body of regional HPC organizations, whose goal is to explore how Colorado State University, the University of Colorado, Colorado School of Mines, the University of Wyoming, NCAR, the Department of Energy's National Renewable Energy Laboratory, and NOAA's Boulder Earth System Research Laboratory can share experiences, tools, hardware, software, courses, seminars, applications, and other interests in HPC to benefit the region. On 23-24 September 2011, CISL staff participated in the first annual Front Range HPC Symposium, which attracted over 90 registered participants to a two-day series of lectures, tutorials, and affinity group discussions at the Colorado School of Mines campus.

CISL's work in this area is supported by NSF Core funding, NSF MRI grant CNS-0821794, and UCAR non-federal funds.

‹ CISL leadership in cyberinfrastructure National CI engagement ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
    - Broadening participation
    - CISL leadership in cyberinfrastructure
      - Regional CI engagement
      - National CI engagement
      - International impacts
      - Interactions with industry
    - CISL participation in the HPC community
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

National CI engagement

CISL has a strong presence in national CI development, including both the HPC and networking communities. Working with national entities broadens NCAR's impact by fostering the maturation of national HPC CI, leverages national resources and partnerships to tackle national problems, and is a natural and mutually beneficial component of a national center's role.

CISL actively participates in the NSF's broader national high-performance CI through participation in NSF-funded high-performance CI projects, national conferences, and governmental advisory panels. For example, CISL contributed to the TeraGrid's technical and management processes and served as a TeraGrid resource provider (RP) between August 2007 and July 2011. During that period, NCAR's Blue Gene/L system, Frost, delivered roughly 50M CPU-hours to 53,630 jobs for TeraGrid-allocated projects. In addition, many of NCAR's data CI, collections, and science gateways (such as the Earth System Grid and the Asteroseismic Modeling Portal) now interoperate with other TeraGrid resources and users.

Since July 2011, NCAR has transitioned into a user support and allocation management role within the XSEDE project, the follow-on to TeraGrid, and has been prototyping data-intensive architectures that can interoperate with XSEDE systems. This relationship with XSEDE has been crafted to provide support for atmospheric scientists who use XSEDE resources for their research. XSEDE is funded through a five-year grant from the NSF Office of Cyberinfrastructure.

CISL staff presented their work on science gateways at the TeraGrid'11 conference in Salt Lake City, Utah on 18-21 July 2011. Matthew Woitaszek of NCAR gave a joint presentation on the Asteroseismic Modeling Portal (AMP) with Victor Hazelwood from the National Institute for Computational Sciences (NICS), and Don Middleton of CISL gave a talk on his work with Purdue University to develop an integrated end-to-end TeraGrid climate modeling environment. The TeraGrid'11 conference hosted hundreds of participants and showcased the capabilities, achievements, and impact of the TeraGrid in research and education.

Matthew Woitaszek (left) from NCAR and Victor Hazelwood (right) from NICS gave a presentation at TeraGrid'11 on the secure implementation of a grid-based NCAR science gateway called the Asteroseismic Modeling Portal (AMP) on the NICS system, Kraken. AMP facilitates modeling and analysis for a broad international community of researchers. Its web-based interface allows astronomers derive the properties of Sun-like stars from observations of their pulsation frequencies. This work allows the AMP community to securely utilize multiple platforms on the TeraGrid for their research.

In addition, CISL is an active participant in the ACM SIGARCH / IEEE Computer Society Supercomputing conferences, which attract thousands of HPC experts from government, academia, and industry every year. CISL staff members serve each year on the infrastructure committee, present technical papers, and operate an NCAR exhibit booth on the conference floor. CISL is also active each year at the Supercomputing Student Job Fair, which is an opportunity to reach a broad population of students and other job candidates. CISL also participates in the design, implementation, and operation of SCInet.

CISL staff members also serve on a number of advisory panels, including the NSF Office of Cyberinfrastructure's Advisory Committee for Cyberinfrastructure, the Petascale External Advisory Committee of the NSF Blue Waters Project, and the Technical Evaluation Panel of the Department of Defense HPC Modernization Office.

CISL is a recognized leader and participant in many national networking projects that are tightly integrated with regional networks. CISL designs, plans, engineers, installs, operates, maintains, develops strategy, and performs research for NCAR and UCAR state-of-the-art data networking and telecommunications facilities, providing a vital service to NCAR's research communities by linking scientists at partner institutions to CISL's supercomputing

resources. On behalf of UCAR, CISL/NETS continues to lead and participate in important national networking initiatives. The tangible benefits of such participation include economical, diverse, high-performance networking for UCAR and its member universities. However, the intangible benefits are at least as important. Participating in these initiatives reinforces UCAR's public mission of providing services to its members while simultaneously fostering cooperative ventures among these institutions. As a leading participant in such community alliances, NETS contributes to strengthening UCAR's value as an institution and helps UCAR fulfill its leadership obligations for NSF funding.

With the exception of CISL's participation in XSEDE, CISL's national leadership activities are funded by NSF core funds.

‹ Regional CI engagement

International impacts ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
    - Broadening participation
    - CISL leadership in cyberinfrastructure
      - Regional CI engagement
      - National CI engagement
      - International impacts
      - Interactions with industry
    - CISL participation in the HPC community
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

International impacts

CISL is highly visible on the international front and engaged with international climate and weather organizations, programs, centers, and projects. Our international impact spans data services and exchanges, analysis and visualization tools, computational support, strategic advisory functions, training, capacity building, and international conferences.

Attendees at a presentation during the September 2011 CAS workshop in Annecy, France. The program of this biennial conference focused on a wide-ranging set of issues of interest to the international supercomputing community in the atmospheric sciences.

CISL contributes to developing the World Meteorological Organization (WMO) Information System (WIS). Under the auspices of the United Nations, the WMO is designing, developing, and deploying WIS as a next-generation globally federated information system for weather, climate, hydrology, oceanography, and many other disciplines. CISL plays a strong role in the management and technical direction of WIS and has contributed ideas, strategies, and services developed through our work with CDP, ESG, CADIS, and TIGGE. CISL staff serve on several WIS committees, including the driving Intercommission Coordination Group (ICG-WIS), the Expert Team on GISC and DCPC Demonstration Program (ET-GDDP), the ICG-WIS sub-committee on WIS Center Identification, and the Inter-Programme Expert Team on Metadata and Data Interoperability (IPET-MDI). In addition, CISL operates the U.S. archive and portal for the WMO THORPEX Interactive Grand Global Ensemble (TIGGE), an international weather forecast multimodel inter-comparison collaboration with the European Centre for Medium-range Weather Forecasts (ECMWF) and the China Meteorological Administration (CMA). In tandem with this important global effort, CISL serves on the WMO GIFS-TIGGE (Global Interactive Forecast System) Working Group.

There are several noteworthy formal international data exchange agreements associated with the development of the NCAR Research Data Archive (RDA). ECMWF and JMA routinely share data under longstanding MOUs with NCAR. These reanalyses and operational model outputs add to the RDA and are important because they are not available anywhere else in the U.S. CISL reciprocates by preparing observational datasets and delivering them to support future reanalysis efforts. CISL also has a MOU with the Chinese Academy of Science in which a few datasets from the RDA have been replicated in China, and we have received some Chinese data that has been included in the RDA. There have also been technical meetings with CAS, and CISL has hosted a visiting scientist. In collaboration with NOAA, CISL participates in a biennial data-sharing activity with Russia. Meetings with personnel from the All Russian Institute for Hydrometeorology in Obninsk are very productive with new archives of upper-air soundings from the former Soviet Union being added to the RDA, and the digitization of many historical marine surface observations that have be added into the International Comprehensive Ocean-Atmosphere Data Set.

CISL's analysis and visualization tools (e.g., NCL, PyNGL, and VAPOR) are popular in centers and universities around the world. VAPOR, for example, is currently expanding ocean visualization capabilities under support from the Korea Institute of Science and Technology Information. NCL is used in 114 different countries, and CISL has conducted NCL data analysis training workshops in Australia, Turkey, Germany, and Switzerland. The RDA is an extremely valuable international scientific data resource, providing important collections to the global community and making EU collections available to U.S. scientific communities. CISL's Science Gateway Framework (SGF) is currently being run as Earth System Grid Federation (ESGF) gateways in support of WCRP/CMIP5 in Europe and Australia as well as the U.S. Similarly, CISL is a primary partner in the CADIS effort, which makes Arctic Observing Network (AON) data available for the International Polar Year (IPY). CISL also provides computing support for the Antarctic Mesoscale Prediction System (AMPS), an experimental, real-time numerical weather prediction capability that supports the United States Antarctic Program, Antarctic science, and international Antarctic efforts.

CISL hosts and organizes the popular international Computing in Atmospheric Sciences (CAS) workshop every other year in Europe. In September 2011, CISL organized the tenth biennial CAS workshop. More than 100 scientists, industry experts, and computing professionals from 13 countries attended and discussed challenges and new approaches to advance climate and weather research in the coming exascale era and beyond. International presenters at the workshop discussed, from various perpectives, a wide range of topics of keen interest to provisioners of cyberinfrastrucutre for atmospheric science, such as the prospects for exascale (10^{18} floating point operations per second) computing facilities, the growth in electrical power consumption and associated operating costs, and the requirements of data management and data-intensive computing. Among efforts to reduce operating costs and energy requirements, presenters discussed new, experimental technologies that could limit power use, new architectures to improve efficiency, and alternatives like cloud computing and Internet-based science gateways. Presenters touched on a number of other topics related to climate and weather modeling, such as computational benchmarking methods, and new uses of GPU-based computing.

Also in FY2011, CISL was involved as a zero-dollar participant in an international project to study the computer science challenges facing future exascale climate models. CISL's role in this effort is to supply application support. Finally, CISL staff members collaborate with many more foreign institutions and serve on various international committees and advisory panels, including the German Climate Computing Center (DKRZ) Advisory Committee.

‹ National CI engagement

Interactions with industry ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
    - Broadening participation
    - CISL leadership in cyberinfrastructure
      - Regional CI engagement
      - National CI engagement
      - International impacts
      - Interactions with industry
    - CISL participation in the HPC community
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

Interactions with industry

CISL maintains close informational relationships with HPC, networking, and related vendors as a way of providing information to vendors regarding the computational requirements of the atmospheric and related sciences and to track technology. To this end, CISL maintains an up-to-date set of nondisclosure agreements with HPC-related vendors that allows CISL to keep abreast of the latest technical developments and plans in this fast-moving industrial space. CISL also routinely receives loaner equipment and new software products from vendors for evaluation and testing under these agreements. For example, in FY2011, computer scientists in CISL received early samples of the Intel MIC many-core processors from Intel Corporation for evaluation, and CISL's Mass Storage group received the new high-speed 5-terabyte tape drives being produced by Oracle's StorageTek unit.

CISL's Network Engineering and Telecommunications Section (NETS) interacts with many networking companies. NETS provides them with feedback on feature requests and keeps them informed about services that would benefit UCAR, the Front Range GigaPop consortium (FRGP), and our research and education community. In turn, NETS receives product road maps and other information about products and services we utilize in running and maintaining the networks we manage. NETS interacts with many vendors, professional associations, and consortia including ADVA Optical Networking, BICSI, Cisco Systems, EDUCAUSE, Internet2, Juniper Networks, North American Network Operators' Group (NANOG), National LambdaRail (NLR), and The Quilt coalition.

NETS staff provides input and receives product information on ADVA equipment through their Research and Education Technical Advisory Group. NETS technicians are RCDD certified through the BICSI professional association. UCAR has a non-disclosure agreement with Cisco Systems that keeps NETS appraised of product road maps, and NETS participates in special-purpose discussions with Cisco about future purchases and product requirements for UCAR and the FRGP. UCAR is a member of the higher-education information technology association EDUCAUSE and participates in training and conferences. UCAR is a participating member and represents the FRGP as a network member of the Internet2 research and education networking consortium. NETS participates in special-purpose discussions with Juniper Networks about future purchases and product requirements for UCAR and the FRGP. NETS network engineers participate in NANOG engineering meetings to improve the Internet's networking technologies and operational practices. NETS manager Marla Meehl concluded her term of service on the NLR Board of Directors in FY2011. NETS assistant manager Jeff Custard serves on the Board of Directors for the FRGP to influence the national agenda on information technology infrastructure, with particular emphasis on networking for research and education.

During NWSC construction in FY2011, CISL's Operations and Services Division benefited from many interactions with the facility design, construction, and infrastructure equipment industries. Collaborations with engineers and the general contractor developed a variety of innovative means and methods for building the facility. OSD collaborated with a vendor to custom-design heat pumps that will re-use waste heat from the computer room to significantly reduce the building's energy consumption. CISL's discussions with a computer rack manufacturer resulted in an inventive application of t-slot framing components for the hot aisle containment structure. The manufacturer of the t-slot material studied the CISL solution to enhance their product offerings. Another beneficial industry interaction occurred during a factory witness test visit. CISL engineers discovered a more efficient backdraft damper to use in the fan wall which allows sections of the fan wall to be powered off to further enhance overall energy efficiency.

CISL also routinely invites vendors to attend and present at HPC-related conferences and workshops that it holds, such as the Computers in Atmospheric Science conference and the recent Programming Weather, Climate, and Earth System Models on Heterogeneous Multi-core Platforms workshop, both held in September 2011.

In FY2011, CISL staff members also continued to provide advice to industry, for example through service on the IBM Deep Computing Advisory Board, the Intel HPC Round Table, and the Microsoft Technical Computing Executive Advisory Council. As a result of the work done by CISL on the design and construction of the NCAR-Wyoming Supercomputing Center facility, CISL staff also served on the Uptime Institute's Oversight Board. The Uptime Institute provides education, publications, consulting, certifications, conferences, seminars, independent research, and leadership for data center professionals and the enterprise data center industry.

This collaborative work with industry is supported by NSF Core funds.

‹ International impacts CISL participation in the HPC community ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
    - Broadening participation
    - CISL leadership in cyberinfrastructure
    - CISL participation in the HPC community
  - CISL Profiles in Science

2009-2014 Strategic Plan »

CISL participation in the HPC community

As part of its leadership role in the HPC community, CISL organizes, hosts, or participates in several large-scale conferences. Through this participation, CISL fosters the interchange of ideas, technical information, best practices, and research findings.

For example, CISL engages the HPC community via:

- SC conferences: CISL is a longtime participant in the IEEE and ACM-sponsored SuperComputing (SC) conference series, the premier HPC event in the United States. CISL staff members participate on organizing and event committees, organize Birds of a Feather sessions, and routinely submit technical papers to this conference. CISL also participates in the SC Student Job Fair, a prime venue for meeting candidates from a variety of backgrounds who are interested in careers in HPC and related scientific fields.
- LCI conferences: CISL participates on the steering committee of the Linux Cluster International (LCI) conference. The conference attracts the world's top practitioners of clustered computing who gather to share experiences and update colleagues on the latest developments in the field.
- CAS conference: To foster international dialogue by peer centers, CISL hosts the Computing in Atmospheric Sciences (CAS) conference every two years under NSF sponsorship. CAS brings together international colleagues to discuss information technology advances and the transformative infrastructure that allows scientists to investigate atmospheric problems as part of the Earth System model.

This work is supported by NSF Core funding.

‹ Interactions with industry CISL Profiles in Science ›

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Log in

2011 CISL Annual Report

- CISL Director's Message
- 2011 CISL Annual Report
  - CISL Director's Message
  - CISL Annual Report Table of Contents
  - CISL Services
  - CISL Science
  - CISL Education
  - Broader Impacts
  - CISL Profiles in Science

2009-2014 Strategic Plan »

Search

CISL Profiles in Science

At fiscal year end, CISL scientists write reports to summarize their research efforts, discoveries, publications, innovations, and other accomplishments. These documents may describe the work of individuals or teams. Some of these reports are archived here as "Profiles in Science."

The following reports describe CISL science in FY2010:

Pouquet, Annick, MHD turbulence at high Reynolds number

Pouquet, Annick, Numerical simulations of rotating turbulence

Rosenberg, Duane, Developments on the spectral codes GHOST, TYGRES, and GASpAR

‹ CISL participation in the HPC community

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Log in

Integrated Science Program | ISP
2011 Annual Report

sponsored by

ISP Annual Report 2011

- Table of Cotents
- Director's Message
- Frontiers and Imperatives
- Program Activities
- Postdoctoral research themes at ISP
- ISP Contacts

2009-2014 Strategic Plan »

Director's Message

ISP Director, Peter Backlund

The **Integrated Science Program** (ISP) was formed in 2009 as an NCAR Directorate entity that supports scientists working on crosscutting research across NCAR Laboratories and other research institutions. The overarching goal of the Integrated Science Program (ISP) is to develop the understanding needed to manage and adapt to climate change, weather, and chemical weather through research that integrates the atmospheric sciences with other scientific disciplines. ISP is:

- Developing new connections among the atmospheric sciences, social sciences, ecology, hydrology, and health sciences
- Fostering collaborations across NCAR laboratories, divisions, institutes, and programs
- Building new relationships with university programs and other research institutions whose expertise complements NCAR expertise
- Promoting innovation in NCAR research and development

ISP is unique within NCAR as a “virtual” organization that does not maintain its own staff (except for a very small central administrative group) and carry out its own projects. All ISP activities are defined and undertaken in cooperation with other NCAR organizations and collaborators in the university community and other research institutions. ISP helps define, set up, and fund projects that are carried out by staff from NCAR labs and outside collaborators.

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Log in

Integrated Science Program | ISP
2011 Annual Report

sponsored by

ISP Annual Report 2011

Table of Cotents
Director's Message
Frontiers and Imperatives
Program Activities
Postdoctoral research themes at ISP
ISP Contacts

2009-2014 Strategic Plan »

Frontiers and Imperatives

The work of ISP addresses frontiers and supports the imperatives of the NCAR Strategic Plan:

Two ISP projects are focused on NCAR Frontier 1: To advance modeling and analysis focused on informing climate change adaptation and mitigation.

- The **Integrated Assessment Modeling** (IAM) project is focused on developing and applying integrated socio-economic and biophysical models of the climate system to investigate how changes in human systems are coupled with the Earth's climate system.
- The **NCAR Vulnerability, Impacts, and Adaptation** (NVIA) project is focused on interdisciplinary basic research that integrates climate, weather, social, ecological and heath sciences to investigate the effects of climate change and extreme events on human populations at local, regional and global scales.

One ISP project is focused on the NCAR Imperative to **Develop and transfer scientific applications, technology, and information products that address societal needs**.

- **The Weather Communication and Warning** (WCW) project is conducting research intended to improve understanding of how people react to weather information and enhance communication of weather, climate, and hydrological forecast information to the public and decision makers.

Two of the ISP projects are focused on elements of NCAR's imperatives, "prediction and attribution" and "model development":

- **Climate Change and Marine Ecosystems** is focused on modeling, understanding and projecting the impacts of climate change on marine ecosystems.
- Carbon Cycle Observations and Modeling is focused on comparison of carbon cycle observations to simulation results from **Community Earth System Model** (CESM) and other biogeochemical modeling systems.

In its first two years of operations, ISP has provided full or partial support to thirteen different postdoctoral researchers and fellows. In some cases, postdocs are being shared with other institutions, including the areas of climate and health (in collaboration with RAL, ASP, and the Centers for Disease Control), climate and terrestrial ecosystems (in collaboration with the National Ecological Observatory Network), and climate and marine ecosystems (in collaboration with Rutgers University). In other cases, ISP is collaborating with the NCAR Advanced Study Program to support interdisciplinary postdoctoral fellows who have proposed research projects on topics of interest to ISP.

All ISP activities are defined and undertaken in cooperation with other NCAR organizations and collaborators in the university community and other research institutions.

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Log in

Integrated Science Program | ISP
2011 Annual Report

ISP Annual Report 2011

Table of Cotents
Director's Message
Frontiers and Imperatives
Program Activities
Postdoctoral research themes at ISP
ISP Contacts

2009-2014 Strategic Plan »

Program Activities

In FY11, ISP conducted 3 ongoing research projects, each of which was initiated in FY10.

- The **Integrated Assessment Modeling** (IAM) project is focused on developing and applying integrated socio-economic and biophysical models of the climate system.
- The **NCAR Vulnerability, Impacts, and Adaptation** (NVIA) project is focused on conducting interdisciplinary basic research on social, economic, and political activities related to climate at local, regional and global scales.
- The **Weather Communication and Warning** (WCW) project is focused on improving communication of weather, climate, and hydrological forecast information to the public and decision makers.

ISP initiated development of 2 new projects during FY11:

- **Climate Change and Marine Ecosystems** is focused on modeling, understanding and projecting the impacts of climate change on marine ecosystems.
- Carbon Cycle Observations and Modeling is focused on comparison of carbon cycle observations to simulation results from **Community Earth System Model** (CESM) and other biogeochemical modeling systems.

ISP is also hosting the scientific support office for **Analysis, Integration, and Modeling of the Earth System** (AIMES), which is one of the core projects of the **International Geosphere Biosphere Program** (IGBP). AIMES is focused on achieving a deeper and more quantitative understanding of the role of human perturbations to the Earth's biogeochemical cycles and their interactions with the coupled physical climate system.

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Log in

Integrated Science Program | ISP
2011 Annual Report

sponsored by

ISP Annual Report 2011

Table of Cotents
Director's Message
Frontiers and Imperatives
Program Activities
Postdoctoral research themes at ISP
ISP Contacts

2009-2014 Strategic Plan »

Postdoctoral research themes at ISP

The Integrated Science Program (ISP) sees the support of postdoctoral research at NCAR as an effective means of seeding new, crosscutting research themes in the institution with short-term and collaborative funding. These new activities employ enthusiastic young researchers in building research programs that will remain relevant at NCAR and collaborating institutions well into the future.

ISP is collaborating with the Advanced Studies Program (ASP), the Research Applications Laboratory (RAL), and the Centers for Disease Control (CDC) to bring postdoctoral researchers to NCAR to study issues at the intersection of climate and health. Housed at RAL, these CDC-funded researchers represent the first of what is hoped to be a series of activities oriented to understanding the critical links between climate change and human health. This program is highlighted in the **NCAR Annual Report.**

ISP is collaborating with the National Ecological Observatory Network (NEON) to house two NSF-supported postdoctoral researchers who will conduct research on the interactions of climate change with terrestrial ecosystems. Such interactions will be an important factor in determining the evolution of ecosystems and the services they provide to human societies, the rate and magnitude of climate change, and the severity of climate change impacts during the next century. The co-location of NCAR and NEON in Boulder allows these new researchers to collaborate with scientists from both institutions and develop a well-integrated approach. This program is highlighted in the FY10 **NCAR Annual Report**.

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Log in

Integrated Science Program | ISP
2011 Annual Report

sponsored by

ISP Annual Report 2011

- Table of Cotents
- Director's Message
- Frontiers and Imperatives
- Program Activities
- Postdoctoral research themes at ISP
- ISP Contacts

2009-2014 Strategic Plan »

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Log in

High Altitude Observatory | HAO
2011 Annual Report

HAO Annual Report

HAO 2011 Annual Report
Director's Message
Executive Summary
Table of Contents
Understanding the Solar Dynamo
Understanding Magnetic Flux Emergence
Structure and Dynamics of the Corona and Heliosphere
Terrestrial Impacts of Solar Variability
Community Model Development
Observational Facilities and Data Service
HAO Visitor Program
HAO 2011 Profiles in Science

2009-2014 Strategic Plan »

Director's Message

HAO Director Michael J. Thompson.

It is my pleasure, for the second year, to be writing the introduction to the High Altitude Observatory's (HAO) Annual Report. It has been a busy year, with many successes and accomplishments, as well as some challenges for the Observatory.

A number of our staff had notable achievements during the year. HAO scooped four of the seven UCAR awards at the annual UCAR Awards Ceremony held in December 2010: Astrid Maute was the first ever recipient of the Diversity Award for her long-time involvement and leadership role in the American Association for University Women (AAUW) and particularly for her contributions to the Expanding Your Horizons (EYH) conference; Art Richmond received the Mentoring Award for his exemplary and sustained mentoring efforts that directly enhance the professional development of numerous scientists at all stages of their careers from undergraduates to postdoctoral scientists and beyond; Phil Judge, Scott McIntosh, Steve Tomczyk, and collaborators received the Publication Award for "Alfvén waves in the solar corona," Science, 317, 1192-1196 (2007); and Bruce Lites was only the fourth ever recipient of the Distinguished Achievement Award for his leadership and continuous support of spectro-polarimetry programs at NCAR and in the solar community worldwide. Outside of UCAR, Matthias Rempel was awarded the Karen Harvey Prize by the Solar Physics Division (SPD) of the American Astronomical Society (AAS) for his groundbreaking work on the structure of sunspots and on flows and magnetic fields in the solar convection zone. He delivered his prize lecture at the 2011 SPD meeting in Las Cruces, NM. Also, two staff members were promoted during the year: Alan Burns to Project Scientist III and Scott Sewell to Engineer III.

HAO also honors staff members each year by awarding the John W. Firor Publication Award and the Walter O. Roberts Scientific and Technical Advancement Award. HAO's publication award was presented to Mark Miesch and collaborators for "Structure and evolution of giant cells in global models of solar convection," The Astrophysical Journal, 673, 557-575 (2008). Greg Card and Steve Tomczyk received the scientific and technical advancement award for the outstanding contributions made to the development and deployment of the Coronal Multi-Channel Polarimeter (CoMP) instrument. This year we instituted a new award, the HAO Director's Award, which was presented to Joan Burkepile for her service to and engagement with the Mauna Loa Observatory (MLSO) user community.

Congratulations to all the above colleagues for these well-deserved recognitions.

In September 2010 we held a two-day retreat for all HAO staff at the Lionsgate Event Center, Lafayette, CO, to work on a new HAO Strategic Plan. The retreat was followed by a period of further discussion and iteration of the plan's elements within the Observatory; a small group then proceeded to draft the plan. Following consultation with external stakeholders, our HAO Strategic Plan for 2011-2015 was finished just before Christmas. It is an actionable plan, in that it will direct the investment of efforts and resources in the Observatory throughout the next several years, and we will judge our progress and success against it. It is also a living plan: although it looks forward on a five-year timescale, it will be revisited and renewed halfway through that period.

In the summer of 2011 we reorganized the section structure in the Observatory, reducing the number of sections from four to three. The Atmosphere, Ionosphere & Magnetosphere (AIM) section is retained, but the previous Solar Interior & Variability section, Lower Solar Atmosphere section and Corona & Heliosphere section are replaced by two new sections: the Solar Transients and Space Weather (STSW) section and the Long-term Solar Variability (LSV) section. During the year and the subsequent reorganization, three long-serving section heads stepped down: Yuhong Fan, Bruce Lites, and Keith MacGregor. I thank all three of them for their service to HAO and leadership of their sections, as I do Mausumi Dikpati for her service as acting head of the Solar Interior and Variability section for much of the past year.

Art Richmond continues as AIM section head; and Sarah Gibson and Scott McIntosh are heads of the new LSV and STSW sections, respectively.

The year saw the first science flight of the HAO FPI balloon mission HiWind (PI Qian Wu). Further, two major instrumentation projects successfully completed their preliminary design reviews during the year: these are the Visible-light Spectro-Polarimeter (ViSP) for the Advanced Technology Solar Telescope (ATST), and the white-light COSMO K-Coronagraph. All three represent exciting instrumentation developments for the Observatory. In particular, the K-Coronagraph, which is now being constructed and will be deployed to the Mauna Loa Solar Observatory in 2013, is the first element of the planned Coronal Solar Magnetism Observatory (COSMO). At a time of severe pressures on federal budgets, with consequent impacts on the budgets of NCAR and HAO, it is important for the future of HAO that we are nonetheless able to find internal and external resources to realize new programs and to make progress on our strategic frontier activities.

Support of the broad solar-terrestrial physics community is an essential component of HAO's mission, and numerous activities during the year were directed to this purpose. Space permits me to mention just a few examples. There was strong HAO participation and leadership at the joint CEDAR/GEM workshop, with 16 HAO participants, nine sessions were led by HAO staff, a plenary talk was presented by Stan Solomon, and a huge contribution to the organization of the workshop was made by Barbara Emery. Similarly, 16 members of HAO participated at the SHINE workshop; four sessions were led by HAO staff, Matthias Rempel gave a plenary talk, and the workshop saw the public launch of the CoMP data. Of special note, Joan Burkepile has been appointed to the SHINE steering committee. In the area of education, Phil Judge organized the Eddy Cross-Disciplinary Symposium on Sun-Climate Research, and numerous staff were involved in the supervision of our strongest-ever cohort of six Research Experience for Undergraduates (REU) summer students and two Significant Opportunities in Atmospheric Research and Science (SOARS) protégés. In support of community models, Hanli Liu took over as NCAR co-chair of the Whole Earth Community Climate Model (WACCM) working group within the Community Earth System Model (CESM) project. In community leadership, several HAO staff contributed to The National Research Council's decadal survey in heliophysics, notably Sarah Gibson as a member of the steering committee, and Mike Wiltberger as vice-chair of the Solar Wind Magnetosphere Interaction (SWMI) panel.

In closing, I should mention the NSF Science Review of HAO (the most substantial review of the Observatory in 10 years), which took place in March 2011. The review panel reported that "the Observatory has an impressive and distinguished record of scientific accomplishments and achievements as well as myriad activities to support education and public outreach". Many of those activities are reported further in the succeeding pages of this year's HAO Annual Report. Needless to say, these achievements would not happen without the dedicated and skilled efforts of HAO staff, and I thank them all for their dedication to the Observatory and to the community we serve.

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Log in

High Altitude Observatory | HAO
2011 Annual Report

HAO Annual Report

- HAO 2011 Annual Report
- Director's Message
- Executive Summary
- Table of Contents
- Understanding the Solar Dynamo
- Understanding Magnetic Flux Emergence
- Structure and Dynamics of the Corona and Heliosphere
- Terrestrial Impacts of Solar Variability
- Community Model Development
- Observational Facilities and Data Service
- HAO Visitor Program
- HAO 2011 Profiles in Science

2009-2014 Strategic Plan »

Executive Summary

HAO conducts a comprehensive program of solar terrestrial research, emphasizing the interconnections between physical processes in the solar interior, solar atmosphere and corona, the role of the Sun in geospace variability, and the weather and climate of the upper atmosphere and ionosphere. HAO operates solar observational facilities at the Mauna Loa Solar Observatory (MLSO) in Hawaii and elsewhere. It also supports instrument development, data analysis tool development, database service, and upper atmospheric observational facilities and community model development. All these efforts support the achievement of HAO's vision to:

- Perform world-leading science to understand fundamentally and with predictive capability the sources and nature of solar and geospace variability;
- Provide scientific leadership and facilities to serve the wider community in common pursuit of these science objectives, and both support and benefit from the NCAR community;
- Support the education and training of early-career researchers in solar-terrestrial physics and instrumentation;
- Provide advocacy for solar-terrestrial physics, promoting its results, and articulating its societal importance, to the rest of NCAR, the NSF, the university community, and the public..

HAO's efforts to understand the origins and impacts of the Sun's variable radiative, magnetic, and particulate outputs are furthered through simulations conducted with state of the art numerical models. Models and methods developed by HAO researchers, together with the insights obtained from their use, have earned the Observatory a position at the forefront of worldwide efforts in the area of computational solar physics. Numerical simulations have been performed to address fundamental problems pertaining to: the generation of solar magnetism by hydromagnetic processes inside the Sun; the emergence, properties, and evolution of magnetic fields in the solar surface layers and atmosphere; the physical mechanisms underlying coronal activity, the solar wind, and space weather; and the effects of solar and meteorological forcing on the Earth's upper atmosphere. HAO's breadth of capabilities allows for more accurate prediction and attribution of changes in solar output, space weather, and the related impacts of such changes on the Earth.

HAO's observational program emphasizes scientific community involvement, including an open data policy, student participation, and public access to scientific results. Data from MLSO are made readily available online to the broad solar community both nationally and internationally. The MLSO database currently has 485 registered users from 37 countries, with 179 new registered users since 2009. Two major efforts in FY 2011 were: (1) the successful completion of the critical design review (CDR) of a high sensitivity K coronagraph, and (2) the preliminary design review (PRD) of the Visible Spectropolarimeter (ViSP) for the Advanced Technology Solar Telescope (ATST). In addition, an enhanced copy of the Coronal Multi channel Polarimeter (CoMP) was developed and deployed to the Lomnicky Peak Observatory in Slovakia in April of 2011. The High altitude Interferometer WIND (HiWIND) balloon was successfully launched in June 2011 from Kiruna, Sweden.

One way that HAO scientists serve the community is through support of model development, data analysis, and validation. The Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE GCM) version 1.94 was released in June 2011 as a community model. HAO also takes a lead role in development of WACCM, particularly, its high altitude extension referred to as "WACCM X". As part of our continuing collaboration with the Coordinated Community Model Center (CCMC), we have achieved a major milestone by making the latest version of the Coupled Magnetosphere Ionosphere Thermosphere (CMIT) available for community access through the run on request system at the CCMC. As a broader impact, the availability of the model at the CCMC allows graduate students to access the model and allows it to be used in the preparation of materials for class lectures.

HAO also supports an extensive visitor program. In FY2011 (i.e., the financial year that runs from

October 2011 to September 2011), HAO supported eleven postdoctoral early career scientists and four graduate research assistants to carry out their research under the supervision of HAO scientific staff. Furthermore, six Research Experience for Undergraduates (REU) students and two Significant Opportunities in Atmospheric Research and Science (SOARS) protégés resided at HAO over the summer to gain first hand research experience. HAO also hosted seven affiliate scientists and 123 other visiting scientists (among them 49 were student visitors). One new affiliate scientist, Prof. Viggo Hansteen of the University of Oslo, was appointed in FY2011, which brings to eleven the total of HAO affiliate scientists.

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Log in

High Altitude Observatory | HAO
2011 Annual Report

HAO Annual Report

- HAO 2011 Annual Report
- Director's Message
- Executive Summary
- Table of Contents
- Understanding the Solar Dynamo
- Understanding Magnetic Flux Emergence
- Structure and Dynamics of the Corona and Heliosphere
- Terrestrial Impacts of Solar Variability
- Community Model Development
- Observational Facilities and Data Service
- HAO Visitor Program
- HAO 2011 Profiles in Science

2009-2014 Strategic Plan »

Understanding the Solar Dynamo

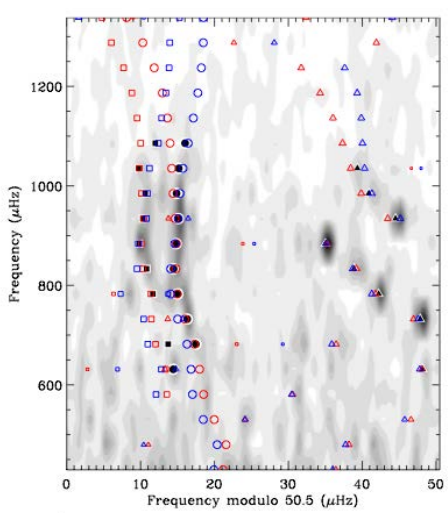
Understanding the Solar Dynamo

The magnetic fields that are responsible for various manifestations of solar activity, from the photosphere through the chromosphere to the corona, originate inside the Sun where the motion of highly electrically conducting plasma acts as a dynamo. HAO scientists carry out a comprehensive program of dynamo related research by using advanced numerical simulations of turbulent convection, studying the large scale differential rotation and meridional circulation in the Sun's interior, and investigating the interactions between these flows and entrained magnetic fields.

An ongoing challenge is to understand how ordered patterns of magnetic activity such as the sunspot cycle emerge from the highly turbulent conditions in the solar convection zone. The answer lies in complex self organization processes linking multiple spatial and temporal scales, and involving helical flows and fields, rotational shear, global circulations, magnetic buoyancy, flux emergence, and subtle boundary layers. Simulations of global solar convection demonstrate that magnetic cycles can occur in convective dynamos even without three elements that play a crucial role in most current dynamo models of the solar activity cycle, namely magnetic flux emergence, a layer at the tachocline of rotational shear, and significant flux transport by the mean meridional circulation. Rather, agents of self organization include helicity and shear, forming persistent toroidal flux structures in the midst of turbulent convection zones, defying previous theoretical expectations. Recent ground breaking simulations demonstrate that these toroidal flux structures can become buoyantly unstable, rising toward the surface. These are the first convection simulations to exhibit the self consistent generation of buoyant magnetic flux tubes by rotational shear that is maintained by the convection itself.

In flux transport dynamo models, the Sun's meridional circulation acts as a conveyor belt, where plasma flows poleward at the solar surface and returns equatorward near the base of the convection zone ("tachocline"). Just as the Earth's great oceanic conveyor belt carries thermal signatures that determine El Niño events, the Sun's conveyor belt affects the timing, amplitude and shape of a solar cycle through its transport of magnetic fields. Numerical simulations of a flux transport dynamo have demonstrated that polar fields are determined mostly by the strength of a surface poloidal source provided by the decay of tilted, bipolar active regions. The profile of a meridional flow with latitude and its change with time have much less effect on polar fields in fluxtransport dynamo models than in models focusing on the transport of magnetic flux at the solar surface. The flux transport dynamo models therefore offer a reasonable explanation to the weakening of polar magnetic fields in solar cycle 23, which were observed to be 50% smaller than those in solar cycle 22.

The base of the Sun's convective envelope is a region widely believed to play a key role in the solar dynamo. The stratification in this region is governed by processes of convective overshooting and element diffusion, and it gives rise to a characteristic signal in the frequencies of solar helioseismic p modes that has been used to determine the depth of the solar convection zone and to investigate the extent of convective overshoot. Recent physically motivated models incorporate a smooth transition in stratification bridging the region from the lower convection zone to the radiative interior beneath, providing better agreement with helioseismic data than would a standard solar model. Convectively excited gravity waves at the base of the convection zone can also be influenced by rotation and the strong toroidal magnetic field that is thought to be present. A simple model, investigating how internal waves with a vertical component of propagation are reflected when traveling through a layer containing a horizontal magnetic field with a strength that varies



with depth, found that the interaction can prevent a portion of the downward traveling wave energy flux from reaching the deep solar interior, limiting the ability of waves to influence the rotational state of the core. Additional simulations, in which the waves were forced selfconsistently by overshoot from an overlying convection zone, revealed complex behaviors produced by wave reflection and the wave field interaction. The spectrum of generated waves differed considerably from the predictions of available analytic models. The changing character of the wave field interaction resulting from distortion of the field by waves and overshoot led to significant variations in the amount of wave energy propagating into the deep radiative interior.

Figure 1. *Echelle diagram for one month of Kepler data for KIC 11026764. This diagrams is obtained by taking chunks of length the mean large separation of the modes in the power spectrum and staking one chunk on top of the other. The different ridges of the modes l=0 (circles), l=1(triangles), and l=2 (squares) can be seen. Over-plotted are the observed*

Efforts to probe the nature of the dynamo are supplemented by work aimed at detecting, measuring, and modeling magnetically induced variability in the oscillations and radiative emissions of solar type stars. Over the past two decades, helioseismology has revolutionized our understanding of the interior structure and dynamics of the Sun. Asteroseismology will soon put this knowledge into a broader context by providing structural data for hundreds of Sun like stars. As shown in Figure 1 (above), asteroseismic data from the Kepler satellite mission have been used in this way to determine the precise age and radius for the Sun like star KIC 11026764. Stellar analogues of the solar cycle can also be sought in Kepler data, through long term measurements of emission in the H and K lines of singly ionized Ca. The broad range of cycle periods observed in stellar magnetic activity variations is thought to reflect differences in the rotational properties and the depths of the surface convection zones for stars with various masses and ages. For example, the 1.6 year magnetic activity cycle in the exoplanet host star ι Hor was established: this is the shortest activity cycle so far measured for a solar type star.

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Log in

High Altitude Observatory | HAO
2011 Annual Report

HAO Annual Report

- HAO 2011 Annual Report
- Director's Message
- Executive Summary
- Table of Contents
- Understanding the Solar Dynamo
- Understanding Magnetic Flux Emergence
- Structure and Dynamics of the Corona and Heliosphere
- Terrestrial Impacts of Solar Variability
- Community Model Development
- Observational Facilities and Data Service
- HAO Visitor Program
- HAO 2011 Profiles in Science

2009-2014 Strategic Plan »

Understanding Magnetic Flux Emergence

Understanding Magnetic Flux Emergence

The strong toroidal magnetic field produced by rotational shear at the base of the convection zone is thought to be the source of buoyant flux loops that rise and emerge to form magnetic active regions on the solar surface. Subsequently, the emerged field evolves in the photosphere, chromosphere, and corona where they play a critical role in structuring and forcing into the atmospheric layers. Observational, theoretical, and numerical investigations that HAO scientists have undertaken provide a vital understanding of how the precursor structures for space weather events such as flares and coronal mass ejections (CMEs) form in the outer atmosphere as well as of the steady mass and energy transport originating from the base of the atmosphere. The main objective is to understand the emergence, growth, decay, and distribution of the surface fields on all spatial scales, their transport by diffusion and flows, the effects of the flux eruption on the surrounding and overlying atmospheric regions, and their eventual contributions to solar irradiance variability.

HAO scientists are making progress towards three dimensional global magneto hydrodynamic (MHD) simulations in which turbulent convection, stratification, and rotation are combined to yield a dynamo that self consistently generates buoyant magnetic loops for the Sun and Sun like stars. Recent steps in this direction involve simulating convection and dynamo action in a fast rotating spherical shell with solar stratification. The simulations of fast rotating Sun like stars have demonstrated that strong “wreaths” of toroidal magnetic field are formed by dynamo action in the convection zone, and that the strongest portions of those wreaths will rise to the top of the convection zone via a combination of magnetic buoyancy instabilities and advection by giant convective cells. Conversely, for the slower solar case, the effects of the convective flow will allow the inserted flux tubes with weaker field strengths (below 50 kG at the bottom of the solar convection zone) to develop emerging loops. Those loops have properties that are consistent with those observed in solar active regions.

The solar photosphere is a transition region in which the primary energy transport mechanism switches from convection to radiative transfer. At the same time, the plasma becomes partially ionized due to the lower temperatures, requiring a more complicated equation of state. The role of the magnetic field is changing too: while the gas pressure dominates the interior of the Sun, the magnetic pressure becomes the dominant contributor in or above the photosphere. Owing to the rather short density scale height, the photosphere is a highly stratified medium in which convective motions easily steepen to supersonic flows and shock waves. The combination of all these conditions makes numerical modeling of the photosphere challenging but also extremely interesting due to the strong interaction between convection, magnetic field, and radiation, and the possibility for in depth comparison with high resolution observations.

By studying the properties of sunspots HAO scientists are learning about the complexities of the photospheric interface. High-resolution simulations are carried out to investigate the connection between the fine structures of sunspot penumbrae and the subsurface magneto-convection processes that are responsive for filamentation of the penumbra and acceleration of the eponymous Evershed outward flow of materials. Simulations at lower resolutions but on larger computational domains (up to 16 Mm deep and 75 Mm wide) are also performed to study the subsurface magnetic and flow structure of sunspots, including large scale-flows in the surrounding moat region. The sunspot fine structures are illustrated in Figure 2. Developed in partnership with the NASA Solar Dynamo Observatory (SDO) Science Center at the Colorado Research Associate (CoRA), these simulations have permitted the critical validation of helioseismic structural inversions of sunspots and their surroundings.

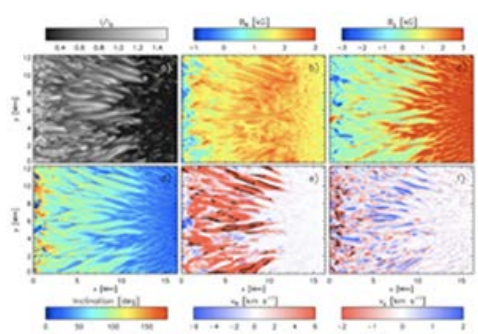

Figure 2. *Sunspot fine structure at the τ = 1 level. Quantities shown are (a) bolometric intensity, (b) radial and (c) vertical magnetic field, (d) field inclination, (e) radial, and (f) vertical flow velocities. A field inclination of 0° corresponds to vertical field with the same polarity as*

the umbra, 90° to horizontal, and 180° to vertical field with opposite polarity of the umbra. Radial outflows are displayed by red colors, solid contours indicate regions with more than 10 km s^{-1} outflow velocity. Vertical upflows are displayed by blue colors, solid contours indicate regions with more than 5 km s^{-1} downflow velocity.

The diagnosis of the prevailing magnetic conditions in the lower solar atmosphere is conducted by measuring the polarization of light emitted by magnetically sensitive spectral lines. Historically, HAO has pioneered the development and use of instruments to make such spectro-polarimetric measurements, along with techniques to infer field strength and direction from those observations. Solar physics is entering a new era of magnetic field measurements, in which emerging technologies and observations from space will revolutionize our overall understanding of the Sun's magnetism and its impact throughout the heliosphere. At the core of these investigations are the observations and detailed analysis of magnetic features as they emerge through the solar photosphere. Through involvement with the spectro-polarimeter (SP) portion of the Hinode spacecraft's solar optical telescope (SOT) instrumentation package, HAO scientists are able to study in detail magnetic flux emergence, decay, and distribution, at a range of spatial scales.

At the smallest scales, the atmosphere of the quiet sun is pervaded by an apparently turbulent magnetic field with various scale sizes extending well below the resolution of present-day instruments. The small-scale structure of solar magnetism might arise from disruption and shredding through the action of convective flows on the field of the large-scale solar magnetic cycle as a result of a dynamo operating at the base of the solar convection zone. Alternatively, it might arise from a small-scale turbulent dynamo (SSD) operating as a result of vigorous turbulent convective motions very close to the solar surface. It is important to distinguish between these two possibilities because the fields arising from a small-scale dynamo may affect the structure of the solar atmosphere independent of the solar magnetic cycle. The SSD mechanism has been suggested by numerical magneto-convection simulations, but so far there is little observational evidence confirming or refuting its presence. The high-resolution and excellent polarimetric sensitivity of the Hinode/SP has permitted observations that suggest the SSD indeed is operating in the solar atmosphere through the detailed examination of very quiet regions.

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Log in

High Altitude Observatory | HAO
2011 Annual Report

HAO Annual Report

- HAO 2011 Annual Report
- Director's Message
- Executive Summary
- Table of Contents
- Understanding the Solar Dynamo
- Understanding Magnetic Flux Emergence
- Structure and Dynamics of the Corona and Heliosphere
- Terrestrial Impacts of Solar Variability
- Community Model Development
- Observational Facilities and Data Service
- HAO Visitor Program
- HAO 2011 Profiles in Science

2009-2014 Strategic Plan »

Structure and Dynamics of the Corona and Heliosphere

Structure and Dynamics of the Corona and Heliosphere

The corona is the outermost layer of the solar atmosphere. It is the source region of the solar wind, which carries continuous plasma outflow and magnetic field from the Sun into interplanetary space, and shapes the Earth's magnetosphere. The corona's magnetic evolution leads to explosive release of energy and plasmas, such as solar flares and CMEs, causing adverse space weather disturbances in the near-Earth environment. Our research in this area aims to understand the structure, energetics, and dynamics of the corona and the solar wind.

The coronal and heliospheric research at HAO is an observationally driven program that is entering an exciting period due to greatly improved instrumentation. The observational determination of the strength and direction of magnetic fields in the corona, a measurement that has heretofore been precluded by substantial technical obstacles, is becoming routine as a result of the successful deployment of the Coronal Multi-channel Polarimeter (CoMP) instrument to the MLSO. These observations of the magnetic corona are carried out with a significant, parallel effort in theoretical studies and numerical simulations. A comparison of CoMP observations of a coronal prominence cavity to synthesized images based on an analytic, spheromak-type magnetic flux rope model is shown in Figure 3. The predicted observable of such a flux rope oriented along the line of sight is a bright ring of linear polarization surrounding a region where the linear polarization strength is relatively depleted. The CoMP observations of a coronal cavity also display the presence of a similar polarization ring. This provides strong evidence for such twisted magnetic structures that are capable of storing energy required to drive solar eruptions.

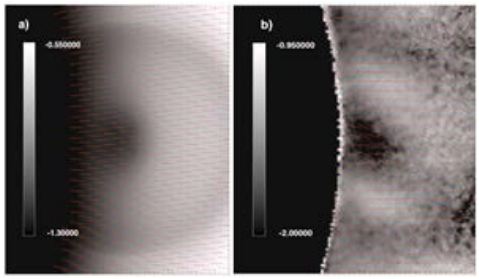

Figure 3. *Line-of-sight-integrated Stokes linear polarization P/I for (a) forward-calculated spheromak configuration and (b) CoMP observations. The ranges of the grayscale bars correspond to (a) 5–28% and (b) 1–11% linear polarization.*

The quiescent prominences within cavities are macroscopically stable and yet internally very dynamic objects. Recent observations by Hinode and at MLSO have revealed complex dynamical phenomena inside prominences, which raise questions on their magnetic nature and stability. In particular, Hinode prominence observations reveal dark and low-density "bubbles" that form, grow, and then undergo Rayleigh-Taylor instability to form dark plumes rising through the prominence into the overlying coronal prominence cavity. The nature of these bubbles, particularly their buoyancy, was hitherto unclear. Optical EUV observations of polar crown prominences from the Hinode and SDO satellites reveal that these "bubbles" contain plasma at temperatures from 250,000 K to 10^6 K, 25-100 times hotter than the prominence. This new finding is one of a growing list of significant results from simultaneous SDO and Hinode observations. The study has thus identified a source of the bubble buoyancy, suggesting that prominences are a novel form of "magneto-thermal" convection in the solar corona, challenging the current concepts of prominence magnetic equilibrium and shedding new lights into coronal cavity dynamics.

Three-dimensional (3D) magneto-hydrodynamic (MHD) models are capable of simulating realistic CME events using observational inputs for both the pre-existing coronal magnetic field and lower boundary driving conditions. MHD simulations of the coronal magnetic field evolution associated with the eruptive flare occurred on 13 December 2006 in the emerging δ-sunspot region NOAA 10930 show that the eruption can result from the emergence of an east-west-oriented twisted flux rope whose positive emerging flux "butts against" the southern end of the pre-existing negative sunspot. The simulated coronal magnetic field reproduces several key features of the eruptive flare, including the morphology of the X-ray loops and the evolution of the flare ribbons as observed by Hinode. These simulations represent initial steps towards determining the 3D magnetic field structure of CME ejecta originating from the lower

solar corona in realistic CME events.

Variations of the global solar corona and solar wind over solar cycle time scales have drawn new interest due to the recent, unusually deep, and extended solar minimum between cycles 23 and 24. The long period of low solar activity from 2006 to 2009 was characterized by weak polar magnetic fields and polar coronal holes smaller than that observed during the previous minimum. Throughout this period, structural evolution continued to be observed from the Sun through the solar wind and to the Earth. Large, low-latitude coronal holes were present on the Sun until 2008 and remained important sources of recurrent high-speed solar wind streams and geospace activity, despite that fact that solar irradiance, activity and interplanetary magnetic fields all had reached levels as low or lower than those observed in past minima. By the end of 2008, these low-latitude coronal holes started to close down, and finally disappeared in 2009, while smaller, mid-latitude holes formed in the remnants of cycle 24 active regions shifting the sources of the solar wind to higher latitudes. As the new solar cycle slowly began, the solar wind and geospace observables stayed low or continued to decline, reaching very low levels by June-July 2009. Despite this ongoing evolution, the global corona in the latest extended minimum never reached the simple dipolar configuration as seen in the past minimum in 1996, with a confined streamer belt at the equator.

The prevalent structure of small-scale quiet-sun magnetism in the outer atmosphere is the supergranular magnetic network (SMN). Using observations of He I 304Å emission from SOlar and Heliospheric Observatory (SOHO) Extreme ultraviolet Imager Telescope (EIT), STEREO's Extreme UltraViolet Imager (EUVI), and Ca IIK from the Precision Solar Photometric Telescope (PSPT), the radius of the SMN was inferred to be lower in 2009 by ~0.5Mm compared to the previous solar minimum in 1996, with a prolonged low taking place between early 2008 and late 2009. This implies that the magnetism of the quiet sun continued to evolve to smaller and smaller length scales due to the slow onset of cycle 24, which allowed the SMN to reduce in scale. Reducing the SMN scale, e.g., the length scale over which mass and energy are magneto-convectively driven into the quiet outer solar atmosphere, will have an impact on the energetics of the quiescent outer atmosphere such as the quiet sun and coronal holes at the root of the fast solar wind. In situ particle measurements from the Wind and ACE spacecraft confirmed that the amount of Helium in the fast solar wind was reduced by almost a factor of two in the middle of 2009. Moreover, the mean charge state of Iron in the fast solar wind was reduced by one ionization stage from 9+ to 8+, precisely when the SMN scale was at its smallest, consistent with a sizeable reduction in the energy output of the lower atmosphere at that time. This is consistent with a diffusion of the magnetic field in the SMN to smaller length scales during the 2009 solar minimum, implying that the number of small flux concentrations that comprise the SMN vertices themselves was reduced and, as such, was the root cause for the drop of plasma energetics in the lower solar atmosphere.

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Log in

High Altitude Observatory | HAO
2011 Annual Report

HAO Annual Report

- HAO 2011 Annual Report
- Director's Message
- Executive Summary
- Table of Contents
- Understanding the Solar Dynamo
- Understanding Magnetic Flux Emergence
- Structure and Dynamics of the Corona and Heliosphere
- Terrestrial Impacts of Solar Variability
- Community Model Development
- Observational Facilities and Data Service
- HAO Visitor Program
- HAO 2011 Profiles in Science

2009-2014 Strategic Plan »

Terrestrial Impacts of Solar Variability

Terrestrial Impacts of Solar Variability

The Earth's mesosphere, thermosphere, ionosphere and magnetosphere comprise the interface region where the dense neutral atmosphere transitions to the tenuous and ionized environment of geospace. The region is directly influenced by the Sun through the absorption of solar UV/EUV and X-ray radiation as well as interaction between the solar wind and the magnetosphere. It is also affected by waves and tides resulting from meteorological weather. HAO's research in this area focuses on interactions between the different regions, with particular emphases on developing advanced numerical models of the upper atmosphere/magnetosphere, its response to variable solar output, and its coupling with the lower atmosphere.

Solar flares are impulsive releases of solar radiative energy, particularly in the X-ray and UV/EUV wavelengths, which are primarily absorbed in the thermosphere and ionosphere. Model simulations show that thermospheric and ionospheric responses differ significantly as a function of the rise and decay rates for flares with the same magnitude and location. The so-called "Neupert Effect," which predicts that a faster flare rise time leads to a larger EUV enhancement during the impulsive phase, causes a larger maximum ion production enhancement. Model simulations also show that increased E´B plasma transport due to increases in conductivity during the flares can cause a significant equatorial anomaly feature in the electron density enhancement in the F region but a relatively weaker equatorial anomaly feature in the total electron content (TEC) enhancement, owing to the dominant contributions by photochemical production and loss processes. The latitudinal dependence of thermospheric response correlates well with the solar zenith angle effect; whereas the latitudinal dependence of ionospheric response appears to be more complex due to plasma transport and the winter anomaly.

The upper atmosphere is strongly modulated by tides and waves from the lower atmosphere. Analysis of mesospheric wind observations from the TIMED Doppler Imager (TIDI) shows that the semidiurnal tide westward zonal wavenumber 1 (SW1) has a peak near the South Pole during the December solstice and near the North Pole during the March equinox whereas the semidiurnal tide westward zonal wavenumber 2 (SW2) peaks at 60°S and 60°N mostly during winter solstices. The effect that the quasi-biennial oscillations (QBO) have on the semidiurnal tide is found to be much weaker than that on the diurnal tide. The March equinox northern SW1 zonal amplitude appears to be stronger during the westward phase of the QBO, which is opposite to the migrating diurnal tide QBO response. Possible sudden stratospheric warming (SSW) event-related changes in the semidiurnal tide are significant but not always consistent. Enhancements in the mid-latitude SW2 component are observed, which may be related to the increase of total ozone at mid and high latitudes during SSW events. The TIDI observations also show a decrease in the SW2 in the opposite hemisphere during a southern SSW event in 2002, and a small increase in the SW1 was recorded in both hemispheres.

The quasi two-day wave (QTDW) zonal wavenumber 3 planetary wave is a recurrent wave feature in the mesosphere and lower thermosphere. The QTDW exhibits strong seasonal variability with peak amplitudes after summer solstice. In late January/early February, satellites also discovered two strong enhancements of the QTDW in meridional wind, with one peak at summer mid-latitudes near 90 km and the other in the tropical lower thermosphere. Studies using the Thermosphere-Ionosphere-Mesosphere Electrodynamics General Circulation Model (TIME-GCM) together with the wave forcing prescribed at the lower model boundary have demonstrated that baroclinic/barotropic instability is capable of amplifying the QTDW, manifesting as Eliassen-Palm (EP) zonal momentum flux divergence in the summer mesosphere. In the summer middle atmosphere, the wave amplitude grows substantially, like an internal wave in the regions of large refractive index.

Meteorological events such as SSWs have attracted substantial research interest in recent years due to extensive observations as well as solar minimum conditions that effectively suppressed solar forcing from above while facilitating meteorological forcing from below. Figure 4 depicts gravity-wave variations during the 2009 SSW event in the Arctic based on the European Center for Median-Range Weather Forecasting (ECMWF) model. It is found that the

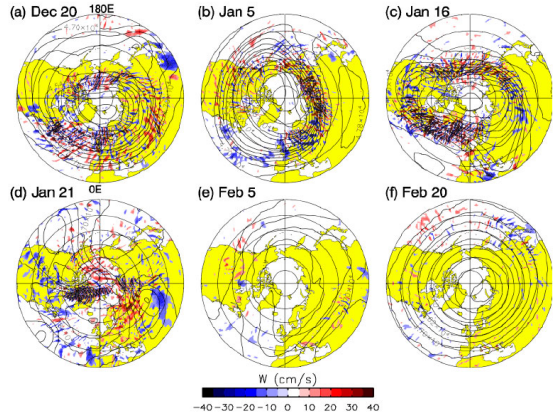

Figure 4. *Evolutions of gravity waves during the 2009 SSW are shown here. Gravity wave enhancements on Jan 5 and 16 and suppressions of gravity waves after the peak SSW (on Jan 21) are clearly displayed. Filled and line contours represent the vertical wind (cm/s) and geopotential height (m), respectively, at 1 hPa on (a) Dec. 20, (b) Jan. 5, (c) Jan. 16, (d) Jan. 21, (e) Feb. 5, and (f) Feb. 20. Geopotential height line contour interval is 400 m. Only vertical winds larger than ±8 cm/s are plotted.*

occurrence and magnitude of gravity waves correlate with the location and strength of the polar vortex that is strongly disturbed by planetary wave (PW) growth. This location dependence on PW phase explains the observed gravity-wave variability during SSW. During the development and the onset of SSW, the zonal-mean gravity wave potential energy density (GW-Ep) increases on January 5 and then on January 15–22 in association with the growth of PW wavenumber 1 and wavenumber 2, respectively. As the initial prominent PW magnitude in the lower mesosphere progresses downward, GW-Ep enhancement also seems to show a corresponding descent from January 5–22. GW-Ep peaks before the wind reversal occurrence and significantly weakens after the SSW. These variations are confirmed by COSMIC/GPS observations. Lidar data from Antarctica also provide validation of gravity waves as derived in ECMWF. This research reveals that the gravity-wave enhancements prior to the 2009 SSW are strongly tied to the increase of gravity-wave excitation through residual forcing in the stratosphere. Decay of gravity waves after the 2009 SSW is most likely caused by the changes in gravity-wave propagation and reduction of in-situ gravity-wave sources by unbalanced flow.

Recently, we undertook an effort to extend the gravity-wave parameterization scheme in the Whole Atmosphere Community Climate Model (WACCM) by including the Coriolis effect in order to better describe inertia-gravity waves (IGW). WACCM simulations with the new parameterization have demonstrated that the QBO can be internally generated through properly selecting the parameters of the scheme. The characteristics of the simulated QBO are found to be consistent with observations. The study demonstrates that the parameterized IGW forcing is capable of generating equatorial wind oscillations with a downward phase progression in the stratosphere using the standard spatial resolution settings in the current model. The period of the oscillations depends on the strength of the IGW forcing, and the magnitude of the oscillations depends on the width of the wave spectrum. The new parameterization affects the wave breaking level and acceleration rates mainly through changing the critical level.

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Log in

High Altitude Observatory | HAO
2011 Annual Report

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HAO Annual Report

HAO 2011 Annual Report
Director's Message
Executive Summary
Table of Contents
Understanding the Solar Dynamo
Understanding Magnetic Flux Emergence
Structure and Dynamics of the Corona and Heliosphere
Terrestrial Impacts of Solar Variability
Community Model Development
Observational Facilities and Data Service
HAO Visitor Program
HAO 2011 Profiles in Science

2009-2014 Strategic Plan »

Community Model Development

Community Model Development

HAO develops large-scale, computational community models that support community research in upper atmospheric, ionospheric, and magnetospheric physics. It is one of HAO's strategic imperatives to advance world-leading numerical models of the atmosphere and Sun-Earth system, make them widely available, and support their use by the scientific community. HAO models include the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (**TIE-GCM**), the Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (**TIME-GCM**), and the Whole Atmosphere Community Climate Model (**WACCM**), and the Coupled Magnetosphere-Ionosphere-Thermosphere (**CMIT**) model developed as part of the Center for Integrated Space Weather Modeling (**CISM**), which is an NSF Science and Technology Center led by Boston University. WACCM is an inter-divisional collaboration that unifies aspects of the upper atmospheric modeling of HAO, the middle atmosphere modeling of NESL's Atmospheric Chemistry Division, and the tropospheric modeling of NESL's Climate and Global Dynamics Division, using the Community Climate System Model (**CCSM**) as a common numerical framework. The high-altitude extension, referred to as "WACCM-X," is the particular responsibility of HAO.

Development of the TIE-GCM version 1.94 was concluded in FY2011. The model was tested and compared to various thermosphere/ionosphere measurements, and it was released to the community in June 2011. The key feature of this new version is the inclusion of the Weimer model of high-latitude electric potential imposed by the magnetosphere, which enable the TIE-GCM to be run using solar wind and interplanetary magnetic field as input drivers. Auroral precipitation patterns corresponding to the Weimer model, and a new variable location of the cross-over latitudes between high- and low-latitude electric potentials, are included in the new release, as well as several standardized diagnostic fields, various new minor features, and some bug fixes.

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High Altitude Observatory | HAO
2011 Annual Report

HAO Annual Report

- HAO 2011 Annual Report
- Director's Message
- Executive Summary
- Table of Contents
- Understanding the Solar Dynamo
- Understanding Magnetic Flux Emergence
- Structure and Dynamics of the Corona and Heliosphere
- Terrestrial Impacts of Solar Variability
- Community Model Development
- Observational Facilities and Data Service
- HAO Visitor Program
- HAO 2011 Profiles in Science

2009-2014 Strategic Plan »

Observational Facilities and Data Service

Observational Facilities and Data Service

- **Mauna Loa Solar Observatory (MLSO)**

MLSO is an NSF-funded facility of NCAR and operated by HAO. It provides observations of the Sun's atmosphere in support of the solar and space weather goal of understanding the Sun's continuous release of plasma and energy into interplanetary space and its impact at Earth. HAO is committed to providing the community with critically important, high-quality, solar observations. MLSO is located at 11,200 feet on the northern flank of Mauna Loa on the island of Hawaii. MLSO currently houses five instruments that acquire unique observations of the Sun from the photosphere through the corona, which provide information needed to understand the Sun's continuous release of plasma and energy into interplanetary space. In 2010, CoMP was deployed to MLSO to provide the first routine measurements of the coronal magnetic field, which are now available from the MLSO home page. HAO also maintains the Global Oscillation Network Group (GONG) site, which was upgraded in July 2010 to include a full disk H-alpha imager that acquires images every minute. The observations are now served real-time from both the GONG and the MLSO home pages. HAO plans to relocate its current Coronado H-alpha telescope to its new Mesa Lab spar in Boulder for education and public outreach groups to observe the solar chromosphere. Additional changes involving MLSO and its data services include: (1) improved calibration of all Mk4 K-coronameter images; (2) the addition of an historic total solar eclipse archive served from the MLSO website that includes digitized images of solar eclipses dating back to 1869 to study the morphology of the solar corona over multiple solar cycles; (3) high-speed internet upgrade to 25 Mbps (from 1.3 Mpbs) that allows all data, including the new CoMP and GONG Ha data to be transmitted in real-time to optimize data usage for better space weather prediction operations; (4) new formatted CME event lists that provide easier-to-use tables for CME studies; and (5) a featured events web-page that includes movie highlights of solar activity and other solar-related phenomena.

The MLSO database serves the broad solar community both nationally and internationally. It currently has 485 registered users from 37 countries, with 179 new registered users since 2009. The total number of users is unknown since registration is not required to download MLSO observations. The MLSO community breakdown is as follows:

National Universities and Colleges:	99 users from 40 institutions
National Labs/ Observatories:	84 users from 23 institutions
Intl. Universities and Colleges:	91 users (50 Univ. in 23 countries)
Intl. Labs / Observatories:	106 users (53 labs, 20 countries)
Other Education/Public Outreach:	16 users from 3 countries
Individuals/ Unidentified:	87 users
Industry:	2 users

Coronal Multi-channel Polarimeter (CoMP): The CoMP instrument was deployed to MLSO in February 2010, and commissioned in October 2011. The instrument is now taking routine measurements of coronal magnetic fields and serving these data to the community in real-time via the MLSO website. The public launch of the CoMP data took place at the July 2011 SHINE meeting in Snowmass, CO.

K-coronagraph: HAO is designing and fabricating a new K-coronagraph, the first element of the Coronal Solar Magnetism Observatory (COSMO) supported by NSF special funding. The COSMO K-coronagraph

Figure 5. *(Left) MLSO data holdings.*
(Right) Publications led by scientists at HAO (blue) and in other organizations (red). Note that the numbers for Year

(COSMO K-Cor) will be deployed to the Mauna Loa Solar Observatory in 2013 to replace the aging Mk4 K-coronameter. COSMO K-Cor successfully completed its Preliminary Design Review (PDR) in August 2011. A panel of coronagraph and optical experts from the National Solar Observatory, the Naval Research Lab and the Earth Observing Lab/NCAR reviewed the COSMO K-Cor preliminary design. The panel was pleased with the quality and detail of the presentations. The panel noted that COSMO K-Cor is poised to successfully address its science goals and provide the highest quality images of the low corona ever recorded.

Considerable progress has been made since the PDR. The optical design has successfully completed its critical design review (CDR) and optical elements are currently being purchased. The mechanical and opto-mechanical designs will be ready for a CDR in January 2012. Design and fabrication of COSMO K-Cor are expected to complete by the end of FY12 when it will be deployed to the Mesa Lab HAO dome facility for optical alignment and calibration testing. Final deployment to the Mauna Loa Solar Observatory and commissioning is on schedule for summer of 2013.

The CEDAR database provides long-term service of various data sets, numerical model outputs, as well as geophysical indices and tools needed for data interpretation. HAO became a Madrigal node in September 2009, and Barbara Emery has been the madrigal manager at HAO since November 2010. About 4GB of recent ISR data sets from Jicamarca, Arecibo, Millstone, Sondrestrom, and the new ISR at Poker Flat were added to the CEDAR database in FY2011. Another 35GB of global total electron content (TEC) data from the GPS satellites were also added to the database. Some data formats and codes have been revised during FY2011 in order to successfully access these madrigal files via the Virtual Solar-Terrestrial Observatory (VSTO) in June 2011. Other data sets updated in the regular CEDAR Database include geophysical indices, the Colorado State sodium lidar data provided by Joe She, the Arecibo potassium lidar data from Jonathan Friedman, and the daily global estimates of neutral density derived from satellite drag measurements. Database statistics have been collected on-line since 2009. Statistics are also available on-line, and have shown that usage is picking up after a low point in 2010. Figure 7 shows the user and data holding statistics from 2005 to September 2011.

2011 are for the first 9 months through September.

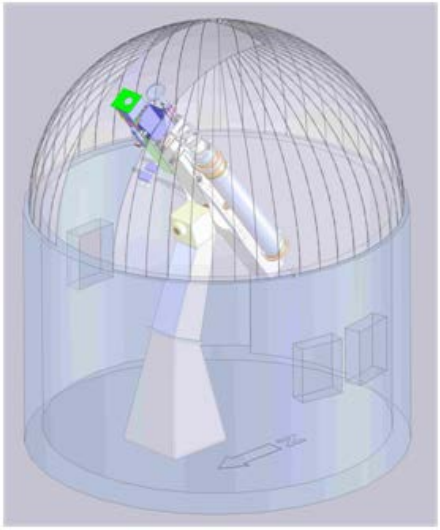

***Figure 6**. A mechanical design of the K-coronagraph on the spar in the Mauna Loa dome.*

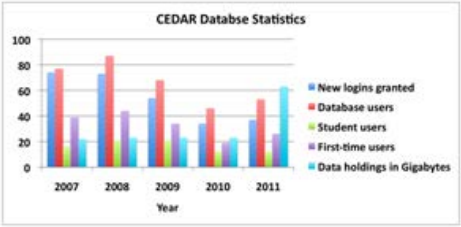

***Figure 7.** CEDAR database user and data holding statistics from 2005 to September.*

- **Community Spectro-polarimetric Analysis Center (CSAC)**

CSAC is an HAO imperative activity that provides the worldwide community with resources for analyzing the Stokes polarimetry measurements of remotely sensing magnetic fields in the lower solar atmosphere. The tools provided by CSAC allow users to perform data reduction and calibration in order to extract the magnetic field vector and associated thermodynamic properties from the observed data. Users can also display and manipulate the derived vector magnetic fields. Over the past year CSAC has focused on maintaining the Hinode/SP data archive, distributing the reduced data and "inverted" vector magnetograms through its own web interface and through several community/mission archives. CSAC has published the IDL interactive data analysis tool to the community, which permits the user to explore the information-rich SP datasets. CSAC has produced documentation on the Hinode/SP instrument and on the data reduction package of its Hinode/SP effort, and it is now in the process of documenting the inversion algorithm named the Milne-Eddington gRid Linear Inversion Network (MERLIN). The code is designed to invert the SP measurements into the vector magnetic field

- **Design of the Visible Spectro-Polarimeter (ViSP)**

ViSP is a spectro-polarimeter designed at HAO for NSF's Advanced Technology Solar Telescope (ATST). In January, HAO successfully completed a 15-month effort for the Preliminary Design Review (PDR) of the

ATST/ViSP. In September, the ATST management conducted a project-wide budget review to address ways to fulfill instrumentation needs on a reduced budget. HAO successfully met the goals of this meeting, leading to the next contractual phase for the construction of the ViSP.

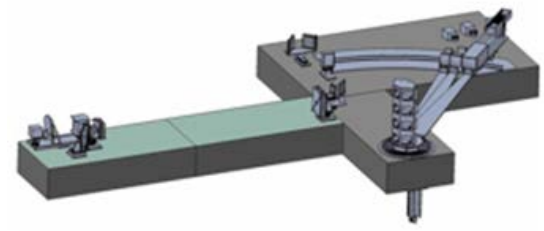

Figure 8. *The post-PDR design of the ATST/ViSP.*

HAO has also broadened its official participation to the ATST. Early in FY11, the ATST created a Polarization Working Group to address polarimetry questions about the telescope and the instruments. HAO is a member of this group, and has now attained a primary role in the design of polarization optics for the ATST. HAO's participation to the ATST project, through both science definition and instrumentation development, has triggered a series of studies to assess the feasibility of the project's science goals and the definition of the corresponding instrument requirements.

- **Prominence Magnetometer (ProMag)**

A crucial component in HAO's program on flux emergence and studies of its impact on the outer solar atmosphere is the development of the next generation of spectro-polarimeters and imaging spectro-polarimeters. The first instrument of the new line is the ProMag, which was deployed at the National Solar Observatory (NSO) Evans facility at the Sacramento Peak Observatory in early 2011. ProMag is now operation as a facility instrument with a dedicated observer, and is designed to provide new insight into the magnetic structure and evolution of prominences above the solar limb by studying the linear and circular polarization states in a number of strong chromospheric lines. In addition, ProMag will provide insight into the stability criteria of these structures that often produce significant space weather effects. ProMag is transitioning to science operations at the NSO, with support from the Air Force Office of Scientific Research (AFOSR) that has made possible to hire a resident instrument scientist and observer to operate the instrument through June 2014. The instrument is currently undergoing a re-design phase aimed at improving the implementation of dual-beam polarimetry.

Figure 9. *The Prominence Magnetometer (ProMag) installed on the Evans Coronagraph at NSO.*

- **Development of the Coronal Solar Magnetism Observatory (COSMO) and Chromospheric Magnetograph (ChroMag)**

MLSO has been collecting synoptic coronal data for over 40 years in support of the solar and heliospheric community. Driven by society's need to understand the origins of space weather, NCAR scientists at HAO, along with colleagues at the University of Hawaii and the University of Michigan, proposed to the NSF to build the COSMO instrument suite. The facility will take continuous synoptic measurements of the entire corona in order to understand solar eruptive events that drive space weather and to investigate long-term and solar-cycle phenomena. The primary instrument will consist of a large 1.5-meter coronagraph with two detector systems: a narrow-band filter polarimeter and a spectro-polarimeter. Supporting instruments are a white-light coronagraph (K-Cor) to record the evolution of the electron-scattered corona (K-corona) and a chromosphere and prominence magnetometer called ChroMag.

COSMO ChroMag will be HAO's first attempt to produce a synoptic imaging spectro-polarimeter to diagnose the evolution and dynamics of the crucial chromospheric interface between the photosphere and corona. HAO is proceeding with the construction of a prototype ChroMag instrument. It is our intent that the prototype will be deployed at the new spar facility at the Mesa Lab in early 2012. This prototype ChroMag will be capable of making full-disk polarimetric observations of several emission lines, including the 587.6 and 1083 nm spectral lines of He I, the 656.3 nm line of Hα, the 854.2 nm line of Ca II, and the 617.3 nm line of Fe I. It scans through these lines at high cadence (< 1 minute), and at moderate spatial resolution of about 2 arcsec. COSMO ChroMag will provide valuable context for existing and forthcoming space missions in addition to providing valuable chromospheric magnetograms for community MHD modeling efforts.

- **High-altitude Interferometer WIND experiment (HIWIND)**

HIWIND is a NASA-funded stratospheric balloon-borne Fabry-Perot Interferometer (FPI). It is designed to measure thermospheric neutral winds by monitoring Doppler shift in the O 630 nm airglow emission during both daytime and night. The HIWIND balloon was successfully launched on 14 June 2011 from Kiruna, Sweden. It ascended about 26 miles (43 kilometers) into the atmosphere and headed west across the Atlantic Ocean, passing above Greenland on its way to

Canada in round-the-clock sunlight. The flight was terminated on June 17 and the payload landed with a parachute descent 300 miles northeast of Cambridge Bay in Canada. The experiment obtained very high quality daytime thermospheric wind data for the first time in 16 years. A proposal has been submitted to NASA to re-fly HIWIND in the near future

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High Altitude Observatory | HAO
2011 Annual Report

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HAO Annual Report

HAO 2011 Annual Report
Director's Message
Executive Summary
Table of Contents
Understanding the Solar Dynamo
Understanding Magnetic Flux Emergence
Structure and Dynamics of the Corona and Heliosphere
Terrestrial Impacts of Solar Variability
Community Model Development
Observational Facilities and Data Service
HAO Visitor Program
HAO 2011 Profiles in Science

2009-2014 Strategic Plan »

HAO Visitor Program

HAO supports an extensive visitor program. The HAO visitor program attracts a diverse group of university students and early career scientists and engineers. Key metrics include the actual numbers of postdoctoral visiting scientists, graduate research assistants, affiliate scientist visits and short-term and middle-term scientific visitors we attract into the program. In 2011, HAO appointed one new affiliate scientist, Prof. Viggo Hansteen of the University of Oslo, bringing our total complement of affiliate scientists to eleven. In FY2011, HAO supported 11 postdocs and 4 graduate research assistants (GRAs) to carry out their research under the supervision of HAO scientific staff. HAO also hosted 7 affiliate scientists and 123 other visiting scientists (among them 49 were student visitors). Figure 10 shows the numbers of workshop and visitors hosted by HAO from 2005 till September 2011.

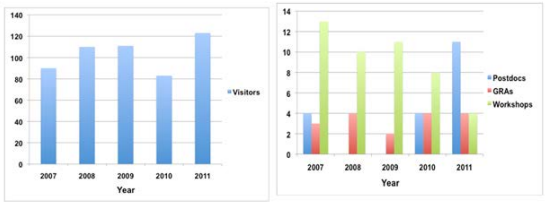

Figure 10. *HAO Visitor Program statistics from 2005 to September 2011.*

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HAO 2011 Profiles In Science

- Joan Burkepile
- Alan Burns
- Roberto Casini
- Rebecca Centeno-Elliott
- Ingrid Cnossen
- Alfred de Wijn
- Giuliana de Toma
- Mausumi Dikpati
- Barbara Emery
- Yuhong Fan
- Sarah Gibson
- Phil Judge
- Delores Knipp
- I-Te Lee
- Bruce Lites
- Hanli Liu
- Boon Chye Low
- Gang Lu
- Astrid Maute
- Savita Mathur
- Scott McIntosh
- Mark Miesch
- Liying Qian
- Matthias Rempel
- Arthur Richmond
- Stan Solomon
- Michael Thompson
- Steven Tomczyk
- Wenbin Wang
- Michael Wiltberger
- Qian Wu
- Chihoko Yamashita
- Liang Zhao

Annual Reports

HAO 2011 Lab Annual Report

NCAR Annual Report Links

Awards

2011 Mentoring Award

Profiles In Science

2010 Profiles In Science

2012 Profiles In Science

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Earth Observing Laboratory | EOL
2011 Annual Report

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EOL Annual Report

- Director's Message
- Executive Summary
- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Director's Message

Director's Message

Vanda Grubišić, EOL Director

Welcome to the FY2011 Earth Observing Laboratory (EOL) Annual Report.

It is my pleasure to write these introductory words to this annual report, which summarizes many of our accomplishments in what was both a busy year and a year of change for the Laboratory.

Since January 2010, when Roger Wakimoto bid his farewell to EOL to assume the directorship of NCAR, Sue Schauffler was at the helm of the Laboratory as the Interim Director. She selflessly performed this role until July 2011 when I joined the NCAR team as the NCAR Associate Director for EOL. We are grateful to Sue for her compassionate leadership of EOL in this fairly long interim period.

It is an honor and privilege to be the seventh director of this extraordinary organization, which for more than 40 years has been providing world-class observational facilities, field support and research services to the NSF-funded user community. In fulfilling its mission to *"develop and deploy observing facilities and provide data services needed to advance scientific understanding of the earth system,"* EOL has enabled and actively contributed to significant progress in the atmospheric sciences. Known for its can-do spirit, EOL is an organization of more than 180 devoted individuals who find their calling in providing service to the community and in making sustained efforts toward continued success of this unique end-to-end observational science enterprise. I am fortunate and humbled to lead this team.

Many exciting activities and accomplishments are described in this Laboratory Annual Report. Let me highlight here only a few with congratulations to the EOL staff who has been involved in them:

- During this past year, the National Science Foundation (NSF) conducted an external scientific review of NCAR, which included EOL. The review of EOL was very positive. The NSF Site Visit Team (SVT) found EOL to be *"fundamental to NCAR"* and *"a highly capable organization that has demonstrated excellence, strong commitment and high performance in its mission to serve the broad atmospheric science."*
- The end of FY2011 marked the formal end of the Major Research Equipment and Facilities Construction (MREFC) award for HIAPER. All planned airframe and infrastructure modifications for the NSF/NCAR GV aircraft, as well as the fourteen HAIS instrumentation projects, are now complete and FAA certified, ready to be used by the community.
- An EOL team, led by Terry Hock, won the 2011 Colorado Governor's Award for High-Impact Research for innovation and transformation over the last five years of dropsonde technology and its delivery systems.

I invite you to review other remarkable Laboratory activities and accomplishments presented in the following pages.

Vanda

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Earth Observing Laboratory | EOL
2011 Annual Report

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EOL Annual Report

- Director's Message
- Executive Summary
- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Executive Summary

For 50 years, NCAR has been charged by the National Science Foundation with providing observing facilities and associated services for the community of university atmospheric scientists, with the understanding *"that the extent of such an [effort] requires facilities and technological assistance beyond those that can properly be made available at individual universities"* (NCAR "Blue Book," 1959) Much of this part of the NCAR charge now rests with the Earth Observing Laboratory (EOL), which defines its mission to be:

To develop and deploy observing facilities and provide data services needed to advance scientific understanding of the earth system.

When EOL wrote its Laboratory Strategic Plan in 2009 we framed our activities as a lab in the context of our mission statement, which is further encapsulated in our "Four Ds": Deployment, Development, Data Services and Discovery. This annual report describes the efforts EOL undertook in 2011 to carry out the objectives described in its Strategic Plan.

Deployment

Jasna Pittman (Harvard University) fine tuning an instrument used on the NSF/NCAR GV during HIPPO. (©UCAR, photo by Carlye Calvin.)

Deployment activities in EOL are encompassed by two separate Imperatives in our Strategic Plan: **Imperative I**, to *"Maintain the EOL facilities that are deployed using NSF "deployment pool" funds so that they are ready for reliable and safe operation in anticipated field programs;"* and Imperative II, *"Support observing needs of research programs at a level that serves NSF, university, and NCAR program needs."*

EOL works each day to maintain and improve the NSF Lower Atmospheric Observing Facility (LAOF) resources with which we are entrusted, and to ensure their safe and reliable operation for deployment. Several of these activities are described in Imperative I.

EOL's support of these NSF LAOF naturally extends to the field phase, and this is encompassed in Imperative II. We describe eight field programs conducted in FY 2011 in the **Imperative II section**, including the fourth and final fifth phase of the landmark HIAPER Pole-to-Pole Observations (HIPPO) Campaign, which deployed the NSF/NCAR GV Research Aircraft in the first comprehensive, global survey of the distribution of greenhouse gases and black carbon in the atmosphere. EOL also participated in studies involving winter storms, winter pollution, and polar regions/climate change.

Development

EOL's Development activities are described by **Imperative III** of our Strategic Plan: *"Anticipate future needs resulting from changing priorities, aging equipment or emerging opportunities, and develop new technology (instrumentation, software, and infrastructure) to meet those needs."*

EOL's FY 2011 Developments included: the testing

An extremely high-profile instrumentation development effort in FY 2011 was the advancement of dropsonde technology that enables this perennially-requested instrument to be used in even the newest unmanned airborne platforms.

and completion of the next generation Airborne Vertical Atmospheric Profiling System (AVAPS) Dropsonde system; the Laser Air Motion System (LAMS); the Compact Atmospheric Multi-species Spectrometer (CAMS); the delivery and testing of the final HIAPER Airborne Instrumentation Solicitation instruments; and the addition of Ka-band radar to the S-Pol radar. These developments ensure that EOL is well-positioned to meet immediate and near-horizon community needs.

Many of EOL's Development efforts are contained in our Frontiers, the focus of which is on emerging opportunities or developing needs in the atmospheric science community that EOL could target. In FY 2011 EOL addressed some of our Frontiers through continued exploratory work on the feasibility of developing a Phased-Array Radar that is envisioned to replace the ELDORA airborne radar; construction and testing of an innovative modular 449 MHz wind profiler network to expand and replace our 915 MHz boundary-layer wind profiling capability; and forging a new partnership with the Montana State University to create a water vapor DIAL instrument.

Data Services

EOL is committed to data processing, quality control, and archival for field projects, which are parts of our expanding services that will be provided to the community, as expressed in **Imperative IV**: *"Provide comprehensive data services, open access, and long-term stewardship of data."* This includes efforts to complete development of the Metadata Database and Cyberinfrastructure (EMDAC) to access and browse products and data from field projects while integrating with the Community Data Portal.

Discovery

EOL field campaigns often offer students or the general public a chance to learn about our instruments and platforms, such as this tour at the San Juan airport during the ICE-T campaign. (Photo by Alison Rockwell.)

EOL strives to promote curiosity about Atmospheric and Earth sciences and to inspire development of the next generation of observational scientists and engineers. This is integral to **Imperative V**: *"Attract and inspire new generations of scientists, engineers and the general public to atmospheric science, conveying the excitement and intrinsic value of observational research."*

In FY 2011 EOL was active in a number of Education and Outreach activities, including seven educational deployments, participation in a large number of school and school group visits, and support for secondary school teachers, including climate study in their science curriculums. FY 2011 was also another record year in terms of applicants for EOL's Summer Undergraduate Engineering Internship Program (SUEIP), which focuses EOL's outreach efforts on the engineering community in a manner analogous to what UCAR/NCAR currently does for young scientists.

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- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Imperative I

Maintain the EOL Facilities that are Deployed Using NSF "Deployment Pool" Funds so that they are Ready for Reliable and Safe Operation in Anticipated Field Programs

Robust performance of weather, climate, and chemistry models depend on accurate observations and measurements. EOL's central mission, and our first Imperative, is the maintenance of NSF-funded Lower Atmospheric Observational Facilities (LAOF) for research in atmospheric science, with emphasis on systems that are beyond the capabilities of most universities or smaller groups.

The fulfillment of Imperative I drives countless day-to-day efforts to preserve and consistently improve the NSF LAOF resources with which we are entrusted, and to maintain their readiness for our vigorous deployment schedule (see **Imperative II**). In the preparations for each field campaign, all EOL instrumentation slated to deploy undergoes exhaustive testing by our engineers and technicians to ensure optimal performance during the campaign. After the field phase commences it often becomes necessary to make adjustments to overcome difficult or unforeseen environmental conditions in order to meet the Principal Investigators' (PIs') scientific objectives for the experiment.

S-Pol Radar

Deployed for the first time in 1996, the S-band Dual Polarization (S-Pol) Doppler Radar remains a one-of-a-kind, dual-polarimetric, 10-cm weather radar. S-Pol's flexible design makes it unique in that it can support different operating modes and advanced waveforms for researchers to choose from. Housed in eight standard-sized sea containers, the radar is transportable and can be deployed to remote locations around the world; previous deployment locations include Brazil, Italy, Barbuda, and Taiwan. S-Pol provides necessary measurements of cloud and precipitation microphysics and dynamics, ultimately leading to improved forecasting of cloud and precipitation formation, severe storms, tornadoes, floods, hail, damaging winds, aircraft icing conditions, and heavy snow.

The NSF/NCAR S-PolKa Radar set up for operations in support of the DYNAMO field campaign. (Photo courtesy of Scott Ellis, NCAR.)

In FY 2011 several improvements to S-Pol were made in preparation for its deployment in June 2011 to the Maldives for the Dynamics of the FY 2012 Madden-Julian Oscillation (DYNAMO) field campaign. Remote status monitoring software was completed for the radar, which will allow technicians to monitor the antenna, transmitter, data, and hardware from a remote location, and which will actually page an off-site technician in the event any of these are performing outside expected parameters. The radar was also deployed with new remote operations capabilities, including remote restart of the system should it stall, and operators can set radar scans. Hardware was also purchased for the centralized data archiving.

Another major upgrade to EOL's remote sensing capabilities in 2011 was the development of a Ka-band (0.86 cm) wavelength radar for S-Pol (called S-PolKa when the Ka-band is installed), which was needed to meet PI requirements for simultaneous dual-wavelength measurements for DYNAMO. The concurrent dual-polarization measurements provided by S-PolKa will allow scientists to infer microphysical properties in precipitation systems. More discussion of the Ka-band development can be found under **Imperative III**. Once the S-Pol radar returns from DYNAMO we will begin preparing it for operations as part of the Front Range Observational Network Testbed (FRONT). Discussion of this activity can be found in **Frontier IV**.

ELectra DOppler RAdar (ELDORA)

The ELDORA Radar mounted on the tail of the NRL P3 Research Aircraft.

ELDORA, NCAR's airborne dual-Doppler 3-cm (10 GHz) weather radar, was designed and built for installation on the NSF/NCAR Electra aircraft in 1993. Now available on a Naval Research Laboratory P3 aircraft, ELDORA is still the most sensitive airborne X-band tail weather radar available to the research community.

Its primary mission has been to collect high-resolution dual-Doppler winds and reflectivity (cloud and/or precipitation) for kinematic and dynamic studies of mesoscale precipitation systems. ELDORA's mobility is particularly advantageous in observing large mesoscale weather systems in remote regions over land or over the ocean. Since 1993, ELDORA has been deployed in nine domestic and international field campaigns on four continents and over three oceans, most recently during the T-PARC campaign.

In FY 2011 improvements were made to extend the life of this aging instrument, even as development of the "next generation ELDORA" – Phased Array Radar – is underway (see **Imperative III**). Modules for an automated ELDORA Data Quality Control (QC) and navigation corrections were developed in 2011 as well.

NSF/NCAR GV HAIS Instruments

Expanding EOL's current suite of airborne instruments to provide the community with a comprehensive selection of unique state-of-the-art measurement capabilities has been a major focus for EOL since the acquisition of the GV. The acquisition of the HIAPER Airborne Instrumentation Solicitation (HAIS) instruments, an assortment of 14 different equipment packages that were developed by groups outside of EOL for delivery and operation on the GV, has played a significant role in the final configuration of the GV and its value to science. The delivery and acceptance of the HAIS instruments, overseen by GV Chief Scientist Al Cooper, was completed in 2011, and the final three instruments were tested on the required HAIS Instrument Test Flights. Many HAIS instruments have already participated in recent field campaigns such as HIPPO and PREDICT, and several will be essential to upcoming proposed field campaigns such as the Deep Convective Clouds and
Chemistry (DC3) project and the Southeast Asia Composition, Cloud, Climate Coupling Regional Study (SEAC4RS). The realization of the full potential of the GV would have not have been possible without the involvement of the community to understand and develop these new airborne instruments, and the excellent collaboration and partnership between EOL and the respective instrument providers.

Instrument Name	Developer	Description
Ver tical Cavity Surface Emitting Laser Hygrometer (VCSEL)	Zondlo SW Sciences	Measurements of water vapor concentration at a minimum rate of 25 sps over the entire range of the troposphere and lower stratosphere.
Small Ice Detector, Ver sion 2 (SID-2H)	**Heymsfield** NCAR	A particle light-scattering instrument for measuring size distributions of particles in the 1 to 70 µm size range and for discriminating between ice crystals and supercooled water droplets in mixed phase clouds.
HIAPER Atmospheric Radiation Package (HARP)	Shetter NCAR	**Spectrally-resolved actinic flux measurements, spectroradiometric actinic flux and** irradiance measurements.
Quantum Cascade Laser Spectrometer for HIAPER	Wofsy Harvard	Concentration data versus time for CO2, CH4, and CO (N2O optional).
Advanced Whole Air Sampler (AWAS)	Atlas U. Miami	Collection of ambient air samples autonomously for subsequent analysis of trace gas chemical and/or isotopic composition.
Autonomous Airborne Ozone Photometer	Rawlins PSI, Inc.	**Quantification of ozone mixing ratios at 1 sps using the method of UV** absorption.
Microwave **Temper ature Profiler** (MTP)	Mahoney JPL/Caltech	Measurements of brightness temperature at three frequencies between 55.5 and 58.8 GHz to be used to retrieve a temperature **profile at aircraft's flight altitude.**
Chemical Ionization Mass Spectrometer (CIMS)	Huey Georgia Tech	Measurements of nitric acid, pernitric acid, and sulfur dioxide in standard CIMS negative-ion mode. Measurements of organics such as methanol, acetaldhyde, acetonitrile, and acetone in CIMS positiveion mode.
Fast Ozone Instrument	Campos NCAR	**Quantification of ozone mixing ratios at 5 sps using the method of** chemiluminescent reaction with nitric oxide
High Spectr al Resolution Lidar	Eloranta U. Wisconsin	Calibrated vertical cross sections of cloud and aerosol optical depth, backscatter cross section, and depolarization.
2D-S (Stereo) and Cloud Particle Imager (CPI)	Lawson SPEC, Inc.	CPI portion to provide 8-bit (gray level) images of particles, and 2D-S portion of probe to provide two different (orthogonal) views of particles
GPS Multistatic and Occulation Instrument	Garrison Purdue	Measurements of water vapor distribution in the troposphere, ocean surface roughness, and soil moisture
Tr ace Organic Gas Analyzer (TOGA)	Apel NCAR	In situ measurements of oxygenated volatile organic compounds (OVOCs), non-methane hydrocarbons (NMHSs), and halocarbons.
Time of Flight Aerosol Mass Spectrometer (ToFAMS)	Jimenez U. CO	6 measurements of total PM1 mass concentrations for non-refractory (NR) species, size-resolved PM1 composition for NR species, single particle composition, light scattering signal intensity for particles above 250 nm correlated with mass spectral signal, and surrogate nonsphericity.

NSF/NCAR C-130 Avionics

The NSF/NCAR C-130 aircraft.

The NSF/NCAR C-130 aircraft has a 10-hour flight endurance, a 2,900 nautical mile range at up to 27,000 ft, and an impressively large payload capacity of up to 13,000 lbs. With a standard suite of thermodynamic, microphysics and radiation sensors, it offers a roomy fuselage with a selection of adaptable inlets and optical ports, and the ability to carry instruments and sensors in pods and pylons on both wings. Its extensive wing and fuselage modifications, power and signal wiring for instrumentation, and multiple configuration capabilities – particularly for chemistry experiments – make it one of the most capable heavy-lift research aircraft in existence.

In FY 2011, we completed C-130 infrastructure upgrades that included a modern avionics package, which was installed using American Recovery and Reinvestment Act (ARRA) funds. This upgrade involved a complete reworking of the cockpit and avionics in the aircraft. The new avionics are similar to those on the NSF/NCAR GV aircraft, which greatly facilitates flight crew cross-training on the two aircraft and maintenance of the system. Upgrades to the NSF/NCAR C-130's propeller control system were begun in FY 2011 as well and are nearly complete. As a result, the C-130 is in a condition that will allow NSF to provide the aircraft to the community for at least another two decades.

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- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Imperative II

Support Observing Needs of Research Programs at a level that Serves NSF, University and NCAR Program Needs

In FY 2011 EOL organized, conducted or otherwise participated in eight field programs that spanned a variety of scientific inquiry: the fourth and fifth campaigns of HIAPER Pole-to-Pole (HIPPO) (June-July 2011, August-September 2011); Western Airborne Mercury Observations (WAMO) (October 2010); Concordiasi (August - November 2010); the Persistent Cold Air Study (PCAPS) (December 2010 - February 2011); the Winter Storms and Pacific Atmospheric Rivers (WISPAR 2011) (January - March 2011); the Deep Convective Clouds and Chemistry (DC3) – TEST (May 2011); and the Ice in Clouds Experiment - Tropical (ICE-T) (July 2011).

HIAPER Pole-to-Pole Observations (HIPPO) Global Phases IV and V

Arctic sea ice in mid-June during HIPPO-IV (Photo by Jasna Pittman, Harvard University.)

HIPPO, a massive three-year, five-mission global research campaign, ended in September 2011 and is already revealing exciting new details about the latitudinal and vertical distribution of greenhouse gases and other atmospheric constituents. EOL and the HIPPO research team completed five multi-leg missions from Arctic to Antarctic latitudes, and from near the surface to the lower stratosphere. These missions, carried out in 2009, 2010 and 2011, sampled over one hundred chemical, aerosol, and state variables with sensors aboard the NSF/NCAR GV aircraft. These measurements are of significance to the climate community because they help track the movement of greenhouse and related gases through the atmosphere and improve our ability to resolve emissions associated with human activities, indirect effects of climate change, and natural variations. A strategy similar to that used by **Stephens et al. (2007)** can now be used with a much more extensive dataset that spans the vertical extent of the troposphere.

During HIPPO, scientists measured cross sections of atmospheric concentrations, approximately pole-to-pole, from the surface to the tropopause at different times of the year to see how seasonal changes affect atmospheric chemistry. For all five missions, EOL deployed the NSF/NCAR GV with a comprehensive suite of instrumentation to measure carbon cycle tracers and related species throughout the campaign. During the research flights the GV repeatedly climbed as high as 8.5 miles and dipped down to several hundred feet above sea level as it sampled more than 100 atmospheric constituents, including greenhouse gases, aerosols and a suite of natural and industrial chemicals.

In FY 2011 EOL conducted HIPPO Phase IV and the final Phase V, in June-July and August-September 2011, respectively. All Phases of HIPPO were successful in terms of data acquisition, and have been heavily covered by the news media, sparking an impressive amount of public interest in the project. The education and outreach components of HIPPO have been especially successful (see **Imperative V**).

International Conference on Airborne Research for the Environment (ICARE)

In October 2010 the NSF/NCAR C-130 and EOL scientists participated in ICARE, an international conference hosted by Meteo France and the European Facility for Airborne Research (EUFAR) in Toulouse, France. During ICARE, scientists and aircraft operators involved in airborne geosciences research were invited to share experiences at specialized workshops and to contribute to a look ahead at user requirements and operator development strategies. The conference was a chance for researchers to compare notes on aircraft developments and operational issues (e.g.

aircraft certification and airspace issues), as well as open doors for opportunities for international scientific collaboration.

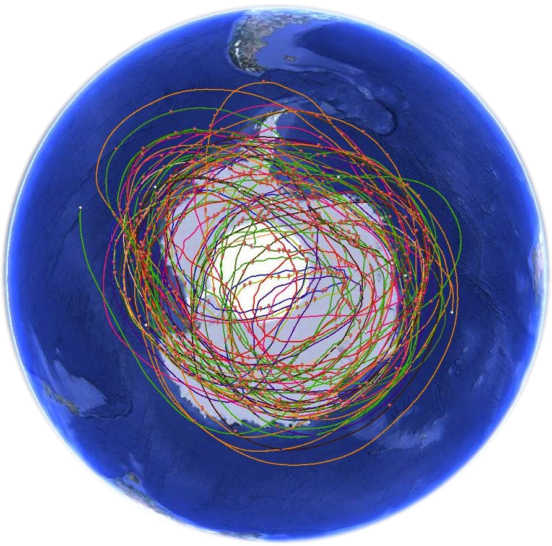
More than 10 aircraft from agencies all over the world participated in the conference, affording a unique opportunity to compare and inter-calibrate airborne instruments through a series of inter-comparison flights. Data from those flights were made available in real time to researchers and students at the conference. It is envisioned that the inter-comparisons will improve the data quality for future airborne research, and it will likely result in publications describing the results. The conference was an opportunity for EOL to showcase the NSF/NCAR C-130 along with other international airborne research capabilities, to connect with scientists, operators of aircraft, and instrument developers on an international scale, and to facilitate future research collaborations with our international partners studying the Earth System.

Western Airborne Mercury Observations (WAMO)

WAMO was conducted on the ferry to ICARE.

Bioaccumulation of mercury is a problem with global and national significance; however there are large gaps in our understanding of the atmospheric mercury cycle. The information obtained in this project will significantly expand our knowledge of the chemical processing of Hg in the atmosphere and increase our understanding of the sources and sinks of mercury in the U.S. The project was a collaborative effort between the Universities of Washington and Nevada on atmospheric mercury, and built capabilities that will be critical for a larger project, proposed for 2013, to assess mercury sources, sinks and processing across North America.

Concordiasi



The paths of the 13 Driftsondes that were launched for Concordiasi show the excellent data coverage that was achieved. Each Driftsonde circled the continent multiple times during the course of several months. The points on each of the paths show where each dropsonde was released.

The Concordiasi project was a joint US/French initiative that used a constellation of stratospheric superpressure balloons deployed from McMurdo Station, Antarctica to study the atmosphere over that continent and answer critical questions on chemistry and microphysics. EOL's participation in Concordiasi was funded by NSF's Office of Polar Programs and provided dropsonde observations using the EOL Driftsonde system. The main goal for the data gleaned from Concordiasi was to provide validation data for polar-orbiting satellite instruments over Antarctica whose measurements will be used to improve our understanding of the link between the Polar Regions and climate change. EOL staff deployed to McMurdo in late 2010 to prepare gondolas and assist scientists from Centre National d'Etudes Spatiales (CNES, France's equivalent to NASA) in launching balloons during the program.

Thirteen Driftsonde flights were successfully completed, with typical durations exceeding 50 days, up to five Driftsondes circling in the polar vortex at once, and over 650 dropsonde profiles collected. This exceptional operational success is expected to result in a reanalysis dataset that will be used to better assess precipitation and the mass budget of the Antarctic ice sheet, test and improve assimilation of infrared and microwave satellite observations over high latitudes, and help improve understanding of the relationship among ozone depletion, polar stratospheric clouds, and stratospheric dynamics. Lagrangian ozone and particulate measurements gathered at the balloons' flight level, dynamics seen with dropsondes, and model output are being used together to constrain uncertainties in the rates of catalytic reactions involved in ozone depletion and to perform assimilation experiments of stratospheric ozone. The dense coverage of soundings (see figure, left) is the first time in history there has been this many soundings in such a short period of time in such a wide spatial density over Antarctica, and the data will keep scientists busy for years to come.

Persistent Cold-Air Pool Study (PCAPS)

The goal of PCAPS was to study the persistent temperature inversions that occur each winter in the Salt Lake valley. Both the initiation and breakup of these persistent inversions, which occur frequently in the western US and throughout the world, are difficult to forecast. Air pollution can reach unacceptably high levels in persistent inversions in urban basins, and the breakup can carry pollution vertically to produce regional-scale air pollution and climate impacts. Because of poor mixing, fog and stratus can build up in the inversion, leading to hazardous episodes of persistent freezing rain, drizzle or fog and interfering with ground transportation and aviation.

PCAPS was a collaboration between the University of Utah, Michigan State University and NCAR/EOL and ran from December 1, 2010 to February 7, 2011. EOL deployed the ISS (Integrated Sounding System) and the Integrated Surface Flux System (ISFS) to the field for PCAPS.

A prototype 449 MHz 3-antenna wind profiler was tested in Salt Lake City during the field campaign and its sensitivity and altitude coverage exceeded that of our co-located 915 MHz profiler.

EOL often leverages resources by incorporating technical developments into overall field project planning, and PCAPS was a perfect example of this. A prototype 449 MHz 3-antenna wind profiler was tested in Salt Lake City during the field campaign and its sensitivity and altitude coverage exceeded that of our co-located 915 MHz profiler. Further discussion of this prototype 449 MHz profiler system can be found in **Frontier III**.

Winter Storms and Pacific Atmospheric Rivers (WISPAR 2011)

The EOL dropsonde team in the Operations Room on Edwards Air Force Base during the WISPAR campaign. The three test flights in January 2010 allowed them to verify operations and identify technical issues with the new autonomous dropsonde system and for NASA to certify safe operations of the launcher.

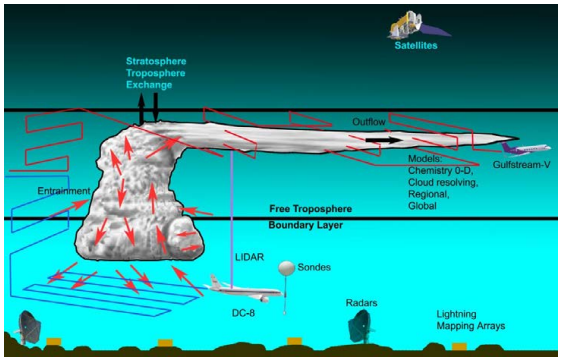
Another example of the interdependent nature of EOL's deployment and development efforts is EOL's support of the WISPAR project. From January to March 2011 the EOL dropsonde team deployed to Edwards Air Force Base, CA in support of NOAA's WISPAR field campaign. The focus of the research was to improve understanding of how Atmospheric Rivers (ARs) form and behave, and to evaluate the operational use of unmanned airborne systems (UAS), in this case NASA's Global Hawk, for studying these phenomena.

EOL used this opportunity to test our autonomous dropsonde launcher for the Global Hawk, which has been in development in a partnership with NOAA since 2009. There were three test flights in January 2010 to verify operations and identify technical issues with the system and for NASA to certify safe operations of the launcher. During the first two test flights, an F-18 jet flew alongside the Global Hawk to film the sonde ejections to verify safe separation from the UAS. The system also made history during the final test flight as it launched its 70th dropsonde from the Global Hawk over the Pacific ocean, the largest number of dropsondes ever deployed during a single flight.

Over the Pacific Ocean ARs transport large amounts of water vapor – about seven times the average daily flow of water from the Mississippi River into the Gulf of Mexico. The ability to monitor offshore ARs is expected to give researchers the ability to predict all manner of precipitation along the west coast, from storms that could produce beneficial increases in snowpack, to rainfall that could cause damaging floods. The long endurance of the Global Hawk coupled with the capability of deploying many sondes will enable unprecedented research into atmospheric river events and the forecasting of winter storms.

Deep Convective Clouds and Chemistry (DC3) – TEST

In May 2011 EOL conducted flights with the NSF/NCAR GV to test instruments required for The Deep Convective Clouds and Chemistry (DC3) field campaign, which will occur in summer 2012. Most instrumentation being flown on the GV for this project is new and nearly 20 cabin or wing-mounted instruments were tested during the 20 hours of flight time. The test flights also marked the passage and subsequent certification of the final three of the HAIS instrument suite: the Chemical Ionization Mass Spectrometer (CIMS), the



The focus of the DC3 campaign will be to study the impact of continental, midlatitude deep convection on the upper troposphere and lower stratosphere (UTLS) composition and chemistry above the continental U.S. during the lifetime of a storm and during the period 12-48 hours after active convection.

Trace Organic Gas Analyzer (TOGA), and the Time of Flight Aerosol Mass Spectrometer (ToF-AMS).

The focus of the DC3 campaign will be to study the impact of continental, midlatitude deep convection on the upper troposphere and lower stratosphere (UTLS) composition and chemistry above the continental U.S. during the lifetime of the storm itself and during the period 12-48 hours after active convection.

The UTLS is an important region for Earth's climate because water vapor, ozone, cirrus clouds and aerosols in this region strongly contribute to radiative forcing of the climate system. The UT and LS have very different chemical compositions resulting in strong gradients across the tropopause. The UTLS is also a highly dynamic region influenced by a broad range of scales, from deep convection and gravity waves, to tropospheric weather systems and the stratospheric large-scale circulation.

For DC3, the NSF/NCAR GV aircraft will be the primary platform to study the high altitude outflow of the storms, and will be instrumented to measure a variety of gas-phase species, radiation, and cloud particle characteristics. The GV will also document the downwind chemical evolution of the convective plume. The NASA DC8 aircraft will complement the GV via in situ observations to characterize the convective storm inflow and provide remote sensing to aid in flight planning and column characterization.

In addition, ground-based radar networks will be used to depict the physical and kinematic characteristics of storms and provide guidance to the aircraft operations. Also, measurements from ground-based VHF lightning mapping arrays will help constrain the impact of lightning on outflow composition.

Ice in Clouds Experiment - Tropical (ICE-T)

Particle probes mounted on the wings of the NSF/NCAR C-130 were used to sample clouds and particles so researchers could measure their chemical, physical, and cloud activating properties. (Photo by Alison Rockwell.)

EOL's NSF/NCAR C-130 supported ICE-T, led by NCAR's Andy Heymsfield, in July 2011 to provide in-situ instrumentation measuring the chemical, physical, and cloud activating properties of aerosols. The objective of the Ice in Clouds - Tropical (ICE-T) experiment is to show that under given conditions, direct ice nucleation measurements, or other specific measurable characteristics of the aerosol, can be used to predict the number of ice particles forming by nucleation mechanisms in selected clouds. The PIs also seek improved quantitative understanding of the roles of thermodynamic pathway, location within the cloud, and temporal dependency.

The ICE-T study, based in the US Virgin Islands, drew on lessons learned in ICE-L (2007), but extended the investigations to towering warm cumulus clouds, where both primary and secondary ice formation processes occur.

In addition to learning how ice particles form and affect clouds, ICE-T researchers are also hoping to improve measurement techniques for future airborne research campaigns. For example, graduate students compared three types of inlets to find out which design is able to most effectively capture the air inside of a cloud.

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Log in

Earth Observing Laboratory | EOL
2011 Annual Report

EOL Annual Report

- Director's Message
- Executive Summary
- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Imperative III

Anticipate Future Needs Resulting from Changing Priorities, Aging Equipment or Emerging Opportunities to Develop New Technology

At NSF's direction, NCAR and EOL have assembled a set of facilities and instruments that serve the community well, but community priorities and technological opportunities call for continuing development so that these observing systems remain matched to community needs. Even with proper maintenance, systems become obsolete or impossible to maintain, and it is necessary to plan for their replacement or end-of-life. EOL must also be sensitive to changes in priorities and needs of the atmospheric science community and must adjust its capabilities as required to meet those needs. Imperative III calls upon EOL's scientific and engineering leadership and expertise for a healthy development effort and for the retention and training of staff who can conduct that research and development. It also requires the development of life-cycle and end-of-life plans for major facilities, instruments and software (see Imperative IV for more information on data services and software developments).

An extremely high-profile instrumentation development effort in FY 2011 was the advancement of dropsonde technology that enables this perennially-requested instrument to be used in even the newest unmanned airborne platforms. Other projects include the Compact Atmospheric Multi-species Spectrometer (CAMS) for the GV, the Laser Air Motion Sensor (LAMS), and the Ka-Band radar. Other, longer-horizon developments, such as the 449 MHz profiler system, are discussed in our Frontiers.

AVAPS Dropsonde System

The new dropsonde system, designed for installation on the NASA/NOAA Global Hawk, can dispense up to 88 Miniature In-situ Sounding Technology (MIST) sondes during a single flight, and the data system installed on the aircraft was designed to process up to eight sondes in the air at once.

Starting in FY 2009, EOL and NOAA partnered to develop a first-of-its-kind dropsonde system for use on the NASA/NOAA Global Hawk (GH) unmanned aircraft. The AVAPS team worked on the design, manufacturing and testing of the system, which resulted in a fully-automated dropsonde system where all operations are remotely controlled from the ground, literally with the click of a mouse. This next generation AVAPS system was tested and completed for installation on one of the NASA Global Hawk Unmanned Airborne Systems (UAS) in January 2011. It can dispense up to 88 Miniature In-situ Sounding Technology (MIST) sondes during a single flight, and the data system installed on the aircraft was designed to process up to eight sondes in the air at once. This will have a major positive impact on researchers' ability to take more accurate global warming and ozone depletion measurements, better predict hurricane tracking and landfall, and improve weather forecasting.

In February and March 2011 the dropsonde-equipped Global Hawk completed three long duration flights over the Pacific Ocean during the Winter Storms and Pacific Atmospheric Rivers (**WISPAR**) campaign. Creation of the Global Hawk dropsonde system provided a strong head start for EOL to create a more automatic, next generation dropsonde system for the NSF/NCAR GV. That system is currently being developed, and is expected to be operational by FY 2013. The

improved capabilities of the new GV Dropsonde system will give EOL the ability to support a wider range of science objectives and flight conditions, including high turbulence. The new system will use the smaller MIST sonde and will allow rapid ejection of sondes, up to one per minute as opposed to the current rate of one every 3 to 5 minutes. The ability to deploy a "curtain" of sondes will result in higher resolution profiles of weather and other atmospheric phenomena.

EOL plans to continue to stay abreast of developments in atmospheric UAS technology since there is synergism between traditional research aviation and UAS airborne research, especially with respect to sensor development, miniaturization of instruments, remote operations of instruments from the ground, and the use of satellite communications for real-time data transfer. Further development and/or modifications of other EOL instrumentation for use on the GH or other large UAS platforms are likely in the future.

Compact Atmospheric Multi-species Spectrometer (CAMS)

The Compact Atmospheric Multi-species Spectrometer (CAMS) is a trace gas chemistry instrument that is being developed for Upper Troposphere/Lower Stratosphere (UTLS) research on the GV. This instrument,will detect formaldehyde and potentially other trace gases such as methanol, acetylene, ethylene, formic acid, and/or ethanol. The CAMS instrument is based upon Difference Frequency Generation (DFG) technology and includes a number of advances to further improve measurement performance, extend capabilities for additional gases, and to achieve significant weight and size reductions along with capabilities for autonomous operation.

CAMS was successfully tested during the DC3 Test flights in May 2011 and in subsequent laboratory tests. It was shown to have a detection limit of 40-50 pptv for 30-second average measurements. This detection limit meets the goal of the DC3 PIs, who requested a limit of 50 pptv for 30-second averaged data to sample the background upper troposphere mixing rations of CH20.

Laser-Air Motion Sensor (LAMS)

The LAMS installed on the NSF/NCAR C-130 for flight testing. By focusing a continuous-wave coherent laser beam about 20 m ahead of the aircraft, the instrument is able to make accurate wind velocity measurements in undisturbed air and measure the aircraft's true air speed.

High-resolution wind measurements from aircraft enable flux measurements using eddy-correlation methods. Air motion relative to an aircraft is usually measured with a 5-hole gust probe, which employs pressure sensors. Although robust, the method is not highly accurate, in part because the aircraft shape and motion modify the air flow field. Ideally, air motions should be measured some distance from the aircraft, where the airflow has not been modified by deformation around the fuselage. To address this issue, EOL engineers developed the Laser Air Motion Sensor (LAMS) for deployment on the GV and the C-130. By focusing a continuous-wave coherent laser beam about 20 m ahead of the aircraft, the instrument is able to make accurate wind velocity measurements in undisturbed air and measure the aircraft's true air speed.

The current version of the LAMS sensor measures the air speed towards the aircraft with an accuracy of about 10 cm/s; this is almost a factor of 10 more accurate than what can be obtained using in-flight aircraft calibration maneuvers. Fabrication of LAMS subsystems occurred in FY 2011, including an in-house 5W fiber amplifier, while additional fiber amplifiers are still needed to complete the 3-beam system. In early FY 2012, the existing single beam system will be loaded onto the C-130 for test flights during the fourth Instrument Development and Education in Airborne Science (IDEAS IV) campaign. A complete test of the 3-beam instrument is planned for 2012.

Ka-band Radar

EOL's radar capabilities were upgraded in FY 2011 to include a second Ka-band (0.86 cm) wavelength radar in response to PI-requested simultaneous dual-wavelength measurements for the FY 2012 DYNAMO field campaign. The development of the Ka-band dual-polarization, Doppler radar, mounted on the lower right edge of the S-Pol radar, extends measurements of precipitation to cloud scale processes in two ways. First, as a stand-alone sensor, the Ka-band radar expands EOL's remote sensing capability into measuring kinematic and microphysical properties of clouds. Second, when mounted on S-Pol, the two radars become S-PolKa

EOL technicians install the Ka-band radar in preparation for the DYNAMO field campaign. As a stand-alone sensor, the Ka-band radar expands EOL's remote sensing capability into measuring kinematic and microphysical properties of clouds. When mounted on S-Pol, the two radars become S-PolKa and have matched beam widths, range resolution and pointing angles.

and have matched beam widths, range resolution and pointing angles.

These scanning dual-wavelength measurements are unique in the atmospheric sciences. Most importantly, when S-PolKa is paired with other EOL remote sensing instruments such as HCR and HSRL, EOL can provide unique multiple wavelength capabilities (S- Ka- W- lidar) with applications in several research disciplines. These combined sensors will contribute to understanding the climate system through a better understanding of humidity profiles in clear air, microphysical processes in clouds and cloud aerosol interactions.

Airborne Phased Array Radar (APAR)

EOL is in a unique position to play a leading role in airborne phased array technology, specifically with respect to the airborne antenna. The availability of and direct access to the C-130 combined with in-house scientific and engineering expertise create an exceptional opportunity for EOL to make significant contributions to the next generation radar capability.

Due to the limitations imposed by mounting ELDORA on a non-NCAR aircraft and the instrument's aging components, it is necessary to explore new technology such as electronically scanned phased array antennae to replace ELDORA after its useful lifetime. Such phased array technology would help advance science in several areas related to mesoscale meteorology, in that higher temporal and spatial resolution measurements are needed to investigate detailed storm structures and evolution. For airborne applications, reduced attenuation using a longer wavelength would allow for deeper beam penetration into severe weather.

To help meet these needs, EOL continued its collaboration in FY 2011 with MIT Lincoln Labs on the development of the next generation phased array radar that we envision will eventually replace ELDORA. Initial activities with MIT centered on risk assessment of the project: the evaluation of phased array element designs that best match science community needs for these high-resolution measurements. EOL's Remote Sensing Facility will prepare a phased array radar development white paper in FY 2012 outlining a staged approach for the APAR development.

HIAPER Cloud Radar (HCR)

HIAPER Cloud Radar (HCR) diagram.

To complement the HAIS projects, EOL is developing the HIAPER Cloud Radar, which will be mounted in a wing-pod on the GV, providing high resolution, research-quality data at altitudes not previously available to the atmospheric research community. HCR will be the only cloud radar available on the GV. EOL is using a phased approach to build the HCR. Construction of a ground-based prototype (Phase 0) was completed in FY 2010 and Phases A and B are currently underway. Phase A consists of a pod mounted W-band Doppler radar capable of flying on the NSF/NCAR GV. Pulse compression and dual polarimetric capability are planned for Phase B, and a second wavelength (Ka-band) is planned for Phase C. In addition, the HCR will be deployable in a ground-based container that also houses the High Spectral Resolution Lidar (HSRL), thus providing simultaneous radar/lidar observations. Both instruments run unattended on the ground, enabling longer-term and remote observations.

In FY 2011 EOL received critical components for the single-antenna, airborne configuration of HCR. Performance and functionality of subsystems such as the transmitter, T/R switch network, controls, power and data acquisition, were verified and documented. Mechanical parts and electrical wiring for front-end electronics were manufactured, implemented and tested, and core software for data acquisition, display and control has been tested and functions correctly. Some changes were made in current mechanical and electrical design after review by RAF, and the airborne

data acquisition system is being implemented. With the front-end electronics, transmitter and current data acquisition system, HCR is ready for radar performance tests on ground, and in 2012 it will be tested in an altitude chamber to simulate and monitor the performance under low-pressure conditions.

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Log in

Earth Observing Laboratory | EOL
2011 Annual Report

sponsored by

EOL Annual Report

- Director's Message
- Executive Summary
- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Imperative IV

Provide Comprehensive Data Services, Open Access, and Long-Term Stewardship of Data

One of NSF's core expectations in the NSF - UCAR Cooperative Agreement focuses on data issues, specifically calling for NCAR to "serve as stewards of high quality scientific data on behalf of the community through maintenance, enhancement and curation." For EOL, this charge falls on the shoulders of the Computing, Data and Software Facility (CDS). CDS is responsible for developing and maintaining EOL's computing infrastructure, data and metadata services, collaborative tools, and software engineering, all of which are integral to Imperative IV. CDS serves as the umbrella for all data management activities in EOL, and takes a proactive approach in working with PIs to meet NSF's **requirement that, beginning in January 2011, grant proposals include comprehensive data management plans**.

Developments in Data Services

EMDAC

In addition to providing and supporting instrumentation that helps scientists obtain critical observational data, EOL also supports data packaging, storage, and management through the EOL Metadata Database and Cyberinfrastructure (EMDAC). EMDAC is a comprehensive metadata database and integrated cyberinfrastructure that will eventually be the hub of all EOL data services and that will allow us to provide accurate and timely data services for the science community.

The scope of EOL's support to the science community we serve has expanded to include datasets from new origins, e.g. satellite or network data sets, which we collectively quality assure and put into common formats to ease our users' analysis process. Advances in satellite communications and internet distribution have pushed and enabled us to publish data, information and imagery to the science community at a much faster pace. Through EMDAC, EOL will create bridges to multi-agency data portals, creating compatible metadata and data access infrastructure. This will connect EOL to the common services currently available while also allowing us to meet future needs through a modular and extensible architecture.

In addition to unifying our databases, our user community has outlined other specific tasks that are required to complete EMDAC, including:

- Improve interfaces for data access, ingest, and distribution
- Develop, distribute, and support interfaces to fourth generation languages from community-developed codes used in the analysis of our datasets
- Build a scalable database to handle growing data volumes and file types
- Centralize and improve data metrics collection and reporting
- Establish long-term data stewardship processes

Prototype versions of both the next generation Field Catalog and the Cooperative Distributed Interactive Atmospheric Catalog System (CODIAC) data distribution tools, both integral components of EMDAC, were developed in FY 2011. Local and remote in-field data distribution was added during the July 2011 Ice in Clouds Experiment (ICE-T) campaign, and the new Field Catalog will be deployed alongside the prior version during TORERO 2012: Tropical Ocean Troposphere Exchange of reactive halogen species and oxygenated VOC, in January-February 2012.

Cross-Platform Software

EOL expects the research community to benefit in many ways from common, cross platform software development and management. Among these benefits: 1) EOL can make efficient use of limited software engineering resources because of the many areas of expertise (e.g., software architecture, real-time data acquisition, signal processing, web application frameworks); 2) Team-developed code ensures that EOL has the ability to respond in the event that a particular software engineer is not available; 3) Multi-platform (e.g. Linux, Mac, and Windows) development allows EOL to meet the software needs of a broad community; 4) Using common tools to manage EOL's software engineering process reduces the overhead required for important functions such as revision control, bug tracking, and software packaging; and 5) By sharing software libraries across the lab, EOL can leverage the extensive testing that occurs and

use the most reliable, proven software in our observing systems. An example of these benefits is the EOL-developed Aeros airborne display software was ported to the MacOS platform for use in ICE-T. Also, in FY 2011, EOL adapted the NCAR In-situ Data System (NIDAS) for the Integrated Surface Flux System (ISFS) to acquire data via cell-phone links, and the SD3C architecture was ported to the new HCR platform and Ka-band systems.

Local Traditional Knowledge (LTK) Data Collection Projects

An exciting new project is EOL's participation in Local Traditional Knowledge (LTK) data collection that focuses on indigenous peoples. This activity, which addresses two of the NSF Cooperative Agreement core expectations –*"serve as stewards of high quality scientific data on behalf of the community, through maintenance, enhancement and curation,"* and *"address challenging scientific problems that require long term focus and integration across global, regional and local scales"* – is part of a long-standing collaboration among NSF, the Arctic research community, the National Snow and Ice Data Center (NSIDC), UNIDATA, NCAR's Computational Information Systems Laboratory (CISL), and EOL.

Advanced Cooperative Arctic Data and Information Service of the ARCTIC OBSERVING NETWORK ACADIS

LTK activities in FY 2011 focused on the Bering Sea, which is one of the most biologically productive marine environments, includes habitats that are of global importance, and is undergoing rapid changes due to climate change. NSF has funded EOL's participation in several programs including the Bering Sea Ecosystem Study (BEST), the Bering Sea Integrated Ecosystem Research Program (BSIERP), and the Advanced Cooperative Arctic Data and Information Service (ACADIS) for the Arctic Observing Network (AON). As part of these programs, the LTK projects emphasized the importance of a variety of historical records and stories of tribal elders in documenting the changes that have come to the region due to climate change. These projects are dedicated to fostering understanding and sharing of knowledge between Arctic residents, scientists, educators, policy makers, and the general public.

The data from the region are eclectic and include written interview transcripts, audio or video tapes and files, photographs, artwork, illustrations, maps, digital geographic information such as GPS tracks, data created using the Geographic Information System (GIS), and quantitative data such as temperature, snow thickness, and wind speed/direction. Staff from EOL's Computing, Data and Software (CDS) Facility played an important role in designing and developing the GIS mapserver site that hosts these data.

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Log in

Earth Observing Laboratory | EOL
2011 Annual Report

sponsored by

EOL Annual Report

- Director's Message
- Executive Summary
- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Imperative V

Attract and Inspire New Generations of Scientists, Engineers and the General Public to Atmospheric Science

The promotion of atmospheric science is crucial to inspire the development of the next generation of observational scientists and engineers, and is an institutional charge that EOL considers extremely important. With the assembly of observational facilities that EOL manages, we are in a unique position to provide exceptional education and training to new observational atmospheric scientists and engineers, and to inform and excite the public with the impact of observational research.

Students in science and engineering can be motivated to pursue careers in observational meteorology through exposure to NSF LAOF, and to EOL development activities. EOL can also help the public understand better the value of observational atmospheric science through demonstrations of direct measurements of the atmosphere combined with explanations of what scientists learn from these observations. Contributing in this way is part of the EOL mission, and the mechanisms EOL provides to support and inspire undergraduates and graduates, high school students, teachers, and faculty will ensure the field of atmospheric science remains vibrant well into the future.

In FY 2011 EOL participated in seven educational field deployments, including one aimed primarily at minority-serving institutes. FY 2011 also saw the 11th year of EOL's Summer Undergraduate Engineering Internship Program, and the development of a Technical Internship Program for science support students.

Educational Deployments

Darkness didn't keep UND graduate students Brandon Bigelbach, Joel Siegel, and Aaron Kennedy from deploying a Doppler on Wheels unit on 19 November 2010 during one of SNOwD UNDER's four storms. (Photo by Justin Walker, Center for Severe Weather Research.)

NSF makes a subset of NSF/LAOF available for educational purposes to colleges and universities across the continental United States every year. This effort is managed by EOL and is designed to expose undergraduate and graduate students in science and engineering to observational meteorology, without requiring faculty to design and propose a full-scale scientific field campaign.

NSF funded seven educational projects in FY 2011, all involving the Doppler On Wheels (DOWs) radars:

1. The Northern Autumn Plains Echo Patterns (NAPEP) at St. Cloud State University, Minnesota in October 2010
2. The University of Illinois DOW Education, Research and Outreach (UIDOW) Project at the University of Illinois Urbana-Champaign in November 2010
3. Student Nowcasting & Observations of Winter Weather with the DOW at University of North Dakota Education in Research (SNOWD-UNDER) in November-December 2010
4. DOW Observations of New England Storms (DOWNEWS) at Lyndon State College in northern New England in February 2011
5. Coordinated Mesoscale Measurements in Mississippi (CM3) at Jackson State University, Mississippi in February-March 2011
6. University of Nebraska DOW Education and Outreach (UNDEO) in March-April 2011
7. Teaching flow Over Mountains (TOM), which was a collaborative effort by the Department of Atmospheric and Oceanic Science (ATOC) at the University of Colorado (CU) and the Department of Marine, Earth, and Atmospheric Sciences (MEAS) at North Carolina State University (NCSU), held in Boulder, CO, March-April 2001

Careers in Science (CIS)

A group of students at Elmhurst College listen to a presentation in front of the CSWR Doppler on Wheels (DOWs). A total of roughly 170 students attended all three presentations, and 140 students attended the following demonstrations on the DOWS.

Funded by the NCAR Diversity Program, CIS is a special Educational Deployment aimed to expose approximately 500 students from accredited post-secondary minority-serving institutions in three states to various career opportunities that exist within a scientific institution such as NCAR, and to encourage them to pursue further education in the fields of technology, engineering and science support. The CIS team, comprised of EOL, UCAR Education and Outreach, and Center for Severe Weather Research (CSWR) staff, visited three colleges in the greater Chicago area in late October, 2010. At each school, the team showcased a variety of jobs that support field campaigns, discussed a specific field campaign (VORTEX II), and had the CSWR Doppler on Wheels (DOWs) available for a hands-on demonstration after the initial presentation and discussion. A total of roughly 170 students attended all three presentations, and 140 students attended the following demonstrations on the DOWs. The visits proved to be excellent opportunities to gain insight about what techniques might be most effective to foster a pool of diverse students in the atmospheric research disciplines that will ultimately feed into careers at NCAR and other research institutions. An idea that grew out of CIS was to develop an internship more closely focused on the technical and mechanical support side of atmospheric science. The EOL Technical Internship Program (TIP) was created in FY 2011 as a result of this and targets two-year technical and vocational schools in the Denver/Boulder Metro area; the first TIP cycle, also funded by the NCAR Diversity Program, will run in spring of FY 2012.

Education and Outreach Support in Field Deployments

EOL staff members are also routinely involved in education and outreach (E&O) activities spearheaded by the requesting investigators for a particular field campaign. In FY 2011, EOL staff mentored and assisted University of Utah graduate students in the execution of the Persistent Cold-Air Pool Study (PCAPS) in winter 2010/2011, and gave lectures on instrumentation and science to the students. The students were in charge of all aspects of planning and implementing day-to-day PCAPS operations including forecasting, scheduling and directing intensive observing periods. The graduate students also helped EOL staff with the launching of soundings, instrument maintenance of both the ISS and the ISFS, and teardown of the systems at the end of the campaign.

Summer Undergraduate Engineering Intern Program (SUEIP)

2011 SUEIP interns and their mentors: (L-R) Jim Ranson, Krishnakumar Ramkumar, Lucas LaPlace, Monica Jacobs, Kyle Quintero, Brad Linseth, EOL Director Vanda Grubišić, Chris Burghart, Linda Cully, Nick Potts and Janine Aquino.

EOL has pioneered a variety of Education and Outreach programs, and we consider our Summer Undergraduate Engineering Internship Program one of the most successful. Now in its 11th year, the internship focuses on undergraduate students in various fields of engineering, complementing existing programs within NCAR that primarily target students in geosciences. Each year, EOL receives hundreds of resumes from engineering students vying for three or four positions on projects proposed by EOL staff. The internship runs for 12 weeks each summer, during which each student works with EOL engineers on a well-defined and manageable project that is of direct significance to EOL's activities. EOL coordinates SUEIP activities with UCAR's Significant Opportunities in Atmospheric Research (SOARS) program, including joint social events for students and mentors. In FY 2011 nearly 150 students applied for the three available positions proposed by EOL staff. The internship ran from the end of May and lasted into August. The three students participating in the program were:

1. Monica Jacobs, who had just finishing her first year at Cornell University (NY), worked with Janine Aquino of the Computing Data and Software Facility (CDS) helping to modify EOL's production website and reviving software to help with research-grade processing of sounding comparisons.
2. Krishnakumar Ramkumar, a senior at Portland State University (OR) in electrical engineering, worked under Brad Lindseth in EOL's In Situ Sensing Facility (ISF) to develop the front-end for the new 449 MHz Wind profiler RF power amplifier and produced designs to fit the assembly into a movable box.
3. Kyle Quintero has one more semester to finish at Colorado School of Mines. He also worked with Brad Lindseth in ISF, modeling optimal shipboard placement of the 915 MHz Wind profiler for DYNAMO as well as designing the RF power amplifier section for the 449 MHz Wind profiler.

In addition, Lucas LaPlace, an intern from the University of St. Croix, worked with Jim Ranson in the Design and Fabrication Services (DFS) Facility to design a 1/2 scale Chaotic Pendulum for UCAR Education and Outreach. Lucas used SolidWorks mechanical design software and took field measurements of the full scale Chaotic Pendulum at the Mesa Lab. Using the measurements, he modeled a scale model of the Pendulum, defining both custom machined parts and off the shelf components.

SUEIP has been renamed for 2012 as the Summer Undergraduate Program for Engineering Research (SUPER).

Other Education & Outreach Activities

NCAR Research Experience for Teachers Institute (RETI)

Secondary school science teachers in the RETI program visited NCAR in July 2011 to develop climate change curriculum. In the process they had an opportunity to visit EOL's Design and Fabrications Services Machine Shop to learn about the technology and instrumentation that makes climate studies possible.

An example of how observational data gleaned from EOL-driven research is used in the classroom can be found in RETI, a teacher internship program for secondary level teachers to build a climate change science component into their classroom curricula. It is sponsored by NASA, coordinated by UCAR's Office of Education and Outreach, and involves the efforts of UCAR, NCAR, and the University of Northern Colorado (UNC) Math and Science Teaching Institute (MAST).

In April 2011, the 12 teachers participating in RETI began the program with staff from UCAR, NCAR and UNC. EOL staff highlighted how the teachers could use data from the HIPPO project in their curriculum. Some of the RETI projects were relevant to HIPPO data, including Teaching Basic Climate Change Science to Middle School Students, Modeling and Climate Science, Effects of Climate Change, and Modeling and Atmospheric Science. The RETI program will continue into fall 2012.

Expanding Your Horizons (EYH)

In February 2011, nearly 300 middle school girls descended upon the Engineering Center at the University of Colorado, Boulder for the annual Expanding Your Horizons Conference. EYH is aimed at encouraging young women to engage in hands-on activities and explore career opportunities available to them in engineering, math and science. At the conference, each girl attended three hands-on workshops given by professional women in the community.

EOL and RAL staff jointly conducted a series of workshops, titled "Up Up and Away: Measuring the Atmosphere using a Weather Balloon." During this workshop, they gave a demonstration balloon launch and then conducted a science experiment with the attendees to measure the RH in the room and answer a series of questions.

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Log in

Earth Observing Laboratory | EOL
2011 Annual Report

EOL Annual Report

- Director's Message
- Executive Summary
- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Frontier I

Improve observing capabilities for weather and climate phenomena with high socio-economic impact.

The NSF/NCAR S-Pol Radar with the Ka-band installed (S-PolKa) at the DYNAMO field site in the Maldives. S-PolKa is also part of the FRONT testbed.

EOL has provided prominent support for studies of hurricanes, tornadoes, and other severe storms. The S-Pol radar is unique in that it is a deployable S-band system, coupled to a Ka-band system. The Front Range Observational Network Testbed (FRONT) provides an opportunity to make the capabilities of S-Pol available for longer times, to operate in conjunction with Colorado State University's CHILL radar, and to develop more collaboration with the CSU/CHILL group. This should make the facilities available to more short-term users and for new kinds of observations. FRONT is discussed in more depth in **Frontier IV**.

Another unique potential EOL system for studies of severe weather is airborne phased array radar. Explorations continued in FY 2011 of phased-array technology for the NCAR C-130, where it could be combined with other remote sensors available in EOL and with the many other measuring capabilities that platform provides. Further discussion of the phased array effort can also be found under **Imperative I**.

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Log in

Earth Observing Laboratory | EOL
2011 Annual Report

sponsored by NSF

EOL Annual Report

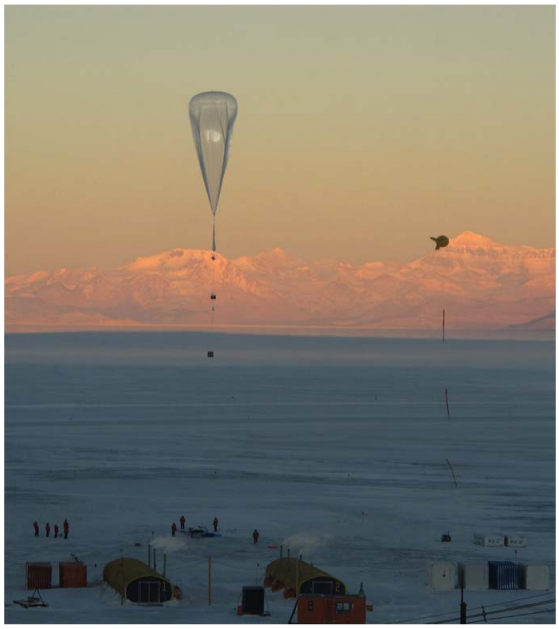
- Director's Message
- Executive Summary
- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Frontier II

Provide New or Significantly Strengthened Capabilities to Support Observational Research in Key Areas Where Support Needs are Growing in Importance

EOL has much to offer in support of climate research, and a significant portion of EOL support throughout its and ATD's history has been devoted to such research. However, the nature of the needs and the opportunities are changing, so there is an opportunity to change the nature of our support. The GV opens new opportunities for global-scale observations, and HIPPO has served to highlight the potential of such observations. FRONT has the potential to provide longer-term observations covering an area similar to a grid box in a climate model, and it can provide a setting for incorporating testbed measurements while longer-term observations provide context for the testing of new instruments. The history and experience of EOL in process studies will also continue to serve the needs of the climate community for such observations.



The Driftsonde is an excellent example of how EOL expands its development expertise into areas of growing importance to the observational scientific community. The Driftsonde releases dropsondes via commands from a ground-based operations center, an ideal capability for remote areas including the tropics and high latitudes.

Another example where EOL's expertise has expanded into development of observational capabilities needed by scientific areas that are growing in importance is the development of the balloon-borne Driftsonde system that releases dropsondes via commands from the ground. This capability is ideal for remote areas including the tropics and high latitudes. In FY 2011 this capability was used in the French/US sponsored campaign, Concordiasi (in Antarctica), which demonstrated the maturity of the EOL Driftsonde system in one of the most challenging environments imaginable. Before Concordiasi, the Driftsonde supported two other international field programs, the African Monsoon Multidisciplinary Analysis (AMMA) project over the African continent in 2006 and T-PARC over the Pacific Ocean in 2008. Each consecutive deployment spurred additional improvements, advances, and refinements. ISF, DFS and CDS staff faced a range of engineering challenges including the need for robust low-weight, low-cost sensors and materials that would function in the harsh stratospheric environment, implementation of reliable global satellite communications protocols, development of complex software to fully automate sounding launch from a web-based ground system, radio interference issues related to GPS, Iridium, and sonde transmitters and receivers, and successfully launching these large balloons in sometimes difficult conditions at McMurdo Station. Additional information on Concordiasi is presented under **Imperative II**.

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Log in

Earth Observing Laboratory | EOL
2011 Annual Report

EOL Annual Report

- Director's Message
- Executive Summary
- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Frontier III

Develop New Capabilities That Focus On Processes at Interfaces in the Atmosphere.

The air-sea interface, the air-land interface, and the tropopause have diverse observational needs: ships, buoys, and aircraft for the first; facilities such as ISFS for the second; and a high-altitude aircraft (perhaps supplemented by high-altitude wind profilers) for the third. EOL has provided excellent support for studies of the air-land interface, but the inability to characterize surface fluxes below hurricanes is a particular aspect of the air-sea interface that could be examined, because it limits the accuracy with which hurricanes can be modeled. In high-wind conditions, research aircraft have been unable to fly low enough to provide good characterization of the momentum and other fluxes that govern hurricane development, and as a result there is considerable uncertainty regarding how to represent such fluxes in models. Similarly, the capabilities of the GV were used in the START-08 experiment to study UTLS dynamics and chemistry and will likely be of increasing importance to studies of the UTLS as the suite of instruments for air chemistry is completed (in 2012).

There are many possible measurement tools and observational opportunities for these interfaces: controlled towed vehicles to extend the reach of research aircraft closer to the surface; possible deployment of ocean sensors like Airborne eXpendable BathyThermographs (AXBTs) for studies of the upper layer of the ocean; measurements of fluxes of trace gases to or from the lower surface (land or sea); new sensors on dropsondes for characterizing the chemistry of the tropopause region; scintillometry as an inexpensive way to extend measurements of near-surface wind and turbulence; the development of remote sensors that measure profiles of trace gases and remote sensors for measurement of fluxes (e.g., via combining a DIAL lidar with a Doppler lidar); and development of large arrays of sensors to increase coverage and resolution of measurements. Other areas with potential include using UASs for boundary-layer studies, the remote measurement of 3-D wind, tethersonde capability to increase the altitude range of B-L measurements, and higher-response measurements from research aircraft to measure fluxes and probe the fine-scale structure of turbulence. Understanding processes at interfaces continues to grow in importance and is prominent in many assessments of needs for the future.

EOL is developing an innovative, modular 449 MHz wind profiler network to expand and replace our 915 MHz boundary-layer wind profiling capability. A prototype of the new profiler network (above) was deployed and tested alongside our current 915 MHz profiler during **PCAPS**.

An additional theme that EOL is exploring is the need for greater coverage through longer timeframes, broader areas, and complex terrain. Sensor simplification and miniaturization is leading to new opportunities in this area. EOL is developing an innovative, modular 449 MHz wind profiler network to expand and replace our 915 MHz boundary-layer wind profiling capability. As a basic boundary-layer wind profiler, the new system will probe higher and be simpler to deploy. The 449 MHz profiler's unique hexagonal-antenna and its modular design will provide for assembly in a variety of configurations to meet the diverse range of experiments that EOL supports. The envisioned system could be deployed as a network of six boundary-layer profilers, a single full-tropospheric profiler, or variations in between. Advanced hardware and innovative signal processing such as spaced antenna winds, range imaging, and adaptive clutter suppression are important features of the 449 MHz profiler development effort. A prototype of the 449 MHz profiler was successfully deployed during the recent PCAPS project in Utah (see **Imperative II**).

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Log in

Earth Observing Laboratory | EOL
2011 Annual Report

EOL Annual Report

- Director's Message
- Executive Summary
- Table of Contents
- Imperative I
- Imperative II
- Imperative III
- Imperative IV
- Imperative V
- Frontier I
- Frontier II
- Frontier III
- Frontier IV

2009-2014 Strategic Plan »

Frontier IV

Develop new calibration and testing facilities, including testbed capabilities, for the community, either in collaboration with other agencies or specifically for NSF-supported research.

FRONT integrates Colorado State University's (CSU) CHILL (left) and EOL's S-Pol (right) radar systems to streamline engineering development and operations for expanded science, research and education opportunities.

The most prominent test-bed development area in EOL is the Front Range Observational Network Testbed (FRONT), which is still evolving and has substantial potential to serve community needs. However, the need for calibration facilities for water vapor sensors is also particularly important to a broad range of sensors operated by EOL. In addition, there is a need for an altitude-chamber / wind tunnel test facility to which EOL would have access, perhaps operated by EOL. Associated with this need, is the need for more attention to measurement science: calibration, uncertainty characterization, and documentation of instrument characteristics.

FRONT integrates Colorado State University's (CSU) CHILL and EOL's S-Pol radar systems to streamline engineering development and operations for expanded science, research and education opportunities. FRONT will provide the scientific community with opportunities to conduct target-of-opportunity scientific field experiments; maintain a long-term mesoscale test bed for assessing instruments, data quality procedures, sensor integration, numerical models, networking capabilities and derived products; provide a framework for local field campaigns; and provide hands-on education.

FRONT's goals are to establish common system software, data formats and data processing environment; share common receiver and system control hardware; and remote-control both radars for unattended operations. The near-term deliverable is S-Pol's move to a new home-base east of I-25 to create a world class dual-Doppler, dual dual-polarization network, with fully available S-Pol functionality. S-Pol's move will occur after its return from the DYNAMO field campaign in Spring 2012 (see **Imperative II**).

In FY 2011 several improvements that will aid FRONT's goals were made in preparation for S-PolKa's deployment to the Maldives in support of DYNAMO, including, new remote operations capabilities, which includes remote restart of the system should it stall. Operators can also now set radar scans, and hardware was purchased for the centralized data archiving. The site lease for the final FRONT location in Firestone, CO has been signed, and in early FY 2012 EOL will procure appropriate zoning permits to improve and build on the site to support the radar at FRONT.

A panoramic view of the FRONT site.

https://web.archive.org/web/20130725203648/http://nar.ucar.edu/2011/lar/eol/frontier-iv[12/30/2016 12:06:14 PM]

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Director's Message

Dear Colleagues:

Greg Holland - Interim Director, NCAR Earth System Laboratory

Jim Hurrell - Director, NCAR Earth System Laboratory

FY 2011 was a year of contrasts. It was a year in which the NCAR Earth System Laboratory reached full stride with Jim Hurrell as our first permanent Director. It was a year of considerable scientific achievements and improvements to our community modeling facilities. Yet it was also a year of substantial staff impacts from an accumulation of several years of difficult budgetary and programmatic times.

Our goals for the establishment of NESL as a strong and flexible laboratory have been achieved. The executive and administrative structure and our strategic plan provide an efficient and flexible capacity for us to develop major initiatives and to respond to both opportunities and difficulties that arise. This structure was endorsed by the NSF Scientific Visit Team (SVT) who commented that it *"create(s) synergy across NESL's three divisions, across NCAR's laboratories, and between NCAR/UCAR and the university community such as to make the whole much greater than the sum of the parts."*

Thanks to your efforts NESL was presented as a strong and viable laboratory, one that embodies all of the principles set forth in the "blue book" that founded NCAR. As the SVT commented: "*Never in NCAR's ~50-year history have the staff in the divisions that now make up NESL shared a stronger sense of purpose".* We are proud of our scientific leadership and accomplishment, the development and maintenance of major community modeling facilities, our highly successful visitor program, our record of community collaboration (international and domestic), and our continuing commitment to scientific evolution and facility development. Again from the SVT: "*The SVT considers NESL's community modeling effort, culminating in the CESM, the WRF, and the WACCM to be among NCAR's greatest achievements in its nearly 40-year history".*

But the review also identified weaknesses including one recommendation that we *"consider the possibility of reshaping and reinvigorating the various in situ chemical measurements projects currently housed in ACD to create a more coherent program that is closely aligned with the interests of the university community".* Here, NESL responded quickly and positively, not just to consider the possibility, but to take constructive action to establish a major community chemistry facility that is expected to mature into a major NCAR activity in support of science and community needs.

As we look to the future, NESL must continue and enhance efforts to develop strategic and stronger partnerships and to seek broad community input into evolving and implementing its strategic imperatives, frontiers and other new research initiatives. This input will be central to ensuring NESL maintains transformative research, works synergistically with the academic community, and strikes the best balance possible between growth into new scientific areas and sustaining excellence in existing core activities. It is also more important than ever for NESL to embrace a leadership role and more actively engage with community leaders, research agencies, professional organizations, policy makers and others to convey significant research findings and to emphasize the importance of investment in research and major facility development. While the science credentials of NESL are well known within much of the scientific community, there are clear requirements for communicating the science more broadly and, thereby, enhancing its visibility to fellow researchers, stakeholders and the general public.

Finally, given significant financial challenges, and the reality that the increasing sophistication of computing and observing capabilities will continue to stress funding for scientific research, NESL must strive to enhance synergy and collaboration and ensure increased NCAR internal collaboration to achieve and maintain world leadership in its priority areas. Further enhancement of such collaborative efforts and development of new ones that bring NCAR-wide perspectives and experience to new and exciting challenges are critical to NESL maintaining and expanding its core activities and fulfilling its leadership role.

Greg Holland and Jim Hurrell

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
  - I.A. Formation and Spread of Aircraft-Induced Holes in Clouds
  - I.B. Atmosphere/Ocean Interactions
  - I.C. Laboratory Studies of Biogenic Hydrocarbon Oxidation Mechanisms
  - I.D. Research using Cloud Resolving Models (CRMs)
  - I.E. Laboratory Studies of Factors Controlling Biogenic Emissions
  - I.F. Organized Motion in Canopy Turbulence
  - I.G. Communicating Science Program
- II. Prediction Across Scales
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Scientific Discovery

NESL Annual Report Table of Contents

I. Scientific Discovery

- I.A. **Formation and Spread of Aircraft-Induced Holes in Clouds**
- I.B. **Atmosphere/Ocean Interactions**
- I.C. **Laboratory Studies of Biogenic Hydrocarbon Oxidation Mechanisms**
- I.D. **Research using Cloud Resolving Models (CRMs)**
- I.E. **Laboratory Studies of Factors Controlling Biogenic Emissions**
- I.F. **Organized Motion in Canopy Turbulence**
- I.G. **Communicating Science**

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
  - I.A. Formation and Spread of Aircraft-Induced Holes in Clouds
  - I.B. Atmosphere/Ocean Interactions
  - I.C. Laboratory Studies of Biogenic Hydrocarbon Oxidation Mechanisms
  - I.D. Research using Cloud Resolving Models (CRMs)
  - I.E. Laboratory Studies of Factors Controlling Biogenic Emissions
  - I.F. Organized Motion in Canopy Turbulence
  - I.G. Communicating Science Program
- II. Prediction Across Scales
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Formation and Spread of Aircraft-Induced Holes in Clouds

NESL/MMM, RAL, NASA Langley, and University of Wyoming scientists conducted research that combines a multi-faceted approach to hypothesize and test the physical and dynamical basis of aircraft-induced cloud holes. Results of their research show that the interactions of the microphysical processes of ice crystal growth in these clouds with the dynamics of the downdrafts around the center of the holes are responsible for the formation of the holes and their growth with time. Because hole-punch clouds are a phenomenon that anyone can see, this research has had broad appeal and is an excellent means for educating the public on basic cloud physics. The researchers applied a novel combination of techniques to understand hole-punch clouds by using satellite observations, aircraft track information, and detailed numerical modeling. A unique aspect of the study is its use of the Weather Research and Forecasting (WRF) model at the Large Eddy Simulation (LES) resolution to explain the importance of the latent heat release from the conversion of cloud water to ice and its role in spreading the holes in supercooled clouds.

Figure: Photos of aircraft-induced hole-punch clouds

Ice streamers nested within or falling from circular holes or elongated channels etched out of midlevel, supercooled clouds were first reported in the meteorological literature in the 1940s. For many years, their cause has been the subject of conjecture. A large horizontal loop in an altocumulus, sketched in a correspondence titled "Man-Made Cirrus?" in *Weather* in 1948, attributed the feature to an aircraft. In 1968 a photograph published in *Weatherwise* generated considerable interest in the "Hole-in-Cloud: A Meteorological Whodunit?" from the U. S. meteorological community (*Weatherwise*, 1968) and set off a round of speculation as to its cause. Most of the proposed mechanisms focused on how the unusual pattern of evaporation might have occurred, including the subsiding of air in the remnants of a hurricane's eye, to local warming of the air in dissipation trails, or distrails, caused by rocket exhaust, passing meteors, or the heat produced by the passage of a jet aircraft (*Weatherwise*, February 1969 and following issues). Another report specifically implicated jet aircraft in the generation of observed hole punch clouds embedded within altocumulus. The author proposed that acoustic shock waves generated by the aircraft produced the ice crystals. As recently as last year, in Moscow, RU, UFO's were attributed to these features ("U.F.O. Bizarre clouds filmed over Moscow. October 2009, **http://www.youtube.com/watch?v=KOWyZUI8a0g** and many other URL's).

Until recently, ice production by aircraft was considered to occur as contrails, which typically form behind jet aircraft as a result of engine combustion when the air temperature is –40°C and below, characteristic of cirrus-forming (ice-cloud) conditions. Jet aircraft fly predominantly at these temperature levels. Hole punch features occur at temperatures above –38°C, where supercooled droplets do not freeze "spontaneously" via homogeneous ice nucleation (T<-–38°C). In the 1980's, propeller-driven aircraft, were shown to generate ice crystals. However, the association of propeller aircraft with hole punch clouds, the observed link of holes to jet aircraft, the physics of how a narrow ribbon if ice crystals generated at the propeller tips can spread to nearly circular holes and the implied duration of these features from the extent of the circular holes, and the broader effects were not understood or explained.

The multi-faceted approach led by NESL/MMM scientists and colleagues moved the understanding of the physics of the process forward:

- From high resolution visible satellite imagery from a subfreezing layer cloud that contained more than 100 spectacular hole punch holes and canals, they measured the rate of spread and persistence of the holes and canal features—the duration of some of the holes exceeded three hours;
- Using FAA private and commercial flight position information for this case above, they evaluated the exact aircraft that produced the holes and canals and inadvertently seeded the cloud and demonstrated that

inadvertent ice production occurs from private, commercial and military propeller, and jet aircraft;

- They provided an explanation for how the ice production occurs for jet aircraft;
- They hypothesized on the mechanisms for the observed spread of the holes and their duration, and, using the WRF model, numerically modeled the layer cloud case, documenting from model runs with and without ice latent heating that ice latent heat release causes circulations that cause the holes to spread in a quasi-circular pattern over a long period of time, producing updrafts of up to 0.5 ms^{-1}, thus providing an explanation for hole and canal production in clouds;
- Using radar imagery, they demonstrated that aircraft departing from a major airport inadvertently seeded a low-level subfreezing cloud which generated copious snow—the bands of the snow followed aircraft tracks and was unlike the non-snow regions surrounding the flight tracks; and
- Using CALIPSO satellite lidar data and CloudSat satellite radar data for two years of continuous measurements, they quantified how frequently subfreezing layer clouds are susceptible to inadvertent seeding near five major commercial airports, evaluating the broader implications of the inadvertent seeding effect in that more aircraft deicing operations due to inadvertent snowfall are likely to be necessary as much as 20% of the time in midlatitude airport locations.

Further information on this research can be found in the paper:

Heymsfield, A. J., G. Thompson, H. Morrison, A. Bansemer, R. Rasmussen, P. Minnis, Z. Wang, D. Zhang, 2011: Formation and Spread of Aircraft-Induced Holes in Clouds. *Science*, **333**, 77-81.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

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NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
I.A. Formation and Spread of Aircraft-Induced Holes in Clouds
I.B. Atmosphere/Ocean Interactions
I.C. Laboratory Studies of Biogenic Hydrocarbon Oxidation Mechanisms
I.D. Research using Cloud Resolving Models (CRMs)
I.E. Laboratory Studies of Factors Controlling Biogenic Emissions
I.F. Organized Motion in Canopy Turbulence
I.G. Communicating Science Program
II. Prediction Across Scales
III. NESL Observational Science
IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Atmosphere/Ocean Interactions

In the past year NESL scientists collaborated with colleagues from Scripps Institute of Oceanography (University of California San Diego) and the Office of Naval Research (Physical Oceanography Program) to loosely couple a large-eddy simulation (LES) model of the high wind hurricane ocean boundary layer (OBL) with the NOAA/NCEP wave prediction code Wavewatch 3 (WW3). This one-way coupling allows researchers to study the structure and dynamics of high wind OBLs forced by wind and wave fields typical of hurricanes. For these process studies, idealized Hurricane Frances surface layer winds were used to drive WW3. The wave spectra generated by WW3 were further processed to produce numerous air-sea interaction variables including wave age, turbulent Langmuir number, profiles of Stokes drift velocity and wind-wave alignment angles. High resolution LES computations carried out on the left and right hand sides of the hurricane storm track, using the WW3 inputs, allowed sceintists to examine the deepening of the OBL induced by inertially rotating winds and with surface wave effects. The figure below compares the maximum vertical velocity variance w^2_{max} from LES of the high wind OBL. The enhanced vertical velocity is induced by coherent Langmuir cells generated by the surface wave fields and suggests that surface waves play a role in the mixing of the hurricane driven OBL. Compared to classical flat wall boundary layers, surface waves increase the vertical velocity by roughly a factor of two.

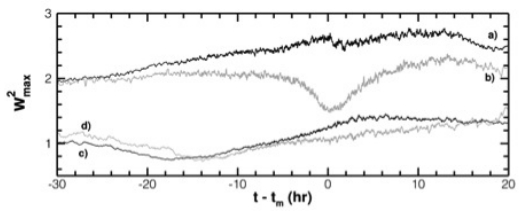

Figure: Temporal variation of the maximum resolved vertical velocity variance w^2_{max} for LES runs with and without wave effects at locations left and right of the storm center. The vertical velocity is normalized by the local friction velocity. Time is referenced to the time of maximum winds t_m. Simulations with wave effects are [a) and b)] and simulations with no wave effects are [c) and d)]. Runs [a) and c)] are carried out on the right hand side of the storm track while [b) and d)] are from simulations on the left hand side of the storm.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
  - I.A. Formation and Spread of Aircraft-Induced Holes in Clouds
  - I.B. Atmosphere/Ocean Interactions
  - I.C. Laboratory Studies of Biogenic Hydrocarbon Oxidation Mechanisms
  - I.D. Research using Cloud Resolving Models (CRMs)
  - I.E. Laboratory Studies of Factors Controlling Biogenic Emissions
  - I.F. Organized Motion in Canopy Turbulence
  - I.G. Communicating Science Program
- II. Prediction Across Scales
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Laboratory studies of biogenic hydrocarbon oxidation mechanisms

Emissions of volatile organic compounds (VOC) into the Earth's atmosphere are dominated on a global scale by natural (vegetative) sources. The most prevalent of these VOC is isoprene [formula C_5H_8, $CH_2{=}CH{-}C(CH_3){=}CH_2$], a species that thus plays a dominant role in the oxidative chemistry of many forested regions. While the degradation of this species under atmospheric conditions has been the subject of numerous studies over the last 20+ years, many unknowns remain. For example, theoretical studies (T. Dibble, J. Phys. Chem. A, 2004, 108, 2208–2215) demonstrated that complex chemical pathways might exist that lead to the formation of four multifunctional species, namely glyoxal, methyl glyoxal, hydroxyacetone and glycolaldehyde, as first-generation isoprene by-products. (Note that these compounds had previously been observed only as second-generation products).

In a collaborative study involving scientists at the University of Colorado and at NESL/ACD, the formation of these four multi-functional species has now been conclusively demonstrated in a series of laboratory experiments. The experiments were conducted in the NCAR Environmental Chamber, and isoprene and its degradation products were detected using a combination of Fourier Transform IR (FTIR) spectroscopy, Proton-Transfer Mass Spectroscopy (PTr-MS) and Cavity-Enhanced UV-Visible Differential Optical Absorption Spectroscopy (CE-DOAS). Of particular note, the species glyoxal (HCOCHO) and methylglyoxal (CH_3COCHO) were detected with very high sensitivity using the CE-DOAS system developed by the group of Rainer Volkamer at the University of Colorado. As shown in Figure 1, clear evidence for first-generation formation of these species (with yields of about 2%) have been demonstrated using the CE-DOAS system interfaced to the NCAR chamber. Complementary studies using the PTr-MS system show the concurrent formation of the other expected products of the chemistry, hydroxyacetone and glycolaldehyde, with similar yields.

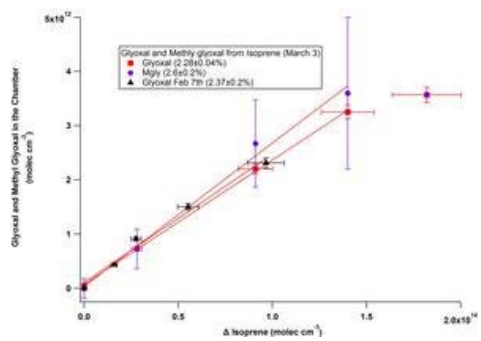

Figure 1. Glyoxal and methyl glyoxal from isoprene.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
I.A. Formation and Spread of Aircraft-Induced Holes in Clouds
I.B. Atmosphere/Ocean Interactions
I.C. Laboratory Studies of Biogenic Hydrocarbon Oxidation Mechanisms
I.D. Research using Cloud Resolving Models (CRMs)
I.E. Laboratory Studies of Factors Controlling Biogenic Emissions
I.F. Organized Motion in Canopy Turbulence
I.G. Communicating Science Program
II. Prediction Across Scales
III. NESL Observational Science
IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Research using Cloud Resolving Models (CRMs)

In FY 2011, NESL/MMM scientists used a cloud-system resolving model to investigate the effects of atmospheric aerosols on deep tropical convection. The model applied the double-moment warm-rain and ice microphysics schemes recently developed by the Hugh Morrison and Wojciech Grabowski. Two-dimensional ensemble simulations (240 members) were run with pristine, polluted, or highly polluted aerosol conditions and large-scale forcing from a 6-day period of active monsoon conditions during the 2006 Tropical Warm Pool - International Cloud Experiment (TWP-ICE). Domain-mean surface precipitation appeared insensitive to aerosols primarily because the large-scale forcing was prescribed and dominated the water and energy budgets. The spread of the top-of-atmosphere (TOA) shortwave and longwave radiative fluxes among different ensemble members for the same aerosol loading was surprisingly large, exceeding 25 W m-2 even when averaged over the 6-day period. This variability was caused by random fluctuations in the strength and timing of individual deep convective events. The ensemble approach demonstrated a small weakening of convection averaged over the 6-day period in polluted simulations compared to pristine simulations, in contrast to the invigoration hypothesis that implies the opposite effect. Despite this weakening, the cloud top heights and anvil ice mixing ratios were higher in polluted conditions (see figure). This occurred because of the larger concentrations of cloud droplets that freeze, leading directly to higher ice particle concentrations, smaller ice particle sizes, and smaller ice fall velocities compared to simulations with pristine aerosols. Weaker convection in polluted conditions was a direct result of the changes in anvil ice characteristics and subsequent upper-tropospheric radiative heating and weaker tropospheric destabilization. Such a conclusion offers a different interpretation of recent satellite observations of tropical deep convection in pristine and polluted environments compared to the hypothesis of aerosol-induced convective invigoration of polluted clouds.

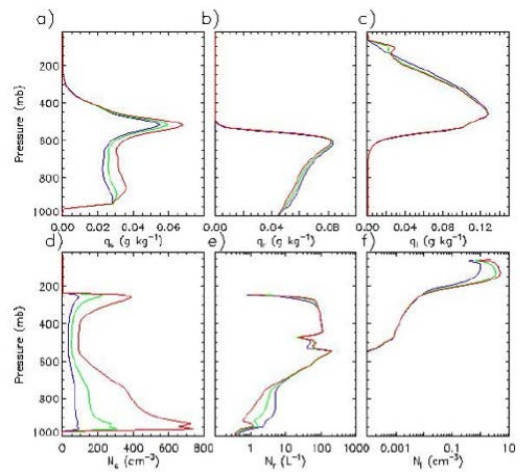

Figure: Profiles of horizontally-averaged a) cloud water mixing ratio, qc, b) rain mixing ratio, qr, c) ice mixing ratio, qi, d) cloud droplet concentration, Nc, e) rain number concentration, Nr, and f) ice number concentration, Ni. Results are averaged between 12 UTC 19 Jan. and 12 UTC 25 Jan. Number concentrations are averaged over grid cells with mixing ratio greater than 0.001 g kg-1 for the given hydrometeor species. Blue lines are for the pristine case, green are for polluted, and red are for highly polluted aerosol conditions.

Other work carried out in FY 2011 included continuation of the NSF-funded Center for Multiscale Modeling of Atmospheric Processes (CMMAP) project. NESL/MMM scientists continued to analyze the large-eddy simulation of a tropical deep convection system (Giga-LES), which resolves a wide range of scales from mesoscale organization down to turbulent motions and hence can be used as benchmark to study the relationship between the resolvable and SGS motions for cloud-resolving models (CRMs). In this study the moisture transport from the PBL to the cloud layer was investigated. The subcloud layer was conditionally sampled into six PBL regimes. Their composite structures and SGS moisture transports were

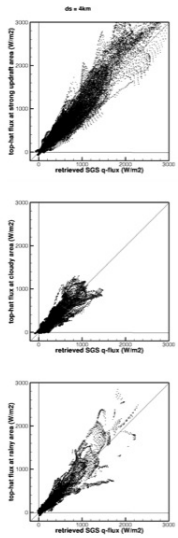

Figure 1: Comparison between the SGS moisture fluxes at the PBL top using the top-hat distribution and those retrieved from the benchmark in (a) PBL with low-level updrafts, (b) PBL under clouds, and (c) PBL with rain.

compared. The largest SGS moisture fluxes from the PBL to the cloud layer were found to occur at three PBL regimes: with low-level updrafts, under clouds, and with rain.

Several models were proposed for representing SGS moisture fluxes in CRMs and tested against the Giga-LES solutions. Here the top-hat-distribution model is shown as an example. Top-hat distribution assumes that all SGS statistics can be approximated by the difference between the averaged properties of SGS updrafts and downdrafts. Thus, the SGS moisture flux is modeled as $\tau_{wq}^{top-hat} = A(\widetilde{w_s^u} - \widetilde{w_s^d})(\widetilde{q_s^u} - \widetilde{q_s^d})$, where *A* is a proportionality constant, tilde represents CRM-grid averaging, subscript *s* indicates CRM-SGS motions, superscript *u* for updrafts and *d* for downdrafts. The figure below compares the modeled SGS moisture fluxes at the PBL top (with *A* tuned to 0.6) to those retrieved from the Giga-LES for the three PBL regimes with largest SGS fluxes. The point-by-point (of all sampled data) correlations indicate that the top-hat distribution can reasonably represent the spatial distribution of the SGS vertical fluxes in CRMs. The correlation coefficients at this height are about 0.95 for these three PBL regimes.

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Log in

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
I.A. Formation and Spread of Aircraft-Induced Holes in Clouds
I.B. Atmosphere/Ocean Interactions
I.C. Laboratory Studies of Biogenic Hydrocarbon Oxidation Mechanisms
I.D. Research using Cloud Resolving Models (CRMs)
I.E. Laboratory Studies of Factors Controlling Biogenic Emissions
I.F. Organized Motion in Canopy Turbulence
I.G. Communicating Science Program
II. Prediction Across Scales
III. NESL Observational Science
IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Laboratory Studies of Factors Controlling Biogenic Emissions

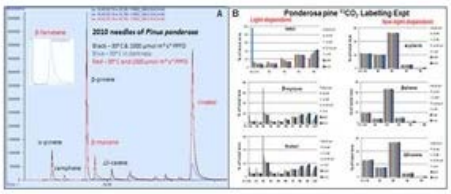

Figure 1. Laboratory observations characterizing sources of monoterpene emissions from Ponderosa Pine. Panel A below represents a gas chromatogram in which each peak represents a different monoterpene released from needles of a Ponderosa pine. Panel B shows the results from a $^{13}CO_2$ labelling experiment.

The characteristic odor we associate with pine forests is largely due to volatile organic compounds (VOC) called monoterpenes, released from pine needles. These terpenes are oxidized in the atmosphere and contribute to ozone formation and the growth of organic aerosols. Until recently, these emissions were thought to arise from static terpene pools found in resin ducts within the needles, in which case their release would be controlled solely by needle temperature. Recent evidence suggests that some monoterpenes are being produced continuously from photosynthetic intermediates and emitted immediately upon production rather than being stored. If this were the case, then light intensity, which controls photosynthesis, should also play a role in controlling monoterpene emissions. And if this is the case, such information needs to be incorporated into existing VOC emission models such as MEGAN. Figure 1 illustrates the results from laboratory studies designed to advance understanding of the processes controlling monoterpene emissions from vegetation. All measurements were obtained at 30°C but the red peaks were obtained in the light, while the blue peaks were obtained in the dark. While emissions of α-pinene, β-pinene and Δ-carene are approximately the same in light and dark, those of myrcene and linalool are clearly much reduced in the dark, suggesting they are produced in the light from carbon recently fixed in photosynthesis. The results from a $^{13}CO_2$ labelling experiment are also shown in Figure 1. The needles are first exposed to normal air and a sample of needle emissions collected for analysis by mass spectrometry. Then the needles are exposed to air containing 100% $^{13}CO_2$. The isotopic composition of any monoterpene emissions arising from stored pools should not change, but if monoterpenes are being produced from carbon newly fixed via photosynthesis, they should become rapidly labeled with heavy ^{13}C. In Panel B, α-pinene, β-pinene and Δ-carene show no change over time, consistent with the lack of any light response in Panel A. On the other hand, myrcene and linalool (as well as methylbutenol (MBO), another VOC known to be produced only in the light) show a rapid disappearance of ^{12}C and increasing amounts of ^{13}C, providing further evidence that they are produced from recently acquired carbon and not solely from storage pools.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
  - I.A. Formation and Spread of Aircraft-Induced Holes in Clouds
  - I.B. Atmosphere/Ocean Interactions
  - I.C. Laboratory Studies of Biogenic Hydrocarbon Oxidation Mechanisms
  - I.D. Research using Cloud Resolving Models (CRMs)
  - I.E. Laboratory Studies of Factors Controlling Biogenic Emissions
  - I.F. Organized Motion in Canopy Turbulence
  - I.G. Communicating Science Program
- II. Prediction Across Scales
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Organized Motion in Canopy Turbulence

NESL/MMM scientists and colleagues addressed stability influences on organized motion in canopy turbulence in their FY 2011 research. Under neutral atmospheric conditions where turbulence production occurs solely through shear, analysis of outdoor data and both numerical and wind tunnel simulations of neutrally stratified canopy flows suggest that organized motions on the scale of the canopy elements are largely responsible for within-canopy exchange.

In the past year, NESL canopy turbulence research has focused on educing how the mixing layer analogy evolves with an increasing importance of buoyancy forces. Analysis of data from: 1) the Canopy Horizontal Array Turbulence Study data (Patton et al., 2011), and 2) recently conducted high-resolution large eddy simulations resolving the details of a horizontally-homogeneous biologically active vegetative canopy interacting with a boundary layer across a range of stabilities spanning from near-neutral to strongly unstable (see figure) -- comprised NESL researchers' two-pronged approach.

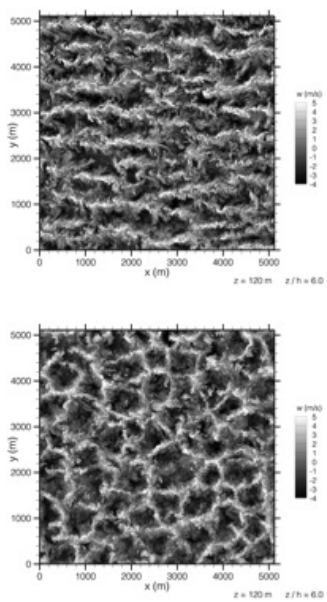

Figure: Example horizontal slices of vertical velocity at a height of 120m from two canopy-resolving large-eddy simulations for two different atmospheric stability regimes; left) near-neutral, right) strongly unstable. Note the very different large-scale structure in the flow. When turbulence is driven more-so by shear than buoyancy (near-neutral, left) the atmosphere organizes into long rolls. However, when buoyancy becomes more important than shear (strongly unstable, right), the hexagonally shaped convective plumes dominate vertical transport. Our current research thread aims to establish how canopy exchange processes evolve under the influence of such stability-driven evolution of the boundary layer and forcing.

Through this effort it has been established that unstable stratification not only modifies the canopy shear instability, but that it also develops convective boundary-layer scale thermals (right side figure), which partitions near-canopy flow into two distinct modes. Below sinking regions where stream-wise velocity shear is high, shear instability eddies appear and dominate heat and momentum transport. Below the upwelling regions of the convective cells where shear is low, canopy-scale convective plumes appear and coalesce forming the upwelling portions of the larger PBL-scale convective cells. The nature and controlling parameters of these canopy plumes remain under investigation. This bi-modal transport has significant implications for modeling and observation of canopy-atmosphere exchange -- which remain to be worked out, but are likely profound. In particular, scientists must be aware that the eddies associated with the shear instability are coherent over a much smaller vertical extent than are the thermal canopy plumes; a finding which poses significant complications for simple parameterization schemes used in weather and climate forecasting.

https://web.archive.org/web/20130726005010/https://nar.ucar.edu/2011/lar/nesl/organized-motion-canopy-turbulence[12/30/2016 12:11:19 PM]

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
  - I.A. Formation and Spread of Aircraft-Induced Holes in Clouds
  - I.B. Atmosphere/Ocean Interactions
  - I.C. Laboratory Studies of Biogenic Hydrocarbon Oxidation Mechanisms
  - I.D. Research using Cloud Resolving Models (CRMs)
  - I.E. Laboratory Studies of Factors Controlling Biogenic Emissions
  - I.F. Organized Motion in Canopy Turbulence
  - I.G. Communicating Science Program
- II. Prediction Across Scales
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Communicating Science Program

The Communicating Science Program is a loose consortium between the UCAR and NCAR, and specifically between the UCAR Communications Unit and Education and Outreach (E&O), and NESL. The program aims to establish contacts with specific societal groups, to develop an understanding of their perspectives and views in relation to major issues that can be positively informed by science, and to develop new communications strategies and language to enable the 2-way flow of information. This goal arose from a series of workshops and discussions with communications experts during 2010, both at NCAR and NSF, from which a white paper was developed outlining the issues and where scientific communication was failing to get its message through.

Once a contact with a particular group has been accomplished, framing the message in an adequate manner involves a difficult balancing act between the art of communication and the rigor and consistency of science. Physical scientists have typically erred on the side of rigor; we are in essence framing our message for scientists. This is not a viable communications strategy, as has been emphasized by Mooney (2010, Do Scientists Understand the Public? American Academy of Sciences, 17 pp. **www.amacad.org/publications/scientistsunderstand.aspx**). Our goals here are to develop an intimate understanding of the groups we are working with and to learn how to communicate our scientific message in a frame that enhances understanding and action on their behalf.

The principles for this activity, together with an initial plan were outlined in a white paper "Communicating Science in an Era of Mass Communication." This laid out a carefully-considered and researched strategy for moving forward, including further training for scientists and developing contacts with specific community groups. The latter requires scientists learn communication techniques that go far beyond the simple scientific aspects to included subtleties of how the message is interpreted within the cultural, religious, economic and political perspectives of the target audience.

Making these community contacts is a slow and careful process in which both sides need to develop an understanding and respect for the views and mores of the other, together with a common language that can facilitate the communication.

Progress during FY 2011 has been pleasing. We have:

- Arranged for the NSF-developed science communications training program: "Becoming the Messenger" to be brought to NCAR for the benefit of UCAR and NCAR staff;
- Joined in education sessions at the 2010 AGU Fall Meeting, and coordinated follow-up sessions for the 2011 Fall Meeting;
- Provided support and encouragement for a climate science communications expert, Susan Hassol, to work within NCAR on the establishment of her science communication program, a project of the non-profit Aspen Global Change Institute that is funded by the Rockefeller Brothers Fund and ClimateWorks Foundation (see **http://climatecommunication.org/**);
- Held a meeting with Elders of the Boulder Seventh Day Adventist Church and participated in an extensive and wide-ranging panel session with the full congregation in their chapel. The panel members were two NCAR scientists, the Pastor and a Church Elder (who is also a scientist). Attendance was excellent, and the discussion on the broad topic of how scientists and the religious community perceive "truth" was in-depth, conducted in an atmosphere of mutual respect, and educational. A follow-up meeting on climate change and its impacts will be held in NCAR in early November;
- Established contacts with the Native American community. This proved to be quite difficult due partly to a strong dislike for authority figures (including scientists), who traditionally have come more to preach and tell the community what to do, rather than work with them on understanding and helping with the issues as they see them. However, we now have made excellent progress, and this will precipitate several community meetings and support for Native American College students to further their education through attendance at tribal council meetings and working with NCAR scientists.

In addition there have been a wide number of other activities undertaken by the UCAR Communications Unit and E&O as part of their own activities, some of which have been contributed to by NESL staff. These activities are reported separately by the Communications Unit and E&O program.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

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NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
II.A. CESM/CCSM
II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
II.B.1. WRF-Chem Highlights
II.C. CAM-Chem Highlights
II.D. Nested Regional Climate Model (NRCM)
II.E. Model for Prediction Across Scales (MPAS)
II.F. WACCM Highlight – Elevated Stratopause Events
II.G. Integration Across Scales – Global, regional and Local Air Pollution
II.H. MEGAN Model
II.I.1. Present Climates
II.I.2. Past Climates
II.I.3. Storage of Heat in the Ocean
II.J. Human Activity in an Earth System Hierarchy
III. NESL Observational Science
IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Prediction Across Scales

NESL Annual Report Table of Contents

II. Prediction Across Scales

- II.A. **CESM/CCSM**
- II.B. **The Weather Research and Forecasting (WRF) Model and Data Assimilation System**
  - II.B.1. **WRF-Chem Highlights**
- II.C. **CAM-Chem Highlights**
- II.D. **Nested Regional Climate Model (NRCM)**
- II.E. **Model for Prediction Across Scales (MPAS)**
- II.F. **WACCM Highlight – Elevated Stratopause Events**
- II.G. **Integration Across Scales – Global, regional and Local Air Pollution**
- II.H. **MEGAN Model**
- II.I. Connecting Past, Present, and Future Climates
  - II.I.1. **Present Climates**
  - II.I.2. **Past Climates**
  - II.I.3. **Storage of Heat in the Ocean**
- II.J. **Human Activity in an Earth System Hierarchy**

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
  - II.A. CESM/CCSM
  - II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
  - II.B.1. WRF-Chem Highlights
  - II.C. CAM-Chem Highlights
  - II.D. Nested Regional Climate Model (NRCM)
  - II.E. Model for Prediction Across Scales (MPAS)
  - II.F. WACCM Highlight – Elevated Stratopause Events
  - II.G. Integration Across Scales – Global, regional and Local Air Pollution
  - II.H. MEGAN Model
  - II.I.1. Present Climates
  - II.I.2. Past Climates
  - II.I.3. Storage of Heat in the Ocean
  - II.J. Human Activity in an Earth System Hierarchy
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

CESM: Community Earth System Model

Overview

An imperative for NCAR is to develop and continuously improve a comprehensive Earth modeling system that is at the forefront of international efforts to understand and predict the behavior of Earth's climate. For many years the Community Climate System Model (CCSM) met this challenge. Its output, for instance, has been used in hundreds of peer-reviewed studies to better understand the processes and mechanisms responsible for climate variability and climate change. In addition, simulations performed with CCSM have made a significant contribution to both national and international assessments of climate, including those of the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Global Change Research Program (USGCRP). A trademark of the CCSM project is that it is a community collaboration. It is unique in the climate modeling sphere because of its commitment to make the model readily available to, and usable by, the climate research community. Community members are actively engaged in the ongoing process of model development.

Recent Accomplishments

CESM1.0

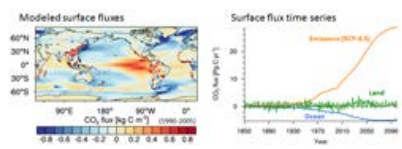

Figure: Surface Fluxes. A) The simulated surface flux of carbon dioxide averaged from 1990-2005 and (B) the globally averaged timeseries of surface fluxes of CO2 in the ocean (blue), land (green) and the specified emissions (orange). [**high resolutin image**]

The development of the model is a continuous process. Version 4 of CCSM was released to the community in April 2010, and it features many notable improvements over previous versions of the model (see, **http://www.ccsm.ucar.edu/models/ccsm4.0/notable_improvements.html**). To address a wider range of pressing scientific questions, additional capabilities have been added to CCSM4.0. These include, for instance, an interactive carbon cycle in the land component and an ecosystem-biogeochemical module in the ocean component. There is also an updated atmospheric chemistry component, a global dynamic vegetation component, and land use changes due to human activity in the land component. A new version of the atmospheric component model now allows scientists to study both the direct and indirect effects of aerosols. The model can be run using the Whole Atmosphere Community Climate Model (WACCM), in order to better understand the role of the upper atmosphere in climate variability and change. There is also an early version of a land-ice component that can be used to simulate changes to the Greenland ice sheet and its role in future climate change (e.g., the rate at which land ice will melt under future emission scenarios and the contribution of the melt to future sea level rise). Additionally, data assimilation using the Data Assimilation Research Testbed (DART) is now possible within the atmosphere and ocean model components allowing for the simulation of initialized forecasts. Since the most widely used description of a model with these capabilities is an "Earth System Model", the project and supported model is now called the "Community Earth System Model", or CESM. The release of Version 1 of CESM occurred in June 2010. The CESM1.0 can be run in numerous configurations, of which CCSM4.0 is one option.

The new capabilities in the CESM1.0 model allow for a wider range of scientific investigations. For example, CESM1.0 has a sophisticated representation of the global carbon cycle. Simulations with prognostic carbon are being used to study the terrestrial and marine uptake of anthropogenic CO2 and how these vary over time. As shown in Figure 1, CESM1.0 simulations suggest that natural carbon sinks in the marine and terrestrial systems vary considerably over the 20th and 21st centuries. Carbon uptake is sensitive to climate variations and an improved understanding of these processes is critical for robust climate prediction.

While climate simulations have traditionally focused on secular changes over century timescales, there is a great need for near-term societally-relevant climate information. With the incorporation of the DART algorithm into the CESM system, there is now the possibility to perform forecasts that have been initialized with observed data. A suite of

CCSM4 decadal prediction ensemble simulations show promise for predictive capability on a several year timescale. As shown in Figure 2, after drift correction, the predicted upper-ocean heat content anomaly in the North Atlantic subpolar gyre shows a good correspondence with a hindcast ice-ocean coupled simulation that is forced with observed atmospheric conditions (which is regarded here as the truth). This suggests some predictability in this metric and ongoing research is examining the details and mechanisms responsible for this predictive capability.

CMIP-5 and IPCC

Both CCSM4.0 and CESM1.0 have been used to conduct an extremely ambitious set of simulations in support of the upcoming Fifth Assessment Report (AR5) of IPCC. The simulations are part of the so-called CMIP-5 experimental design, which is a set of coordinated climate model experiments on two time scales: (1) near-term, initialized decadal prediction simulations; and (2) long-term simulations. The long-term simulations include experiments from 1850 through the end of the current century and beyond and paleoclimate simulations for a number of different time periods. The CESM project has completed a large number of these simulations including experiments with a number of different CESM configurations. These configurations include simulations with an active prognostic carbon cycle, experiments with active atmospheric chemistry, and simulations with several different atmospheric components. The simulation output is being made freely available through the Earth System Grid so that they can be fully utilized by the community for scientific investigations. This will contribute to the scientific assessment being compiled for the IPCC-AR5.

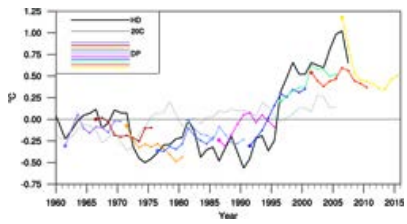

Figure: Annual mean 275-m heat content anomaly. Annual mean 275-m heat content anomaly in the subpolar gyre in the North Atlantic (in oC) from the hindcast experiment (HD; thick black curve), the CCSM4 20C 6-member ensemble mean (thin grey curve), and the DP 10-member ensemble means (colored curves). Large circles indicate the first-year average of each DP ensemble. The HD and 20C anomalies are computed relative to climatologies over the reference periods 1961-2007 and 1961-2005, respectively; DP anomalies are computed relative to the HD climatology, after bias correction. [**high resolutin image**]

CESM Tutorial

Educating the next generation of scientists in the use and development of Earth System Models is a priority for the CESM project. The second, annual, CESM tutorial occurred in August 2011 and, based on participant feedback, was extremely successful. The tutorial included 80 participants from over 35 U.S. and Canadian (UCAR member) universities, six foreign universities, NOAA facilities and three DOE National Laboratories. The participants primarily included graduate students and early career scientists. Web-based tutorial materials have been made freely available and are considerably extending the reach of the in-person tutorials.

2012 and Beyond

A major goal moving forward is to complete the CMIP-5 simulations using CESM1.0. A great number of simulations have been performed and among the many CMIP-5 simulations, a few points to note in particular include:

- CESM will make a unique contribution to AR5 through the completion of CMIP-5 experiments with more than one configuration of the atmospheric model. Different atmospheric components of CESM, for instance, will allow community scientists to estimate the indirect aerosol effect, determine the role of upper-atmospheric processes in climate, and analyze transient chemistry-climate simulations.
- Completion of simulations with the Community Ice Sheet Model (CISM) will place CESM among the very few international modeling groups to directly estimate the response of the Greenland and Antarctic ice sheets to future changes in climate.
- Simulations with CESM will allow scientists to understand and quantify anticipated changes to the carbon cycle and their feedback to climate.
- Work will be completed on ozone, deposition (nitrogen and aerosols) and aerosol concentration fields for both historical and future emission scenario simulations using CESM. Output will also be used as part of the IGBP Atmospheric Chemistry and Climate (AC&C) activity, which is focused on the understanding of the various radiative forcing agents and their changes from 1850 to 2100.

With the completion of many CMIP-5 experiments, a further priority is the development of the next version of the Earth System Model. This includes the development of new model capabilities, such as the incorporation of active Isotopes, and the use of new highly-scalable dynamical cores. These developments will allow for new scientific investigations and for example, will enable high resolution simulations with regional refinement.

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Log in

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
  - II.A. CESM/CCSM
  - II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
    - II.B.1. WRF-Chem Highlights
  - II.C. CAM-Chem Highlights
  - II.D. Nested Regional Climate Model (NRCM)
  - II.E. Model for Prediction Across Scales (MPAS)
  - II.F. WACCM Highlight – Elevated Stratopause Events
  - II.G. Integration Across Scales – Global, regional and Local Air Pollution
  - II.H. MEGAN Model
  - II.I.1. Present Climates
  - II.I.2. Past Climates
  - II.I.3. Storage of Heat in the Ocean
  - II.J. Human Activity in an Earth System Hierarchy
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

The Weather Research and Forecasting (WRF) Model and Data Assimilation System

The WRF-system effort in NESL/MMM supports an extensive WRF community that includes academic, operational, and commercial interests. WRF model components now include: the Advanced Research WRF (ARW) solver, the Non-hydrostatic Mesoscale Model (NMM) solver, WRF-Chem, the Advanced Hurricane research WRF (AHW), WRF-Fire, the Nested Regional Climate Model (NRCM), and the Global ARW. The WRF-Var data assimilation system includes: 3-dimensional variational (3DVAR), 4-dimensional variational (4DVAR), the WRF Data Assimilation Research Testbed (DART) ensemble assimilation system, and nudging methods.

WRF support activities include overall management of the WRF system, incorporating community enhancements and contributions into the model, regular WRF system updates, maintenance of a help service, and national and international workshops and tutorials each year. A key part of the support effort includes ensuring that WRF code improvements/upgrades are readily accessible to other configurations for specific applications; NESL/MMM staff maintains a single-source code repository so the latest versions of all components are available in the most recent release. In addition, the WRF team undertakes WRF-based research and development, provides support for field projects using real-time WRF, and conducts fundamental research on algorithms and techniques for the application of ensemble data assimilation. Substantial experimental and theoretical research is conducted on understanding physical and chemical processes to support development of improved methods for incorporating such processes in WRF. Close collaboration with universities and other NCAR scientists is a feature of this research and applications work. The WRF-Chem model is used for field program analysis, and to investigate regional-scale air quality and interactions between meteorology and chemistry. NESL scientists contribute to development of the WRF-Chem code by implementing new processes related to gas-phase and aerosol chemistry and adding diagnostic variables for the current model. The scientists evaluate and develop the model with several types of simulations, ranging from field program analysis of megacities to chemistry-climate studies. Close collaboration with other NCAR scientists and universities, particularly University of Miami, University of Washington, Penn State University, Yonsei University in Korea, and University of Oklahoma, is a feature of this research and applications work.

In FY 2011 NESL/MMM staff conducted two tutorials in Boulder, one in January–February and another in July. The first was attended by about 65 people and the second by about 60–80 people. MMM also organized and hosted the 12th WRF Users' Workshop in Boulder June 20–24. The first day presented a continuation of the model fundamentals lecture series that was begun last year, with the topic being PBL and land surface modeling. The body of the workshop featured WRF topic areas, while the final day offered instructional talks. Attendance was about 230.

MMM released WRF Version 3.3 in April 2011, offering many new features and improvements. They reflect contributions from throughout the WRF community and speak to WRF's position as a community model.

- Cumulus/convection options: Tiedtke cumulus scheme, new SAS (Simplified Arakawa-Schubert) scheme from the GFS, Zhang-Macfarlane scheme from CESM, University of Washington shallow convection scheme
- Microphysics: SUNY–Stonybrook (5-class) microphysics scheme, updated Thompson scheme, updated Milbrandt scheme, modified Morrison scheme
- Radiation: Goddard shortwave and longwave radiation physics schemes, improved RRTMG longwave scheme PBL and surface layer options: University of Washington TKE scheme, Total-Energy Mass Flux (TEMF) PBL
- HWRF improvements
- Numerous new WRF-Chem capabilities
- WRFDA upgrades: New RRTOV radiative transfer model, redesigned 4DVAR, new control variable option

MMM once again ran the ARW at 3-km resolution to support the NOAA Storm Prediction Center's Spring Forecast Experiment (SFE). As in years past, the forecasts were provided to the experiment participants and to NWS forecasters. This year, for the first time, the simulations were initialized with analyses produced by an ensemble data assimilation system using NCAR's Data Assimilation Research Testbed (DART). This employed a 50-member ensemble to generate the 15-km analyses used, for the experiment period of April 27–June 12. The effort was reported on at the 12th WRF Users' Workshop, with results showing competitive performance compared to previous seasons' forecasts using more traditional approaches.

MMM continued to run the Antarctic Mesoscale Prediction (AMPS) System, a real-time WRF system that provides guidance for forecasters of the United States Antarctic Program (USAP). AMPS employed WRF to complete its support of the 2010-2011 USAP field season. Developed this past season was a capability to produce WRF plots to track the course of NSF's *R/V Nathaniel B. Palmer* as it cruised the Ross Sea and Southern Ocean. The figure below presents an example of one of the ship-following WRF products. This shows the *Palmer*'s location (labeled "NBP") north (above) of the Ross Ice Shelf ice edge and west (leftward) of the Marie Byrd Land Coast, with surface winds, sea level pressure, and 3-hourly precipitation plotted.

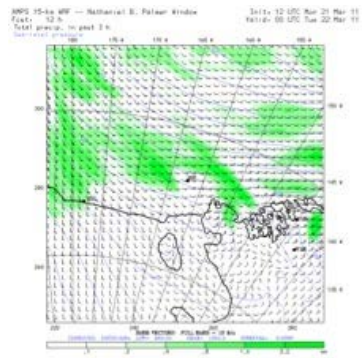

Figure: AMPS 12-hour forecast for area around NSF *R/V Nathaniel B. Palmer*. Surface winds (barbs; full barb = 10 kt), sea level pressure (contoured), and 3-hourly precipitation (mm, shaded) shown. Location of ship marked "NBP." Edge of Ross Ice Shelf to south, with Marie Byrd Land coastline to east (rightward).

MMM also again ran WRF in real-time over the Atlantic Basin for the 2011 hurricane season. The model was set up with a 3-grid configuration with 36-, 12-, and 4-km spacing. This real-time system was run for Hurricane Irene, the hurricane which caused extensive flooding in the Northeast. The figure below shows a sample plot of forecast central pressure and wind speed for Tropical Storm Philippe, for a five-day forecast initialized at 1200 UTC 26 Sept 20111.

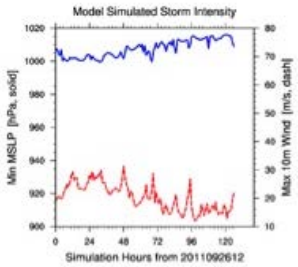

Figure: Forecast central pressure (mb) and wind speed (ms^{-1}) for Tropical Storm Philippe from real-time WRF hurricane run initialized at 1200 UTC 26 Sept 2011.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
  - II.A. CESM/CCSM
  - II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
    - II.B.1. WRF-Chem Highlights
  - II.C. CAM-Chem Highlights
  - II.D. Nested Regional Climate Model (NRCM)
  - II.E. Model for Prediction Across Scales (MPAS)
  - II.F. WACCM Highlight – Elevated Stratopause Events
  - II.G. Integration Across Scales – Global, regional and Local Air Pollution
  - II.H. MEGAN Model
  - II.I.1. Present Climates
  - II.I.2. Past Climates
  - II.I.3. Storage of Heat in the Ocean
  - II.J. Human Activity in an Earth System Hierarchy
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Weather Research and Forecast model coupled with Chemistry (WRF-Chem)

The Weather Research and Forecasting (WRF) model coupled with Chemistry (WRF-Chem) has been and continues to be developed by NOAA scientists, in collaboration with the WRF community including NCAR/NESL scientists. The model is used for investigation of regional-scale air quality, field program analysis, and cloud-scale interactions between clouds and chemistry.

Over the past year, WRF-Chem development by NESL staff has included a wet scavenging routine for soluble gas species, a chemical upper boundary condition to represent better stratospheric chemistry, a diagnostic package for recording chemical species mixing ratios along aircraft or satellite tracks, and a pre-processor for creating biomass burning emission inputs. In addition, a methodology for tracing sources of carbon monoxide (CO) and an empirical, simplified modeling framework for predicting secondary organic aerosol formation in polluted regimes have been implemented in WRF-Chem. The benefits of these last two code developments are highlighted below.

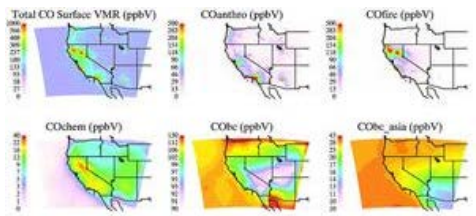

Figure 1. WRF-Chem CO surface mixing ratios ratios (ppbv) of total CO and CO tracers averaged for 20 June – 15 July 2008.

Because air pollution is of concern in many parts of California, CO tracers representing different CO sources in the model aid the analysis of the CO budget. The CO tracers allow estimation of the relative importance of local sources versus pollution inflow. The study found that anthropogenic emissions (on average 61 95 ppbv), local fire emissions of CO (84 194 ppbv), and the inflow of CO from long-range transport (99 11 ppbv) contribute similar amounts of CO to the California region (Figure 1).

Because accurate predictions of secondary organic aerosols (SOA) are important for predicting aerosol evolution and radiative forcing for future climate scenarios, chemistry and climate models must improve their SOA production mechanisms. Current models have based their SOA production on lumped product parameterizations derived from laboratory experiments and generally underpredict the SOA levels up to an order of magnitude. To provide a computationally inexpensive method to calculate SOA mass and hygroscopicity that can be used in global and climate models, an empirical parameterization, based on the observed proportionality of SOA concentrations to excess CO and photochemical age of the airmass, has been formulated. For simulations of the Mexico City region, the results were found to be in better agreement with measured SOA than other methods of predicting SOA (Figure 2). This simple, empirical method has the advantage of being about ten times less computationally expensive than the volatility basis approach, and can be used in regions where the emissions of SOA precursors are not yet available.

Figure 2. (a)) Evolution of the SOA/ΔCO ratio as a function of photochemical age used to derive the simplified SOA parameterization. (b) Average diurnal profiles of observed and predicted SOA concentrations in the downtown Mexico City (March 2006, MILAGRO data)

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

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NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
II.A. CESM/CCSM
II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
II.B.1. WRF-Chem Highlights
II.C. CAM-Chem Highlights
II.D. Nested Regional Climate Model (NRCM)
II.E. Model for Prediction Across Scales (MPAS)
II.F. WACCM Highlight – Elevated Stratopause Events
II.G. Integration Across Scales – Global, regional and Local Air Pollution
II.H. MEGAN Model
II.I.1. Present Climates
II.I.2. Past Climates
II.I.3. Storage of Heat in the Ocean
II.J. Human Activity in an Earth System Hierarchy
III. NESL Observational Science
IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

CAM-Chem Highlights

The development of CAM-chem over the last year has focused on the following areas: 1) ability to use specified dynamics, 2) improve the representation of stratospheric chemistry and wet removal, 3) include the representation of short-lived halogen chemistry in the troposphere, 4) update and expand the representation of biogenic emissions of volatile organic compounds, and 5) high-resolution. The first two items have led to one publication currently under review in Geosci. Model Dev. Disc. The third one has led to two publications currently under review in Atmos. Chem. Phys. Disc.

We are currently performing simulations of tropospheric chemistry with horizontal resolution of approximately 0.5° (50 km at the Equator), leading to improved representation of emission patterns and pollution plumes (Figure 1).

Recent applications of CAM-chem have focused on projections (up to 2100) of short-lived climate forcers (aerosols and ozone) and deposition fields necessary for the CMIP5 simulations using CCSM4. Results from the CAM-chem simulations are discussed in Lamarque et al., Climatic Change, 2011.

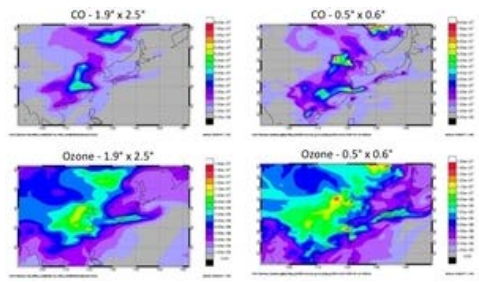

Figure 1. Comparison of surface CO and Ozone over East Asia from CAM-chem at the standard resolution of approximately 2° to the new simulations at approximately 0.5°.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
II.A. CESM/CCSM
II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
II.B.1. WRF-Chem Highlights
II.C. CAM-Chem Highlights
II.D. Nested Regional Climate Model (NRCM)
II.E. Model for Prediction Across Scales (MPAS)
II.F. WACCM Highlight – Elevated Stratopause Events
II.G. Integration Across Scales – Global, regional and Local Air Pollution
II.H. MEGAN Model
II.I.1. Present Climates
II.I.2. Past Climates
II.I.3. Storage of Heat in the Ocean
II.J. Human Activity in an Earth System Hierarchy
III. NESL Observational Science
IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Nested Regional Climate Model (NRCM)

The enabling tool for much of the Prediction Across Scales research is the community NRCM. This involves embedding the Advanced Research WRF (ARW) and Regional Ocean Model System (ROMS) within CCSM. The initial combination has already provided significant advances together with valuable early predictions to industry. NRCM simulations and analyses will advance to multi-decadal simulations at 12-km resolution for all of the North Atlantic and North and Central America, and 4-km resolution over the United States. This work is being carried out in collaboration with DOE, the Research Program to Secure Energy for America, Willis Re, and the Western Governors' Association.

The NRCM is an adaptation of the ARW for use in studies of regional climate in conjunction with the CCSM system. It combines extensive NCAR weather and climate expertise and systems, with goals of providing a testbed for gaining experience in support of the next generation approach to seamless weather/climate modeling, enabling development and testing of new physical and dynamical core approaches, discovering remote impacts of local processes (upscaling), and providing initial assessments of regional climate changes to societal groups. Further, the NRCM program directly supports several high priority NCAR Frontier Programs, including informing climate change adaptation and mitigation, water resource availability, vulnerability and adaptation planning in western North America, and development of new methods to more accurately assess regional climate.

Multi-decadal regional climate simulations have been completed at 12-km grid spacing with the NRCM over the North Atlantic basin and most of North America, spanning a period from current climate out to the 2050s. These simulations provided information on regional climate variability and change in unprecedented detail. In particular, tropical cyclones show an increase in both frequency and intensity in the future with the largest increases for the strongest storms, in agreement with other modeling studies and theory. Many data users within and outside NCAR are analyzing the NRCM data for a variety of applications including water resources over the Western US, ecosystem sensitivity, and rainfall over the Sahel. Work is underway to simulate the regional climate of North America using 4-km grid spacing and time has been awarded on an IBM machine at Argonne National Laboratory to perform these computationally expensive simulations.

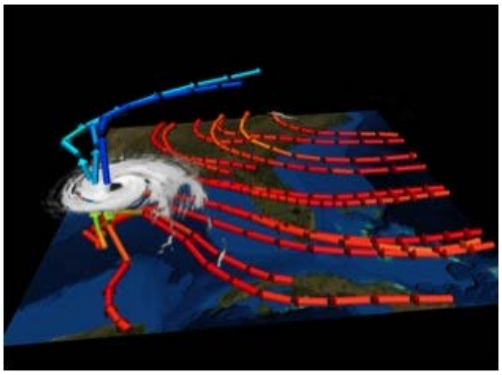

Figure: A simulated hurricane in the year 2055 downscaled from the Community Climate System Model version 3 under A2 emissions scenario using the NRCM. White is outgoing longwave radiation and the arrows are streamlines of 25 seeds that start evenly spaced at 500 meters above the ground, colored by altitude.

In building the capabilities for high-resolution weather, and air quality NRCM-Chem simulations, NESL scientists have added a chemical upper boundary condition to represent stratospheric chemistry and have implemented a reduced chemistry mechanism to reduce computational burden yet have a reasonable parameterization of tropospheric chemistry.

A key modeling need is two-way coupling of the NRCM atmospheric model to an ocean model to address a variety of science questions. Of particular interest is the impact of the two-way atmosphere-ocean feedback on long-term tropical cyclone variability. The Advanced Research WRF (ARW), the model on which the NRCM is based, has been successfully connected to a flux coupler and established on NCAR machines. Now that the NRCM is connected to the flux coupler, a variety of additional Earth system components, including the ocean, can fully interact with the NRCM.

The NRCM continues to be the enabling tool and focus for multidisciplinary collaborative research aimed at understanding regional climate impacts on society. Significant university collaborations include the University of Pennsylvania Wharton School, Texas A&M University, University of New Mexico, Chiang Mai University, Leibniz University of Hannover, and many others through the Willis Research Network. NRCM has been released under WRF 3.3 for community use and is used by many academic and governmental

groups including Bjerknes Centre for Climate Research, the National Centre for Atmospheric Science, UK, and the Coordinated Regional Downscaling Experiment (CORDEX) program. Offshore energy and reinsurance industries continue to play a supporting role in both basic research and in providing industry perspectives on user needs of regional climate information.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

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NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
II.A. CESM/CCSM
II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
II.B.1. WRF-Chem Highlights
II.C. CAM-Chem Highlights
II.D. Nested Regional Climate Model (NRCM)
II.E. Model for Prediction Across Scales (MPAS)
II.F. WACCM Highlight – Elevated Stratopause Events
II.G. Integration Across Scales – Global, regional and Local Air Pollution
II.H. MEGAN Model
II.I.1. Present Climates
II.I.2. Past Climates
II.I.3. Storage of Heat in the Ocean
II.J. Human Activity in an Earth System Hierarchy
III. NESL Observational Science
IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Model for Prediction Across Scales (MPAS)

The Model for Prediction Across Scales (MPAS) goal is to develop a next-generation modeling system suitable for weather, regional climate, and climate and Earth system research and prediction. NESL scientists are working to develop a new weather and climate model as a single system that will be suitable for simulating small scales (e.g., clouds, small hydrologic basins, and small estuaries) and large scales (e.g., planetary atmospheric waves and Earth-ocean circulations) that interact. Strong consensus exists among scientists that the challenge of simulating both climate and weather with a single modeling system will improve model fidelity for both applications, in addition to focusing and leveraging development efforts from both the climate and weather prediction communities.

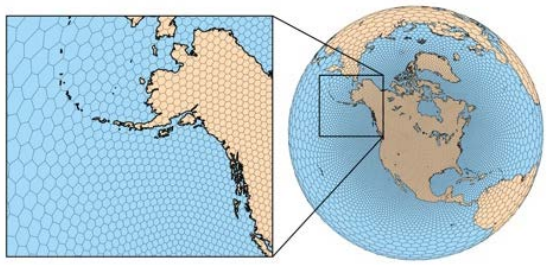

Figure: An MPAS variable resolution mesh with 8x refinement. Variable mesh forecasts using a higher density 8x mesh are given in the figure 2 below.

A critically important component of this project is to develop MPAS components (atmosphere, ocean, land surface models, etc.) that scale well on the new computer architectures, and that are capable of simulating all the scales necessary in NCAR and community research and production applications.

Building on significant progress being made in developing a decadal climate prediction capability using CCSM4, NESL scientists will start decadal prediction experiments using ensemble initialization. This system uses the DART of the Data Assimilation Research Section in IMAGe. The ocean initial conditions obtained using DART reduces the initial state bias in the North Atlantic SSTs compared to previously used ocean hindcast initialization. The framework naturally provides ensemble initialization, which consistently characterizes uncertainties in the decadal prediction.

Accomplishments in FY 2011 include completing initial development of a 3-D hydrostatic global model within the MPAS based on icosahedral grids (hexagons) for discretizing the sphere. NESL scientists are collaborating with LANL for initial testing of the core within the CESM/CAM framework using aquaplanet (APE) and AMIP simulations. Scientists have implemented the WRF/NCRM atmospheric physics suite in MPAS for both weather and regional climate applications. Initial development and testing of the nonhydrostatic atmospheric core within MPAS has been completed and testing at nonhydrostatic scales on the sphere has begun. The transport scheme development is also complete.

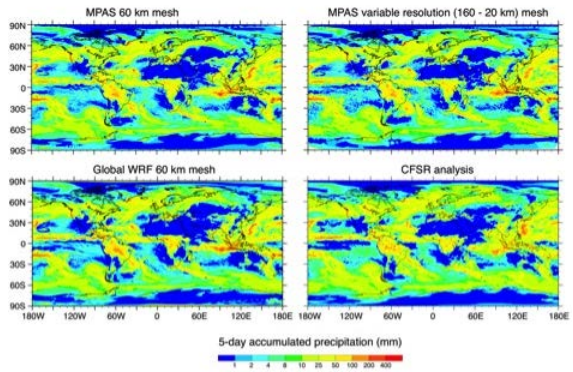

Figure 2: 5-day accumulated precipitation forecasts valid on 0Z 20 October 2010 from uniform and variable-resolution configurations of MPAS model, from the global Advanced Research WRF mode and from the NCEP Climate Forecast Systems Reanalysis.

The FY 2011 activities have allowed evaluation of the viability of the MPAS hydrostatic and nonhydrostatic atmospheric dynamical solvers formulations using hexagonal grids. The solvers have been shown to be sufficiently accurate and reasonably efficient on uniform- and variable-resolution grids. With these models, NESL scientists will soon be in position to take advantage of the NSF Tier 1 and existing NSF Tier 2 machines (e.g., Ranger, Kraken) for the community's global nonhydrostatic simulation needs.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
  - II.A. CESM/CCSM
  - II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
  - II.B.1. WRF-Chem Highlights
  - II.C. CAM-Chem Highlights
  - II.D. Nested Regional Climate Model (NRCM)
  - II.E. Model for Prediction Across Scales (MPAS)
  - II.F. WACCM Highlight – Elevated Stratopause Events
  - II.G. Integration Across Scales – Global, regional and Local Air Pollution
  - II.H. MEGAN Model
  - II.I.1. Present Climates
  - II.I.2. Past Climates
  - II.I.3. Storage of Heat in the Ocean
  - II.J. Human Activity in an Earth System Hierarchy
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

WACCM Highlight - Elevated Stratopause Events

The Whole Atmosphere Community Climate Model (**WACCM**) simulates many features of the stratosphere, including the very active dynamics in Northern Hemisphere winter. During midwinter in some years, there are major breakdowns of the polar winter vortex known as sudden stratospheric warmings. The frequency and development of these events simulated in WACCM are similar to observations. After some observed warmings, the position of the stratopause (the temperature maximum that marks the boundary between the stratosphere and the mesosphere above) in high latitudes is displaced to much higher altitude. The simulation of these events in a free-running model provides a tool for investigating their causes and evolution.

The composite is referred to the date (day 0, indicated by the dashed line) when the temperature maximum that constitutes the polar stratopause suddenly "jumps" discontinuously from about 40 km altitude to near 80 km. The elevated stratopause event is initiated by planetary wave-mean flow interaction, which reverses the zonal wind in the stratosphere from westerly to easterly and drives a strong circulation anomaly, with descent below 70 km and ascent above, just before the stratopause jump at day 0. After the stratopause jump, westerly winds recover in the stratosphere and the stratopause descends gradually, accompanied by strong downwelling driven by small-scale gravity waves.

The details of the mechanism and its relationship to stratospheric sudden warmings are described in a recent paper by de la Torre et al. (*J. Geophys. Res.*, 2011, submitted).

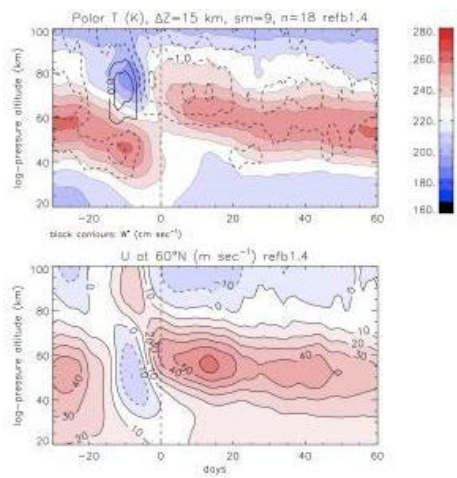

Figure 1. A composite "elevated stratopause" event simulated by the Whole Atmosphere Community Climate Model (WACCM). Upper panel: polar cap (70-90°N) temperature (color bar on right) and mean meridional vertical velocity (contours, at 0.5 cm s-1 intervals). Lower panel: zonal-mean zonal wind at 60°N.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
II.A. CESM/CCSM
II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
II.B.1. WRF-Chem Highlights
II.C. CAM-Chem Highlights
II.D. Nested Regional Climate Model (NRCM)
II.E. Model for Prediction Across Scales (MPAS)
II.F. WACCM Highlight – Elevated Stratopause Events
II.G. Integration Across Scales – Global, regional and Local Air Pollution
II.H. MEGAN Model
II.I.1. Present Climates
II.I.2. Past Climates
II.I.3. Storage of Heat in the Ocean
II.J. Human Activity in an Earth System Hierarchy
III. NESL Observational Science
IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Integration Across Scales - Global, Regional and Local Air Pollution

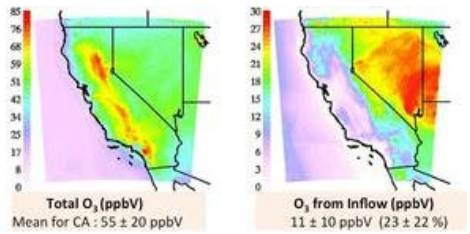

Figure 1. WRF-Chem simulation for California for 20 June – 10 July 2008.

The role of pollution inflow on local air quality is gaining importance as health standards get tighter and local emission controls are not sufficient to ensure attainment. Understanding and quantifying this impact requires an integration across scales of observations and also of modeling tools. We use the regional chemical transport model WRF-Chem in combination with the global NCAR models MOZART-4 and CAM-Chem to shed light into this open question. Spatially and temporal varying global model output is used to provide boundary conditions for the regional simulations. Using synthetic model tracers ("tags") we are able to follow the pollution inflow through the regional domain and estimate its contribution to local surface air quality. As an example, we show in the above Figure results from a WRF-Chem simulation for California (CA) for 20 June – 10 July 2008, in which ozone and ozone precursors entering the domain at the lateral boundary conditions are tagged and followed through the regional domain. High values of afternoon surface ozone in CA are seen around the L.A. basin and throughout the Central Valley. Contributions from inflow are, on average, largest in North California and the mountain areas to the West, averaging 11±10 ppbV over the state. The high standard deviation reveals the large (spatial and temporal) variability in the influence of pollution inflow on surface air quality.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
  - II.A. CESM/CCSM
  - II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
  - II.B.1. WRF-Chem Highlights
  - II.C. CAM-Chem Highlights
  - II.D. Nested Regional Climate Model (NRCM)
  - II.E. Model for Prediction Across Scales (MPAS)
  - II.F. WACCM Highlight – Elevated Stratopause Events
  - II.G. Integration Across Scales – Global, regional and Local Air Pollution
  - II.H. MEGAN Model
  - II.I.1. Present Climates
  - II.I.2. Past Climates
  - II.I.3. Storage of Heat in the Ocean
  - II.J. Human Activity in an Earth System Hierarchy
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Continued Development of the Model of Emissions of Gases and Aerosols from Nature (MEGAN)

NESL scientists and university collaborators have continued to develop that community Model of Emissions of Gases and Aerosols from Nature (MEGAN), which is a modeling system for estimating the net emission of gases and aerosols from terrestrial ecosystems into the atmosphere. A new version of MEGAN was completed in FY 2011 in collaboration with Colorado State University that provides an improved integration with the NCAR Community Land Model (CLM). Advances in MEGAN include algorithms to characterize the response to future changes in CO2 and to account for circadian rhythms that are also known as "biological clocks". In each case, observational studies were conducted to quantify the response of biogenic emissions, such as the hydrocarbon isoprene, to these processes and the results incorporated in to the MEGAN model. Working in collaboration with Lancaster University, NESL scientists developed a revised model that included a circadian pattern of biogenic emissions and used this to derive inputs for the WRF-CHEM model to simulate ozone distributions. Figure 1 shows that ozone differed by 5 ppb or more when the new algorithm was used. The revised model predictions were compared to observed ozone measurements from 290 monitoring sites in the United States which indicated that model accuracy was significantly improved when the circadian rhythm was included. The results are described in more detail in Nature Geoscience (Hewitt et al. 2011, **DOI: 10.1038/ngeo1271**).

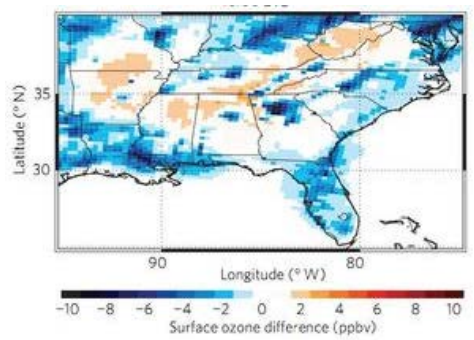

Figure 1. Change in WRF-CHEM simulations of near surface ozone for cases with and without circadian control in MEGAN isoprene emission estimates.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
  - II.A. CESM/CCSM
  - II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
  - II.B.1. WRF-Chem Highlights
  - II.C. CAM-Chem Highlights
  - II.D. Nested Regional Climate Model (NRCM)
  - II.E. Model for Prediction Across Scales (MPAS)
  - II.F. WACCM Highlight – Elevated Stratopause Events
  - II.G. Integration Across Scales – Global, regional and Local Air Pollution
  - II.H. MEGAN Model
  - II.I.1. Present Climates
  - II.I.2. Past Climates
  - II.I.3. Storage of Heat in the Ocean
  - II.J. Human Activity in an Earth System Hierarchy
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Present Climates

Overview

NESL/CGD researchers are exploiting a wide array of observational data sets to diagnose how the atmosphere, oceans, cryosphere, and land surface have evolved in the recent past, and to understand what factors have contributed to those changes, including natural and human-induced processes. Modeling and diagnostic observational analysis of present-day climate variability and change provides a vital test of our ability to predict future climate. A major focus of this research has centered on the hydrological cycle, including precipitation, evaporation, river discharge, ice melt, and sea level. Here we highlight two important changes in the global water cycle: the increasing occurrence of drought over land, and recent sea level rise.

Getting Drier

Surface air temperatures over the continents have been rising rapidly since the late 1970s and are predicted to continue to rise in the coming decades. Warmer temperatures increase atmospheric demand for moisture and thus could lead to drier surfaces if precipitation increases do not catch up. To investigate how drought might change under global warming, historical records of precipitation, streamflow, soil moisture, and the Palmer Drought Severity Index have been analyzed and compared to trends in model-predicted future changes. These analyses suggest that wide spread drying has occurred since the 1950s over most of Africa, East Asia, eastern Australia, the Mediterranean region, and many other places, mainly due to reduction in precipitation (partly due to El Nino and other natural climate variations). But recent warming since the late 1970s has also contributed significantly to the global drying trend. The model-predicted, steady rise in surface temperature and radiative heating during the 21st century will likely lead to more severe droughts in the coming decades over most land areas, including the continental U.S., where natural climate variations had caused an upward trend in precipitation from the 1950s to the 1990s but drier conditions have since prevailed over the western U.S. during the most recent decade. Combined with the underlying drying trend from global warming, the continental U.S., especially the western U.S., may be on a course to prolonged drought conditions.

Rising Sea Level

Peaking between late 2010 and early 2011, the recent La Niña event was one of the strongest in the observational record and accompanied outbreaks of extreme events on a global scale including drought, severe storms, and record floods. The event also accompanied a drop in global sea level unequaled during the altimeter era. Part of our work has focused on diagnosing these events across multiple datasets and timescales, and work addressing these issues remains ongoing. One study, submitted to Science, assesses the event from its associated redistribution of mass from ocean to land domains and its implications for severe storms and floods. With the cooling of the tropical Pacific, much of tropical deep convection was found to migrate to the land domains where the relatively warm surface favors convective activity. With this redistribution came record flooding as was witnessed across the southern hemisphere landmasses. Also thought to play a role in this redistribution of convection and moisture were the record warm sea surface temperatures that neighbored many southern hemisphere land areas and were deemed to be a likely factor distinguishing

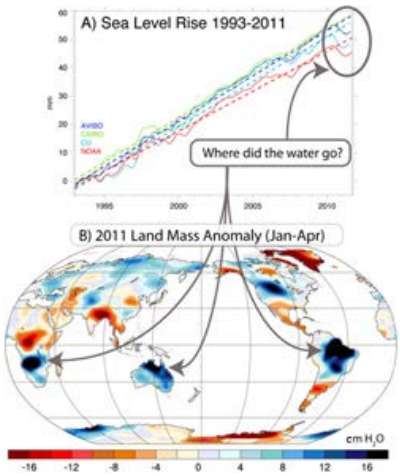

Figure: Where did the water go? (A) Estimated sea level rise during the altimeter record based on the post-processing of satellite data by various centers. The curves are smoothed to emphasize interannual and decadal changes. From 1992 to 2010, small variations associated with ENSO are apparent (e.g. 1997/8) though consistency is lacking between estimates

the present La Niña from previous events. This work is an example of our increasing focus on providing guidance and understanding on both regional and global scales so that impacts associated with climate variability and change may be adequately addressed.

regarding the magnitude and timing of these changes. During late 2010 and early 2011, an intense and robust drop in sea level is reported by all data centers of comparable magnitude, ranging from 6 to 8 mm. (B) Independent estimates of surface mass over land regions from GRACE corroborate a net increase of water storage, largely in the southern hemisphere monsoon domains, that is consistent with extreme events that characterized 2010-11. These events include record floods in Australia and South America that followed major droughts. [**high resolutin image**]

2012 and Beyond

In the coming year we will:

- Compare the evolution of El Nino and La Nina events in observations and CCSM4;
- Perform diagnostic studies of recent climate events;
- Estimate the decadal predictability properties of CMIP5 models;
- Characterize and determine the underlying mechanisms shaping high latitude climate system modes of variability;
- Continue processing new generation of reanalyses, e.g. ERA Interim, ERA-CLIM, MERRA, and JRA-55, to provide guidance on their merits and usability for model evaluations;
- Improve diagnoses and understanding of the energy and water cycles and budgets in nature and CMIP5 models;
- Investigate the role of Arctic sea ice loss in global climate change;
- Assess uncertainties in future climate projections due natural variability.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

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NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
  - II.A. CESM/CCSM
  - II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
  - II.B.1. WRF-Chem Highlights
  - II.C. CAM-Chem Highlights
  - II.D. Nested Regional Climate Model (NRCM)
  - II.E. Model for Prediction Across Scales (MPAS)
  - II.F. WACCM Highlight – Elevated Stratopause Events
  - II.G. Integration Across Scales – Global, regional and Local Air Pollution
  - II.H. MEGAN Model
  - II.I.1. Present Climates
  - II.I.2. Past Climates
  - II.I.3. Storage of Heat in the Ocean
  - II.J. Human Activity in an Earth System Hierarchy
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Past Climates

Overview

Paleoclimates offer a unique perspective to understand the Earth's climate sensitivity and its stability. Paleoclimate archives tell us that Earth has experienced a wide range of climates over various time scales, and that transitions in Earth's climate can take place rapidly. We know that many of these past climates were determined by changes in external forcing factors. To the extent that climate models can reasonably simulate past warm and cold climates, we gain confidence that the models can be used to study Earth's future climate.

Recent Accomplishments

CMIP5, PMIP3, and IPCC

The Coupled Modeling Intercomparison Project (CMIP5) and the Paleoclimate Modeling Intercomparison Project (PMIP3) recognize the importance of using observations of past climate change to validate models that will be assessed in the next IPCC. For the first time, international modeling groups are requested to perform simulations for three past time periods with the *same model and same resolution* as their 20th century and future projection simulations. In 2011, we completed the CMIP5 Tier 1 Last Glacial Maximum (21,000 years ago) and Mid-Holocene (6000 years ago) simulations and Tier 2 Last Millennium simulation with the CCSM4 1° CN model configuration of CESM. Forcings and boundary conditions follow the protocols developed by the PMIP3 for CMIP5.These simulations are being archived on the CMIP5 databases to allow the community to compare past and future climate variability and change, including detection and attribution. These experiments for long-term climate understanding are designed to make better predictions toward future climates with contributions to the USGCRP and IPCC assessment products.

The Last Millennium

The CCSM4 Last Millennium (LM) simulation includes the reconstructed forcings for volcanic eruptions, solar variability and orbital changes in solar insolation, Greenhouse gases, and land use. It reproduces many of the large-scale climate patterns suggested by historical and proxy-data records, including a Northern Hemisphere (NH) cooling from the Medieval Climate Anomaly (MCA, 950-1250 CE) to the Little Ice Age (LIA, 1400-1700 CE) and a pronounced increase in surface temperatures from 1850-2005 CE (Fig. 1). The CCSM4 LM simulation tends to have a greater response to volcanoes than the proxy-records, and a greater warming in the latter half of the 20th century than in the observations. NH temperatures after 1950 are greater in both the LM simulation and most proxy reconstructions than at any other time in the last millennium. Geographically, LM simulated surface temperatures are warmer at the MCA than LIA, with significant polar amplification, and the LM simulation shows a decrease in winter-time precipitation in the southwestern North America during the MCA, in general agreement with paleoclimate precipitation reconstructions.

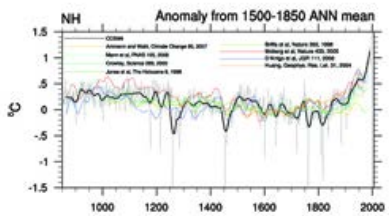

Figure: Simulated Northern Hemisphere mean temperature anomalies. Simulated Northern Hemisphere mean temperature anomalies (annual values in light gray, 30-yr Gaussian smoothed in black) for the CMIP5/PMIP3 Last Millennium (850-2005CE) simulation with the 1 degree resolution of CCSM4 CN configuration of CESM. The simulated temperature anomalies are compared to various smoothed reconstructions (colored lines) from a variety of proxies, including tree ring width and density, boreholes, ice cores, speleothems, documentary evidence, and coral growth. [**high resolutin image**]

Climate Sensitivity for Different Climate Forcings

The CCSM4 Last Glacial Maximum (LGM) simulation includes the reconstructed forcings for lower

atmospheric concentrations of the Greenhouse gases, orbital changes in solar insolation, ice sheets, and changed paleogeography associated with the lower sea level. The estimated equilibrium global mean annual surface temperature cooling is ~5.5°C in the full LGM simulation and ~2.6°C in the LGMCO2 simulation, suggesting that just less than half of the global LGM cooling is due to lowered CO_2 alone. The equilibrium warming estimated for the $4xCO_2$ simulation is ~6.2°C. The full LGM and $4xCO_2$ simulations predict an Effective Climate Sensitivity (ECS) comparable to the Equilibrium Climate Sensitivity found with the CCSM4 slab ocean model of 3.2°C. The $LGMCO_2$ simulation shows a greater ECS of ~4.2°. The CCSM4 shows a greater sensitivity at high northern latitudes to a lowering of CO_2 only, with a decrease in the strength of the Atlantic Meridional Overturning Circulation (AMOC), significant expansion of sea ice, and greater polar amplification in the $LGMCO_2$ simulation.

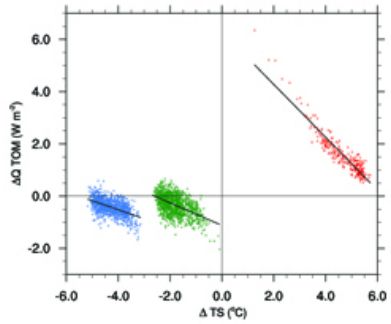

Figure: Gregory figure to estimate climate sensitivity. Annual and global mean net top-of-model energy flux imbalance plotted against the annual and global mean surface temperature difference from the 1850 AD control simulation for the abrupt 4xCO2(red), LGM CO2 (green), and full LGM (blue) simulations with the 1 degree resolution of CCSM4 CN configuration of CESM. Least-square regression lines are shown in black. [**high resolutin image**]

2012 and Beyond

CMIP5 and PMIP3 are long-term protocols designed to address outstanding scientific questions for the IPCC AR5 and beyond. The NESL/CGD Paleoclimate group, in collaboration with university and international partners, will continue to analyze the CMIP5 simulations of past climate to understand the mechanisms and feedbacks that provide the responses seen in proxy reconstructions and to assess how past climate sensitivities can be used to constrain future climate sensitivities.

We will also provide additional past climate simulation, including:

- Completion of simulations with CCSM4 for the Last Interglacial (~125 thousand years ago) and Mid-Pliocene Warm Period (~3 million years ago) to allow a model-data assessment of polar amplification seen in proxy reconstructions. These simulations are part of the PMIP3 protocol and will be assessed in the IPCC AR5.
- Simulations with CESM to understand and quantify the carbon cycle – climate feedbacks for the Last Millennium and Last Glacial Maximum.
- Simulations with the Community Ice Sheet Model (CISM) coupled to CESM for the Last Interglacial to assess the contributions of the Greenland and Antarctic ice sheets to the estimated 6-9 meter higher sea level for this past time period with warmer poles.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

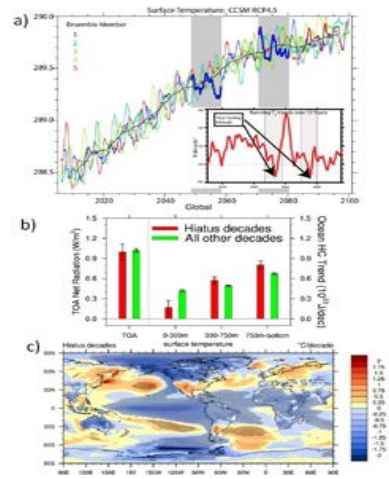
NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
  - II.A. CESM/CCSM
  - II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
  - II.B.1. WRF-Chem Highlights
  - II.C. CAM-Chem Highlights
  - II.D. Nested Regional Climate Model (NRCM)
  - II.E. Model for Prediction Across Scales (MPAS)
  - II.F. WACCM Highlight – Elevated Stratopause Events
  - II.G. Integration Across Scales – Global, regional and Local Air Pollution
  - II.H. MEGAN Model
  - II.I.1. Present Climates
  - II.I.2. Past Climates
  - II.I.3. Storage of Heat in the Ocean
  - II.J. Human Activity in an Earth System Hierarchy
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Understanding slow fluctuations of global temperatures: Where does the heat go when the surface temperature trend is flat?

The warming trend in globally averaged surface air temperatures over the past 100 years has not been a steady rise. Rather, there have been ups and downs from year to year, and from decade to decade. Global warming has occurred in fits and starts, and it is only trends averaged over several decades where a consistent warming trend has been seen. In the most recent 40 years or so when the trend over that period has been positive, there have been three decades when the warming trend has been nearly flat. In particular, observations of global temperatures over the first decade of the 21st century show little warming trend over that time period, while observations of radiation balance at the top of the atmosphere show a net energy input into the climate system that should have produced warming somewhere in the system. Observations of upper ocean heat content did not show much increase over that time period, so it is suspected that the missing heat went into the deep ocean. However, there are few observations of deep ocean temperatures to substantiate this hypothesis. So CCSM4 simulations were analyzed to provide clues as to where the heat may be going during decades when the surface temperature trend is flat.



Figures: a) Annual mean globally averaged surface temperature for the five climate model ensemble members (colored lines), ensemble mean (black line), highlighting two ten year negative temperature trend periods and ten year running trends from that ensemble member (inset). b) Composite global linear trends for hiatus decades (red bars), and all other decades (green bars) for top-of-atmosphere (TOA) net radiation (Wm^{-2}, positive values denote net energy entering the system); global ocean heat content decadal trends (10^{23} J $decade^{-1}$) for the upper ocean (surface to 300 m), and two deeper ocean layers (300-750m, and 750-bottom), with error bars defined as (+/- one standard error * 1.86) to be consistent with a 5% significance level from a one sided Student-t test. c) Composite average SST linear trends for hiatus decades, stippling denotes 5% significance (Meehl et al., 2011). [**high resolutin image**]

A CCSM4 five member ensemble of experiments run for future climate following an intermediate warming scenario (RCP4.5) was analyzed. Eight so-called hiatus decades (ten year periods when the globally averaged surface air temperature trend was slightly negative) were found in the five member RCP4.5 ensemble of CCSM4. Two of these periods from one of the ensemble members are highlighted in Fig. 1a, with the corresponding running ten year linear trend plot inset. Composites of top of atmosphere net energy flux indicate about 1 Wm-2 into the system for hiatus periods as well as all other decades (left part of Fig. 1b), showing that there is excess heat that must be accounted for in the system during those hiatus decades. Indeed, decadal trends of ocean heat content in the right part of Fig. 1b show that hiatus decades have lower values than all other decades for the upper 300 meter ocean layer, but greater trends for hiatus decades in the two deeper ocean layers. Thus, during decades when global temperatures are not increasing in the model, the excess heat is going into the deep ocean.

An indication of the processes by which this occurs is shown in Fig. 1c. The composite trends of sea surface temperatures (SSTs) during hiatus decades in the model show that there are mostly negative SST trends in the tropics, and positive trends in the subtropics. Further analysis reveals surface heat convergence in the subtropical Pacific and Atlantic that takes heat into the deeper ocean, a reduction of deep water formation in the North Atlantic, and less Antarctic Bottom Water formation, all of which contribute to greater heat content trends in the deep ocean layers. Comparison of the model SST trends for hiatus decades to three recent hiatus decades in observations reveals a similar pattern to that in Fig. 1c, suggesting similar processes are likely at work in the observed climate system. Thus, the analysis of CCSM4 provides insight into the limited observations of the deep ocean to show that a hiatus period is a

relatively common climate phenomenon, is consistent with our physical picture of how the climate system works, and does not invalidate our basic understanding of greenhouse-gas-induced warming or the models used to simulate such warming.

Reference

Meehl, G.A., J.M. Arblaster, J. Fasullo, A. Hu, and K.E. Trenberth, 2011: Model-based evidence of deep ocean heat uptake during surface temperature hiatus periods. Nature Climate Change, 1, 360—364, doi:**10.1038/NCLIMATE1229**.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
  - II.A. CESM/CCSM
  - II.B. The Weather Research and Forecasting (WRF) Model and Data Assimilation System
  - II.B.1. WRF-Chem Highlights
  - II.C. CAM-Chem Highlights
  - II.D. Nested Regional Climate Model (NRCM)
  - II.E. Model for Prediction Across Scales (MPAS)
  - II.F. WACCM Highlight – Elevated Stratopause Events
  - II.G. Integration Across Scales – Global, regional and Local Air Pollution
  - II.H. MEGAN Model
  - II.I.1. Present Climates
  - II.I.2. Past Climates
  - II.I.3. Storage of Heat in the Ocean
  - II.J. Human Activity in an Earth System Hierarchy
- III. NESL Observational Science
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Human Activity in an Earth System Hierarchy

Overview

Integrated Assessment Modeling links knowledge across a wide variety of disciplines, including both the natural and social sciences, in a quantitative framework that can inform decisions regarding response options for the climate change issue. Response options include those relevant to emissions mitigation and to adaptation to expected impacts. As a model-based area of applied research, it fits naturally within CGD and NCAR more broadly as a complement to larger-scale modeling efforts of the climate system. For example, IA models can both directly link to Earth System Models by providing inputs and/or using outputs and indirectly inform ESM efforts by prioritizing research directions and identifying interesting scenarios to explore.

The recently established integrated assessment modeling group hired an additional staff member in 2011, an energy modeler, and continued the development and application of an NCAR IA model, the Integrated-Population-Economy-Technology-Science (iPETS) model. This framework currently consists of three components: a global demographic model for projecting future population, urbanization, and living arrangements; a global, 9-region economic model that simulates changes in production, consumption, energy use, and greenhouse gas emissions; and a simple greenhouse gas cycle and climate model for projecting future atmospheric concentrations and changes in global average temperature.

Research in the IAM group involves development and use of the iPETS model, as well as collaborations with other research groups in the community, in order to explore the influence of alternative socio-economic development paths on future greenhouse gas emissions, climate changes, and impacts on society and ecosystems. Over time, the group aims to play an increasing role in developing linkages between integrated assessment models and earth system models such as CCSM, and to improve the treatment of uncertainty in integrated climate change analysis.

Recent Accomplishments

In 2011 a new set of global emissions scenarios developed with the iPETS model was completed that examines the implications of urbanization in Asia for trends for emissions from energy use and for well-being at the household level. This analysis took place in the context of a community-wide model comparison projection, the Asia Modeling Exercise, in which the NCAR IAM group participated. It led to new projections of urbanization in India and China, demonstrating the wide range of plausible outcomes over the coming decades, and improvements in the iPETS modeling framework by adding the effect of income growth on the energy use of households. Results showed that growth in incomes can be expected to lead to a rapid reduction in the household use of traditional fuels such as biomass and coal, particularly in rural China.

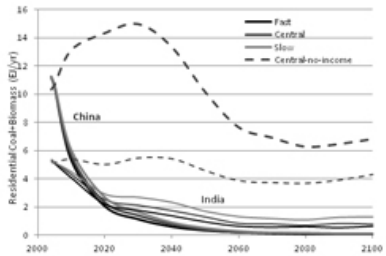

Figure: Residential Coal + Biomass. The effect on household coal and biomass use due to accounting for the effect of income growth on consumption preferences under three different urbanization scenarios, as estimated with the iPETS model. From O'Neill et al., Energy Economics, submitted. [**high resolutin image**]

In addition, substantial model development took place in several aspects of the iPETS framework. An initial means of accounting for land use was added to iPETS, an essential step toward future linking of the model to CESM to explore the effect of land use change on climate outcomes. Progress was also made on developing a new set of global, country-specific urbanization projections, as well as spatially explicit scenarios of population density at the regional and global level.

Along with development and application of the iPETS model, the IAM group participated in collaborative work with other research groups, including an effort to develop new global socio-economic scenarios for use in the IPCC Fifth Assessment Report and beyond. This ongoing effort is intended ultimately to facilitate research on climate change

response options such as emissions mitigation and adaptation to impacts.

2012 and Beyond

In 2012 IAM research will focus on three key priorities. First, substantial effort will be devoted to contributing to the community-wide process of developing new socio-economic development scenarios for use in climate change research. This will involve contributions to the development of the conceptual framework for new scenarios and to quantitative elements of these scenarios such as new urbanization projections.

Second, work will continue on the development of the capacity to model land use within iPETS. This work will involve a better accounting for different types of land, and different economic sectors that use land, within the modeling framework.

Finally, the IAM group will help lead efforts to foster collaboration between the integrated assessment community and earth system modeling. These efforts will be carried out as part of the new CESM working group on Societal Dimensions, as well as within other community efforts.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

NESL Observational Science

NESL Annual Report Table of Contents

III. NESL Observational Science

- III.A. **BEACHON-ROMBAS Field Study**
- III.B. **BEACHON-ROCS Field Study**
- III.C. **Megacities – Impacts of Trash burning**
- III.D. **Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning**
- III.E. **The DISCOVER-AQ Field Campaign**
- III.F. **NDACC Highlight – The 2010-2011 Arctic Polar Vortex**
- III.G. **The 2011 California Airbourne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign**
- III.H. Convective and Microphysical Field Campaigns
  - III.H.1 **VORTEX** 2
  - III.H.2 **MC3E**
  - III.H.3 **MACPEX**
  - III.H.4 **ICE-T**
  - III.H.5. **The PRE-Depression Investigation of Cloud systems in the Tropics (PREDICT)**
- III.I. Data Analysis from Previous Missions
  - III.I.1. **ARCTAS**
  - III.I.2. **OASIS**
  - III.I.3. **CABINEX**
- III.J. Observations from Satellite Platforms
  - III.J.1. **MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics**
  - III.J.2. **Satellite Observations of Global Pollution (Carbon Monoxide)**
  - III.J.3. **HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions**
- III.K. Additional Observational Development Activities
  - **IIII.K.1. Development of a Picarro Gas Analyzer System**

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
- III. NESL Observational Science
  - III.A. BEACHON-ROMBAS Field Study
  - III.B. BEACHON-ROCS Field Study
  - III.C. Megacities – Impacts of Trash burning
  - III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
  - III.E. The DISCOVER-AQ Field Campaign
  - III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
  - III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
  - III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
  - III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
  - III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
  - III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
  - III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
  - III.I.1. ARCTAS
  - III.I.2. OASIS
  - III.I.3. CABINEX
  - III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
  - III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
  - III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
  - III.K.1 Development of a Picarro Gas Analyzer System
  - III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
  - III.I.1. Development of a Picarro Gas Analyzer System
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

BEACHON Rocky Mountain Biogenic Aerosol Study (ROMBAS)

During July and August, 2011, atmospheric scientists converged on the Manitou Experimental Forest to participate in one of the biggest, most comprehensive studies of the role of atmospheric particles in forest – atmosphere interactions. In total, over 30 principle investigators and twice that number of support staff, students, and postdocs participated in the BEACHON-Rocky Mountain Biogenic Aerosol Study (RoMBAS), which was organized jointly by NCAR and the University of Colorado. The site of the study was NCAR's "Manitou Forest Observatory." Constructed in 2008 by NCAR and the USFS and located 1 km west of the Manitou Experimental Forest office, the observatory features a 30 m scaffolding tower for atmospheric chemistry research, a 50 m flux tower for research on atmospheric turbulence, 700 square feet of movable laboratory space, and 75 kilowatts of power. RoMBAS, with its large national and international participation, required temporarily increasing both space (a tripling of the lab space at the site) as well as power (adding almost 100 kilowatts additional power capacity).

Figure 1. Researchers gather for the weekly data meeting at the measurement site.

The objective of RoMBAS was to study the mechanisms by which particles are created in the forest, and the ways that may regulate and link the biogeochemical and water cycles. Several researchers, such as Prof. Uli Poeschl from the Max Plank Inst. for Chemistry in Mainz, Germany, studied the emission of primary biological particles at Manitou and their relation to environmental conditions. Prof. Sonia Kreidenweis' group from Colorado State Univ. also characterized these primary particles, but added a crucial measurement of their ability to form ice clouds. Several research groups measured the formation and properties of secondary organic particles, including some measurements that have not previously been attempted in a forest setting. The latter includes a suite of instruments developed by Profs. Bill Brune at Penn State Univ. and Jose Jimenez at the Univ. of Colorado called "Potential Aerosol Mass Chambers." These devices sampled outside air into cells that expose the air to high levels of oxidizing gases, effectively subjecting the air to several days-worth of atmospheric reactions that lead to particle formation. Instruments then measured the organic vapors and particles that exited the chambers in order to determine the properties of these particles. Researchers also studied the formation of new particles in the air above Manitou. This phenomenon of the birth of new particles, a processed called atmospheric nucleation, is frequently observed at Manitou forest. However, the species responsible for atmospheric nucleation are still not known.

Figure 2. View of site showing two of four temporary buildings leased for the project. On the left are filter samplers that are collecting atmospheric particles for later laboratory analysis.

Overall, the study brought together an unprecedented number of instruments to study important linkages between the forest and atmosphere. Even the weather cooperated in making a successful study, with periods of dry and wet weather allowing for the study of the impacts of humidity and soil moisture. Researchers are now starting to analyze their measurements; it is already clear, however, that BEACHON-RoMBAS will provide many unique insights into the interactions between forest and atmosphere.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

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NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

BEACHON-ROCS Field Study

The BEACHON-ROCS (Rocky mountain Organic Carbon Study) was conducted in July-August 2010 and included an unprecedented suite of gasphase measurements. Ten institutions including 8 national and international Universities participated during BEACHON-ROCS. The study aimed at elucidating OH reactivity, the production of VOCs/OVOCS/SVOCs and HOx chemistry. Particular focus was the quantification of biogenic aerosol precursors and the production of secondary organic gasphase species which play a central role in the oxidizing capacity of the forested atmosphere. Strong connections to ongoing long-term micrometeorological measurements allow putting results from BEACHON-ROCS into the context of seasonal and ultimately interannual variations of chemical species. Early highlights from BEACHON-ROCs include the finding of complex exchange patterns of oxygenated VOCs, such as methanol, acetone and acetaldehyde (see. Fig 1). In addition first flux measurements of formaldehyde based on eddy covariance measurements using a fiber induced fluorescence technique suggest implications for missing in-canopy formaldehyde sources (Di Gangi et al., ACP, Atmos. Chem. Phys., 11, 10565-10578, **doi:10.5194/acp-11-10565-2011**, 2011).

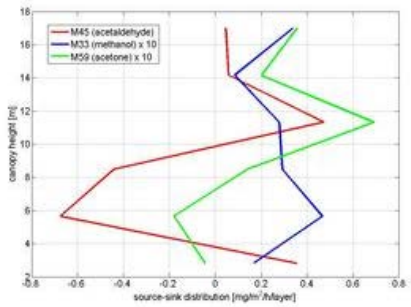

Figure 1. The flux distribution of selected oVOCs observed during BEACHON-ROCS as a function of canopy height.

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Log in

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
- III. NESL Observational Science
  - III.A. BEACHON-ROMBAS Field Study
  - III.B. BEACHON-ROCS Field Study
  - III.C. Megacities – Impacts of Trash burning
  - III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
  - III.E. The DISCOVER-AQ Field Campaign
  - III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
  - III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
  - III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
  - III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
  - III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
  - III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
  - III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
  - III.I.1. ARCTAS
  - III.I.2. OASIS
  - III.I.3. CABINEX
  - III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
  - III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
  - III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
  - III.K.1 Development of a Picarro Gas Analyzer System
  - III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
  - III.I.1. Development of a Picarro Gas Analyzer System
- IV. Modeling in Support of Field Operations

Studying the impact of trash burning on air quality in Mexico City within MILAGRO

Air pollution in expanding urban areas is responsible for serious health effects and the death of millions of people every year. Trash burning is a common disposal method in areas of low socioeconomic level, yet it is uncontrolled in many countries and its contribution to air pollution is unclear due to uncertainties in emissions. According to Christian et al. (Atmos. Chem. Phys., 2010) about 2000 Tg of garbage is generated per year worldwide and about half of that may be burned, emitting into the atmosphere more than 5 Tg/year of organic carbon (OC) which represents 15% of OC global emissions from all biomass burning sources. To estimate the impact of trash burning in Mexico City, we developed a new trash burning emission inventory based on inverse socioeconomic levels and recently measured emission factors, and applied the WRF/Chem model to quantify the effects on pollutant concentrations. We estimated that trash burning emits ~19 tons of primary organic carbon (POA) per day, which is comparable to fossil fuel POA emissions in Mexico City, and causes an increase in average organic aerosol concentrations up to 2 μg m^{-3} in highly populated suburbs (see Figure 1). The mitigation of trash burning could reduce the levels of total organic aerosols by 5% in downtown Mexico City, and 15-40% in the rest of the valley. The trash contribution to carbon monoxide, nitrogen oxides and volatile organic compounds was found to be small (< 3%), and consequently the contributions to secondary nitrate and secondary organic aerosols are also small.

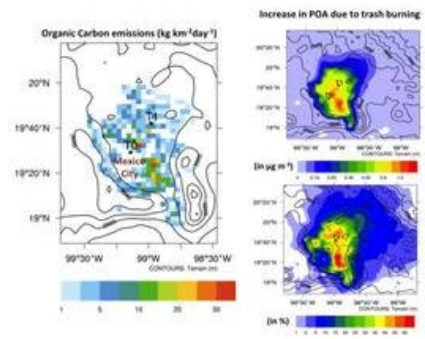

Figure 1. Estimated aerosol organic carbon emissions in Mexico City, and the associated effects on surface primary organic aerosol concentrations as predicted by the WRF/Chem model from 20 to 29 March 2006.

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Log in

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
- III. NESL Observational Science
  - III.A. BEACHON-ROMBAS Field Study
  - III.B. BEACHON-ROCS Field Study
  - III.C. Megacities – Impacts of Trash burning
  - III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
  - III.E. The DISCOVER-AQ Field Campaign
  - III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
  - III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
  - III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
  - III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
  - III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
  - III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
  - III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
  - III.I.1. ARCTAS
  - III.I.2. OASIS
  - III.I.3. CABINEX
  - III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
  - III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
  - III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
  - III.K.1 Development of a Picarro Gas Analyzer System
  - III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
  - III.I.1. Development of a Picarro Gas Analyzer System
- IV. Modeling in Support of Field Operations

DC3 Test Flights and Planning

The Deep Convective Clouds and Chemistry (DC3) field campaign will be held in May-June 2012, and will investigate the impact of deep, midlatitude continental convective clouds, including their dynamical, physical, and lightning processes, on upper tropospheric (UT) composition and chemistry. The campaign will include the participation of both the NSF/NCAR GV aircraft, as well as the NASA DC-8. In preparation for the field campaign, a set of GV test flights were conducted May 1-15, 2011. The goals of the test flights were to test new instrumentation (see below), practice flying near thunderstorms, practice communication between the operations center, aircraft, and radar facilities, and conduct forecasting and decision making for DC3. Overall, the test flights and related activities were a success, and have set the foundation for a productive 2012 field campaign.

Four new instruments to be used in DC3 were tested during the test flights: the Georgia Tech CIMS instrument, which measures HNO_3, HNO_4, HCl, and SO_2; the CAMS instrument, which measures formaldehyde at rapid frequency and with low detection limits; the P-CIMS instrument, which measures H_2O_2 and CH_3OOH; and the TOGA-HIAPER instrument which measures volatile organic compounds, halocarbons, and some nitrogen and sulfur containing species. Results from the test flights, and in some cases from work done subsequently, show that all four instruments are able to make measurements at the desired low concentrations found in the upper troposphere.

Figure 1. Sample data from the TOGA-HIAPER instrument from Flight 2 of the DC3 test flights, 05/04/2011.

The TOGA (Trace Organic Gas Analyzer) instrument is a fast-gas chromatograph / mass spectrometer based instrument, and was designed and built by scientists in NESL / ACD. It is capable of measuring many tens of organic species with a time resolution of 2 min, typically with limits of detection of about 1 ppt. The instrument provided research grade measurements on the test flights, as shown in Figure 1, clearly demonstrating its readiness for the DC3 campaign.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

DISCOVER-AQ Field Campaign

DISCOVER-AQ (Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality) is aimed at improving the diagnosis of air quality conditions from space. We have a need to determine how satellite observations of column-integrated quantities relate to near-surface mixing ratios. Over the course of deployments in 4 regions of the country, DISCOVER-AQ will provide an integrated dataset of airborne and surface observations relevant to this problem. The first such deployment occurred in July 2011 in the Baltimore – Washington, DC metropolitan area. NESL/ACD/CARI contributed by making in situ measurements from the NASA P3-B aircraft of NO, NO_2, NO_y, and O_3. Over 250 vertical profiles were measured over 6 ground sites, so that profiles can be related to the surface measurements, and, in the case of NO_2 and O_3, the column amounts integrated over the P3-B profiles can be related to satellite-derived total columns. These data will allow determination of the conditions under which satellite retrievals are indicative of surface air quality, and they will be useful in planning new satellites. Additionally, we are using the data to assess regional air quality forecast models, with the intent of improving the predictive capability of these models.

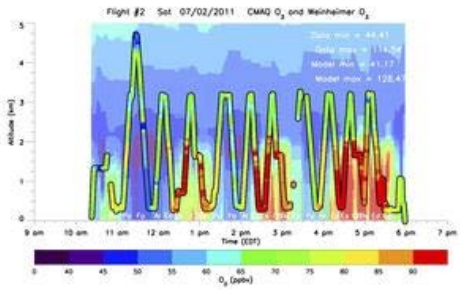

Figure 1. A comparison of model-predicted and measured O_3 during numerous spiral profiles over ground sites in the Baltimore-Washington, DC area (courtesy of M. Follette-Cook & K. Pickering).

It is still very early in the data analysis, but Figure 1 shows a comparison of in situ O_3 measurements with O_3 predicted by the CMAQ (Community Multiscale Air Quality) model. In this particular case the model displayed a tendency to underestimate O_3. This was the 4th of July weekend, with higher than normal vehicle emissions that were likely underestimated in the model, as indicated by a similar plot of the NO_2 comparison (not shown).

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Log in

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

NDACC Highlight – The 2010-2011 Arctic Polar Vortex

An extraordinary polar vortex developed and persisted during the 2010-2011 winter in the Arctic. It has been characterized as unusually compact with high winds maintaining the integrity of the vortex. Often the vortex will form in December at the onset of the polar night and cooling stratospheric temperatures. This dynamical feature moves around the pole and as the winter progresses it may break apart and dissipate in February or March. This particular vortex, however, has been unusually compact, cold and persistent. This caused the cold, dense air to descend from higher altitudes to the lower stratosphere and has allowed a vast amount of inert chlorine in the form of HCl to be converted into activated forms. Observations made by the NCAR/NDACC FTS at Thule, Greenland show that more than 80% of the HCl in the lower stratosphere (from 8-20km) and up to 70% of the total column has been removed. This excess chlorine has greatly increased the catalytic destruction of O_3. The lowest stratosphere has seen more than 44% ozone loss, with similar loss observed from 20-30km and up to 25% loss in the region 30-40km. Integrated, the loss of up to 42% of O_3 is the highest we have observed since beginning measurements in 1999. These loss rates are relative to the mean March total HCl and O_3 respectively, from 2000-2009. The low value of 289 DU was observed on 18 March 2011.

The accompanying Figure 1 illustrates the magnitude of the low temperature, descent and chemical losses seen this March. Each of the 5 plots has 3 curves, curve A (black) is the mean March mixing ratio (or temperature) for years 2000-2009 outside the vortex, curve B (red) is the mean inside the vortex and curve C (blue) is the mean for March 2011. We see chemical losses combined with descent in the O_3, HCl and HNO_3 mixing ratios, large descent isolated from the HF measurements, and the deep cold region of this year's vortex in the contrasting NCEP temperature curves.

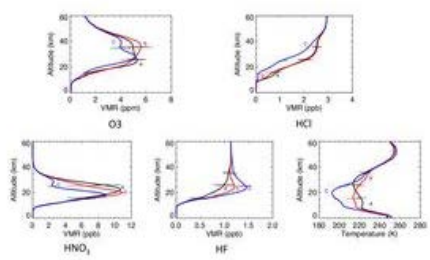

Figure 1. Magnitude of low temperature, descent and chemical losses seen during March 2011.

Atmospheric Chemistry Division at NCAR, with support from NASA, operates an FTS infrared spectrometer at Thule Greenland (76N, 68W). Observations are made for many gases important to stratospheric O_3 loss & recovery, tropospheric chemistry and greenhouse gases.

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NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
- III. NESL Observational Science
  - III.A. BEACHON-ROMBAS Field Study
  - III.B. BEACHON-ROCS Field Study
  - III.C. Megacities – Impacts of Trash burning
  - III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
  - III.E. The DISCOVER-AQ Field Campaign
  - III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
  - III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
  - III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
  - III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
  - III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
  - III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
  - III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
  - III.I.1. ARCTAS
  - III.I.2. OASIS
  - III.I.3. CABINEX
  - III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
  - III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
  - III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
  - III.K.1 Development of a Picarro Gas Analyzer System
  - III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
  - III.I.1. Development of a Picarro Gas Analyzer System
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign

The CABERNET field campaign was conducted in June, 2011 in California. The objectives were to develop and evaluate new approaches for regional scale measurements of biogenic VOC emissions, quantify the response of biogenic VOC emissions to landcover change, investigate the vertical transport of isoprene and oxidation products, and evaluate biogenic emission models. The campaign was led by NESL/ACD and involved collaborators from UC Berkeley and CIRPAS. NESL/ACD scientists deployed a fast response in situ VOC analyzer, a VOC cartridge sampler and an ozone analyzer on the CIRPAS twin otter aircraft and were heavily involved in organizing flight plans and data archiving. In addition, NESL/ACD scientists deployed and operated a relaxed eddy accumulation (REA) system at a UC Berkeley flux tower site in an oak savanna.

Figure 1 shows a typical vertical profiling flight pattern and transect flights that covered landscapes throughout California. Analysis of the data obtained during the campaign is in its preliminary stages. Isoprene flux divergence in the convective boundary layer is shown in Figure 2. These measurements provide a novel approach for estimating OH concentrations and understanding the processes controlling vertical transport of isoprene in the boundary layer.

Figure 1. Isoprene concentrations measured over vertical profiles (top) and horizontal transects (bottom) made during the CABERNET campaign.

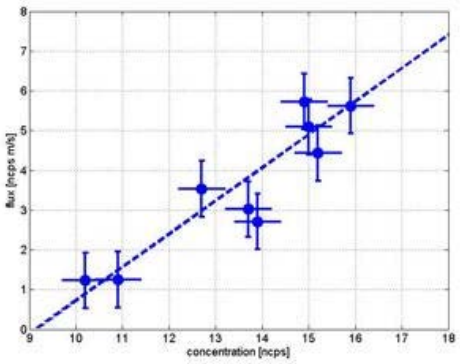

Figure 2. Measurements of isoprene flux divergence in the convective boundary layer.

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Log in

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2

The Verification of the Origins of Rotation in Tornadoes EXperiment 2 (VORTEX2) is a multi-agency field program to study: 1) tornadogenesis, maintenance, and demise; 2) wind fields near the ground in tornadoes; 3) relationships among tornadoes, their parent thunderstorms, and the larger-scale environment; and 4) numerical weather prediction of supercells and tornadoes. The field phases of VORTEX2 took place over the U.S. Great Plains in May and June of 2009 and 2010. Of the 100-plus participants in the field phase, roughly half were graduate and undergraduate university students.

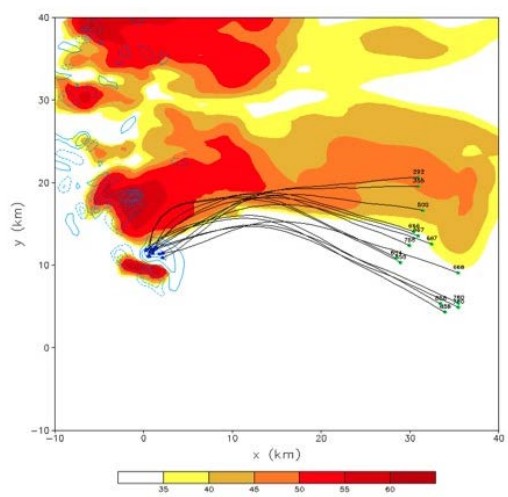

Figure: Analysis of a numerical simulation showing estimated reflectivity (dBZ, shading), circulation at 1 km above ground (blue contours), and trajectories (black lines) with origin height annotated.

In FY 2011, NESL/MMM scientists collaborated with university, NOAA, and private industry partners to develop three-dimensional gridded analyses and numerical simulations of VORTEX2 cases. Much of the focus has been on the Goshen County, Wyoming, tornado of 5 June 2009, which is probably the best-observed tornado in history. Preliminary results support the conclusion that tornado formation (or lack thereof) is attributable to small-scale (of order 1 km) details near the surface of rotating thunderstorm updrafts; for example, if near-surface air parcels pass through precipitation rain shafts with large rain drops, and then enter the thunderstorm updraft, the near-surface rotation in thunderstorms can be increased. Such low-level features are usually not observable by conventional weather surveillance radars. Much of this research has been conducted using radar-analysis software and numerical models (WRF and CM1) developed at NCAR.

Analysis of VORTEX2 field data continues to involve NOAA and numerous university collaborations, particularly Texas Tech University and Penn State University. From this research the tornadic storms research community is gaining a better understanding of the origins of rotation in tornadoes, and scientists expect to transfer these results into operational forecast tools in the future which will help improve weather prediction and could help save lives.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

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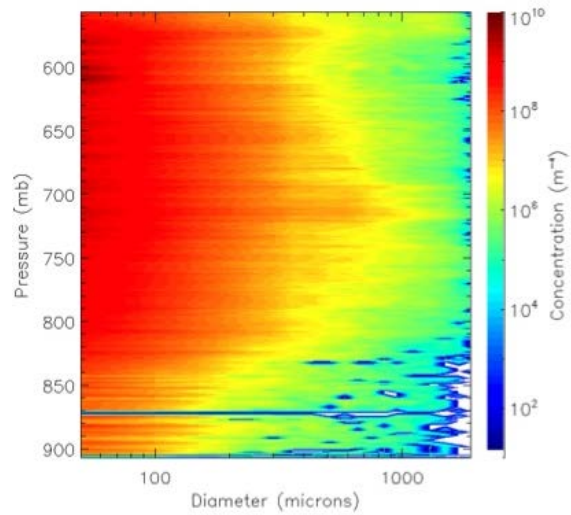
NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

MC3E - The Mid-latitude Continental Convective Clouds Experiment

NESL/MMM scientists participated in The Mid-latitude Continental Convective Clouds Experiment (MC3E) during the spring of 2011. This NASA-organized campaign was designed to characterize convective cloud systems and precipitation as part of the Global Precipitation Measurement Mission. NESL scientists are in the process of analyzing in-situ cloud particle images collected aboard the University of North Dakota Citation aircraft, and using the results to improve satellite retrievals of cloud properties used by the GPM mission. The particles imaged range in size from 1 mm to greater than a centimeter, and can be used to simulate expected cloud properties such as radar reflectivity, extinction, and condensed mass content. Members of the NESL/MMM/PMG Section participated in the field experiment and are processing and analyzing the Citation data.



An example of a vertical profile of particle size and concentration during a stratiform event in MC3E is shown in the figure above, showing large ice particles that formed at the 700mb level, and subsequent melting below 800mb.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

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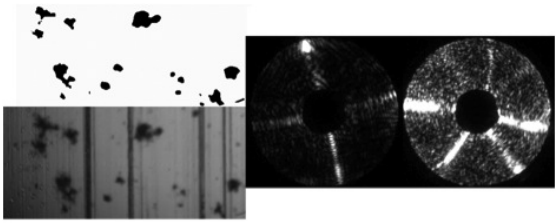
NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment

The NASA-organized Mid-latitude Airborne Cirrus Properties Experiment (MACPEX) took place in March and April 2011. NESL/MMM scientists participated in the field project by supplying two instruments, the Video Ice Particle Sampler (VIPS) and the Small Ice Detector version 3 (SID3). During the field program, the NASA WB-57 aircraft flew 14 missions and two test flights sampling cirrus clouds as far north as Nebraska and as far south as Cuba. The SID3 functioned well on 14 of 16 flights and the VIPS was only down for half of one flight making the VIPS and SID3 two of the most reliable probes on the aircraft. The field project was not without challenges. The VIPS data collection system was completely redesigned in advance of the project and the SID3 required a major repair in the field.

Preliminary analysis is ongoing for both probe datasets and preliminary results have been uploaded and are available to MACPEX participants. These datasets will be highly valuable to the atmospheric science community as they will contain some of the best information to date on small ice crystal properties. The sample volume of the VIPS (in a large part due to the pre-project modifications) will enable the calculation of particle size distributions at exceptionally low particle concentrations. The SID3 is able to detect when ice crystals have rough surfaces which is highly important for radiative transfer calculations. These results will improve the representation of ice clouds and cloud properties in weather and climate models.



This figure shows (left) a typical VIPS image containing ice crystals and the analysis software's particle selection algorithm. On the right are two images from the SID3 which show speckled forward scattering pattern which indicates that the observed ice crystals have rough surfaces.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

ICE-T - The Ice in Clouds Experiment-Tropical

Figure: Photograph of developing towering cumulus cloud subsequently penetrated by the C130 near cloud top at a temperature of about -7C on 12 July 2011 during ICE-T. There were ice particles observed in this cloud even though the top temperature had only reached the -7C level.

During the Ice in Clouds Experiment-Tropical (ICE-T) in July 2011, the NSF/NCAR C130 aircraft flew thirteen research missions and a Lear Jet instrumented and operated by SPEC, Inc. flew ten missions into towering cumulus thru cumulonimbus clouds in the vicinity of the Virgin Islands in the Caribbean. The primary goal of ICE-T is to understand how the first ice particles originate and impact the subsequent spread of the ice in clouds from this climatologically important region. ICE-T provided detailed aerosol and microphysical measurements of the interactions of episodic Saharan dust events with tropical cumuli. The C130 was equipped with a complement of cloud particle probes sizing from micron to cm sizes, online and offline chemical composition measurements of the residuals of evaporated droplets and ice particles, aerosol, cloud condensation and ice nuclei (aerosol and cloud residuals) spectral measurements, and upward and downward viewing Doppler cloud radar and lidar. The Lear was equipped with a full complement of particle probes sizing from micron to ~5 cm sizes. Both aircraft measured air vertical velocities.

The C130 observations focus on the critical temperature range from 0 to -10C (see figure), where primary nucleation on a few ice nuclei is thought to lead to a cascade of ice particles through subsequent secondary processes that are responsible for ice phase precipitation from these clouds and also affect the cloud dynamics. The Lear observations consider a wider range of temperatures, -5 to -20C.

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Log in

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
- III. NESL Observational Science
  - III.A. BEACHON-ROMBAS Field Study
  - III.B. BEACHON-ROCS Field Study
  - III.C. Megacities – Impacts of Trash burning
  - III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
  - III.E. The DISCOVER-AQ Field Campaign
  - III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
  - III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
  - III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
  - III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
  - III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
  - III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
  - III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
  - III.I.1. ARCTAS
  - III.I.2. OASIS
  - III.I.3. CABINEX
  - III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
  - III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
  - III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
  - III.K.1 Development of a Picarro Gas Analyzer System
  - III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
  - III.I.1. Development of a Picarro Gas Analyzer System
- IV. Modeling in Support of Field Operations

PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics

In FY 2011 NESL/MMM scientists collaborated with university participants on the field phase of PREDICT, where data was collected to better understand formation of tropical depressions in the Atlantic Ocean. The project includes testing various theories of cyclone formation using data from the NSF/NCAR G-V aircraft, based in St. Croix U.S. Virgin Islands. The project included several university scientists and numerous graduate students. PREDICT is an NSF-sponsored collaborative effort with the NASA Genesis and Rapid Intensification Processes (GRIP) program and the NOAA Intensity Forecast Experiment (IFEX), both overlapping with PREDICT in time and spatial coverage. The primary universities involved included the Naval Postgraduate School, University of Illinois, State University of New York-Albany, Penn State University, University of Miami, New Mexico Technology University, Cooperative Institute for Mesoscale Meteorological Studies/University of Wisconsin/Madison, Oregon State University, and Howard University.

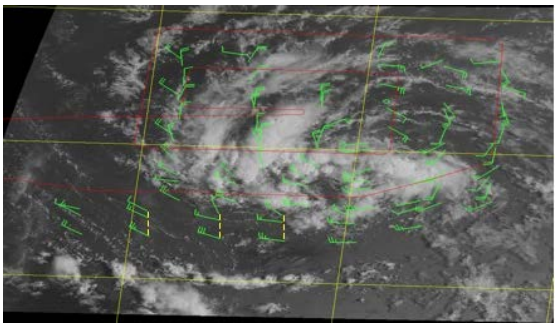

Figure: Flight pattern of NSF/NCAR GV (red lines) as PREDICT scientists observed the structure of tropical storm Fiona. The visible satellite image from 1145 UTC on 30 August is shown along with wind speed and direction symbols (green) at three different altitudes. Yellow lines are latitude and longitude lines every 5 degrees.

The field phase of PREDICT was conducted as planned and observations of eight tropical weather systems were obtained, four of which developed into tropical cyclones. There were four or more flights into three of the systems which provided temporal continuity to the observations. Collaboration with NOAA and NASA aircraft occurred for two systems (Matthew and Karl). The NSF/NCAR GV flew a total of 25 research missions using 173 flight hours, and dispensing 537 dropsondes. A typical flight pattern is shown in the Figure. The GV generally flew between 41,000 and 47,000 feet MSL. Since the field phase ended on 30 September 2010, extensive analysis of the data collected has been done and is still ongoing. One article has been submitted to *Journal of the Atmospheric Sciences* by NESL/MMM scientists, and another, multi-institute paper including NCAR authors was submitted to *the Bulletin of the American Meteorological Society*.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

ARCTAS Field Mission Analysis using MOZART-4

The global chemical transport model MOZART-4 has been used to provide context and interpretation for the ARCTAS (Arctic Research of the Composition of the Troposphere from Aircraft and Satellites) field mission data. The various source contributions to carbon monoxide (CO) and ozone (O_3) have been "tagged" in the model to determine the relative importance of different regions and types of emissions to the atmospheric composition in the Arctic. These results for CO and black carbon aerosol have been presented by Tilmes et al. (ACPD, 2011). Figure 1 shows the source contributions to the tropospheric ozone columns, as published by Wespes et al. (ACPD, 2011). The procedure used for determining the ozone contributions is a unique scheme developed in ACD based on tracing NO emissions from a given source through to the production of ozone. The stratospheric contribution is determined by subtracting the tagging of all NO sources from the total ozone field.

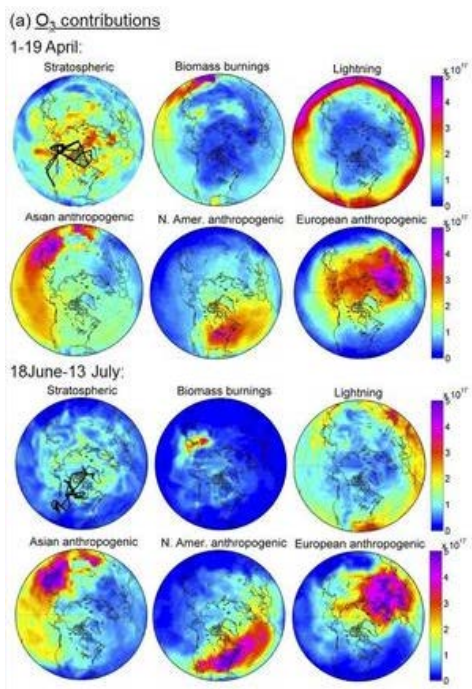

Figure 1. Source contributions to tropospheric (surface to 300 hPa) ozone columns (molecules cm^{-2}) during the ARCTAS campaign as determined from MOZART-4 simulations. NASA DC-8 flight tracks for each period are shown in the Stratospheric contribution plots.

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Log in

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
- III. NESL Observational Science
  - III.A. BEACHON-ROMBAS Field Study
  - III.B. BEACHON-ROCS Field Study
  - III.C. Megacities – Impacts of Trash burning
  - III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
  - III.E. The DISCOVER-AQ Field Campaign
  - III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
  - III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
  - III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
  - III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
  - III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
  - III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
  - III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
  - III.I.1. ARCTAS
  - III.I.2. OASIS
  - III.I.3. CABINEX
  - III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
  - III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
  - III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
  - III.K.1 Development of a Picarro Gas Analyzer System
  - III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
  - III.I.1. Development of a Picarro Gas Analyzer System
- IV. Modeling in Support of Field Operations

OASIS Field Campaign – Master Mechanism Model Development

The OASIS (Ocean-Atmosphere-Sea Ice-Snowpack) field campaign took place in Barrow AK from early March to mid-April, 2009, and was the most comprehensive study to date of Arctic cryosphere-atmosphere exchange processes and polar boundary layer ozone depletion chemistry. The study, which included both gas- and condensed-phase measurements, was led by researchers at UC-Davis (Harry Beine) and Purdue University (Paul Shepson) and involved the participation of about 10 universities and institutes world-wide. NESL scientists successfully operated 10 instruments during the campaign, measuring species such as O_3, NO_{xy}, PAN, OH and OH reactivity, HO_2/RO_2, VOC (including halogenated and oxygenated species), actinic flux, aerosol physical/chemical properties and various met parameters.

Although data analysis is continuing, a total of 18 papers based on the OASIS campaign have either been published in a special section of JGR-Atmosphere, or are under review for this special session. To aid in data interpretation, NESL / ACD scientists have developed a zero-dimensional ("box") model that simulates the complex chemistry that occurs in these springtime polar ozone depletion events, as well as the surface exchange processes that influence this chemistry. The model is an extension of the NCAR Master Mechanism, but includes more detailed inorganic halogen chemistry and (most importantly) reactions that couple the chemistry of inorganic halogens and organics. One of the many applications of the model is to develop an understanding of the PAN budget in these polar regions. Preliminary findings suggest that a very modest PAN deposition rate (0.01 cm/s) to the snowpack would be sufficient to explain the puzzling lack of PAN production typically seen in these Arctic boundary layer studies. (See accompanying Figure 1). In addition to the box model, a 1-D model is being adapted (in collaboration with Alfonso Saiz-Lopez, CIAC, Toledo, Spain) to OASIS-like conditions, to further aid in interpretation of gradient and flux data for VOC and NO_{xy} species above the snowpack.

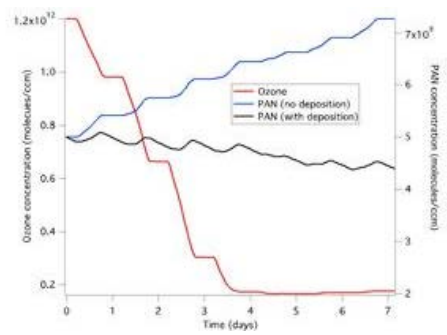

Figure 1. Box model results showing ozone loss during a depletion event, and the effect of a 0.01 cm/sec PAN deposition velocity on modeled PAN concentrations.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

CABINEX: Community Atmosphere-Biosphere INteractions Experiments

The CABINEX (Community Atmosphere-Biosphere INteractions Experiments) campaign in 2009 at the PROPHET tower observatory (Pellston, MI) included multi-university field and modeling investigations to address important questions about biosphere-atmosphere interaction (**http://aoss-research.engin.umich.edu/prophet/CABINEX/science.html**) including how biogenic volatile organic compound (BVOC) emissions impact HOx radical chemistry in the near-canopy environment. It has long been speculated that unmeasured/unidentified reactive BVOC emissions to HOx chemistry are important in the canopy airspace and in the atmospheric boundary layer. NCAR scientists collaborated with other members of the CABINEX science team to quantify the potential reactivity from BVOC emissions that have not been quantified by conventional analytical techniques. A branch enclosure OH reactivity measurement system was developed using a comparative reactivity method. OH reactivity of four different tree species was characterized and extrapolated to the ecosystem scale. The results shown in Figure 1 indicate that known BVOCs such as isoprene and monoterpenes account for the measured OH reactivity in most cases. This suggests that the PROPHET tower ecosystem (a dominant North American forest type) is dominated instead by unaccounted reactive oxidation products of known BVOCs (e.g. isoprene and monoterpenes). Complementary studies were conducted in NCAR chemistry laboratories to demonstrate the potential importance of these compounds. The detailed discussion can be found in Kim et al. (2011).

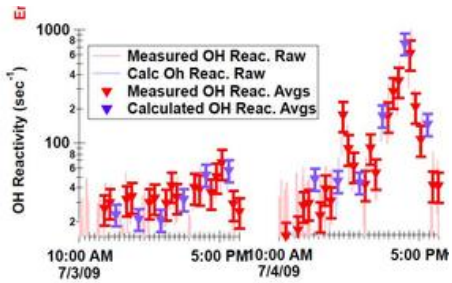

Figure 1. Temporal variations of measured (red) and calculated (blue) OH reactivity from oak tree branch enclosure. Calculated OH reactivity was based on isoprene concentrations inside of the branch enclosure.

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Log in

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

MOPITT – CO Retrievals over Beijing During 2008 Olympics

Using MOPITT V5 data, released in early 2011, we analyzed multispectral CO retrievals over Beijing for August 2007 compared to August 2008 to see the effects of pollution control measures, including traffic restrictions, during the Beijing 2008 Olympics. MOPITT measures a significant reduction in CO, 6.5 ± 1.6 Gg[CO]/day, for Beijing in 2008. We used WRF-chem simulations to attribute changes due to meteorology and bias due to MOPITT sampling, and found the result agrees with the estimated CO emissions. From the emissions inventory by sector (Q. Zhang, personal comm.), we account for the fractional reduction in transportation sector which has a CO/CO_2 emission ratio of 0.04 for Beijing [Wang et al., 2010]. We then estimated the corresponding reduction in CO_2 due to traffic restrictions, 59 Gg[CO_2]/day, which is significant compared to target CO_2 reductions in IPCC scenarios for future emissions. This result suggests that urban traffic controls could have a large impact on global CO_2 emissions. This study has been submitted for publication: Worden, H.M., Y. Cheng, G. Pfister, G. Carmichael, Q. Zhang, D. Streets, M. Deeter, D.P. Edwards, J.C. Gille and J.R. Worden (2011), Satellite-based estimates of reduced CO and CO_2 emissions due to traffic restrictions during the 2008 Beijing Olympics, in review, *Proc. Natl. Acad. Sci.*, USA.

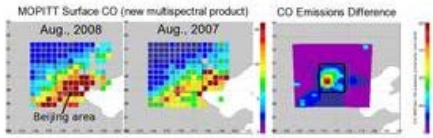

Figure 1. MOPITT surface CO

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

Satellite Observations of Atmospheric Pollution

Satellite trace gas retrievals, such as from the NASA/Terra Measurements of Pollution in the Troposphere instrument MOPITT are used to track pollution sources and the transport of plumes. Figure 1 reveals the extent to which satellite data can be used as quantitative way to track the impact of wildfires on the surrounding air. The image shows MOPITT tropospheric CO concentrations for 1-12 June 2011 over the United States. A dense plume of carbon monoxide moves northeast from Arizona's Wallow Fire over Colorado and Nebraska, with lower amounts of the gas detectable across much of the Midwest. Much of the Atlantic Seaboard and Southeast also experienced high levels of carbon monoxide. Some may be from the Wallow and other fires, but much of the carbon monoxide in that region typically comes from cities and other sources of pollution.

Figure 1. MOPITT tropospheric CO concentrations for 1-12 June 2011 over the United States.

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. BEACHON-ROMBAS Field Study
III.B. BEACHON-ROCS Field Study
III.C. Megacities – Impacts of Trash burning
III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
III.E. The DISCOVER-AQ Field Campaign
III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
III.I.1. ARCTAS
III.I.2. OASIS
III.I.3. CABINEX
III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
III.K.1 Development of a Picarro Gas Analyzer System
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

Gravity wave momentum fluxes in monsoon regions

HIRDLS high (1 km) vertical resolution, near global coverage, and ability to sound down into the upper troposphere make it a unique source of data on atmospheric processes from ~ 10 km into the mesosphere. Several studies have used these data to determine the distributions of gravity waves, and their momentum fluxes. Recently HIRDLS measurements were used to quantify gravity wave momentum fluxes generated from monsoon regions across the globe over the three years 2005-2007. Momentum fluxes in the altitude range 16-60 km over monsoon regions in both hemispheres show good correlations with convective data from NOAA's Outgoing Longwave Radiation (OLR) time series and precipitation data from the Tropical Rainfall Monitoring Mission (TRMM). A temporary increase in measured momentum flux, of approximately 50% over temporal background values, is observed during the ~4 month boreal monsoon period over the 10N-30N latitude band, with around half of the annual momentum flux for this latitude range measured during this period.

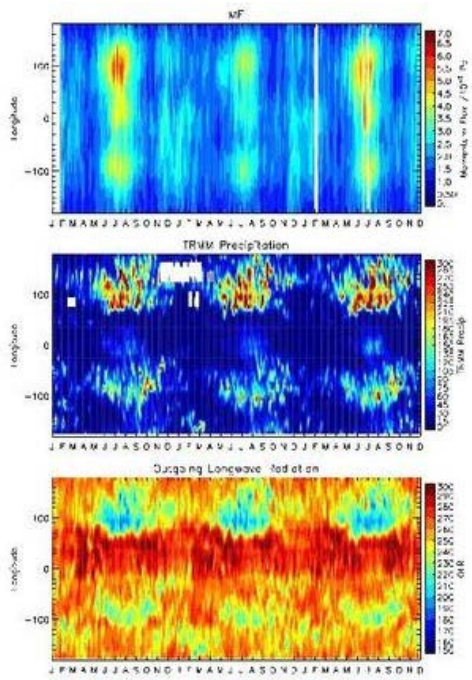

Figure 1. Longitude-time plot of: (top) HIRDLS gravity wave momentum flux in 0.2-100 mb pressure region, (middle) TRMM precipitation and (bottom) NOAA OLR, showing sharp monsoon peaks for the Indian, American and African monsoons. Wright and Gille. (2011), HIRDLS observations of gravity wave momentum fluxes over the monsoon regions, J. Geophys. Res., 116, D12103, **doi:10.1029/2011JD015725**

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Log in

NCAR Earth System Laboratory | NESL
2011 Annual Report

sponsored by

NESL Annual Report

- NESL Director's Message
- Table of Contents
- I. Scientific Discovery
- II. Prediction Across Scales
- III. NESL Observational Science
  - III.A. BEACHON-ROMBAS Field Study
  - III.B. BEACHON-ROCS Field Study
  - III.C. Megacities – Impacts of Trash burning
  - III.D. Deep Convection, Clouds and Chemistry (DC3) Test Flights and Planning
  - III.E. The DISCOVER-AQ Field Campaign
  - III.F. NDACC Highlight – The 2010-2011 Arctic Polar Vortex
  - III.G. The 2011 California Airborne BVOC Emission Research in Natural Ecosystem Transects (CABERNET) Field Campaign
  - III.H.1. VORTEX2 - Verification of the Origins of Rotation in Tornadoes EXperiment 2
  - III.H.2. MC3E - The Mid-latitude Continental Convective Clouds Experiment
  - III.H.3. MACPEX – The Mid-latitude Airborne Cirrus Properties Experiment
  - III.H.4. ICE-T - The Ice in Clouds Experiment-Tropical
  - III.H.5. PREDICT - PRE-Depression Investigation of Cloud systems in the Tropics
  - III.I.1. ARCTAS
  - III.I.2. OASIS
  - III.I.3. CABINEX
  - III.J.1. MOPITT Highlight – CO Emissions from Beijing during 2008 Olympics
  - III.J.2. Satellite Observations of Global Pollution (Carbon Monoxide)
  - III.J.3. HIRDLS Highlight – Gravity wave momentum fluxes in monsoon regions
  - III.K.1 Development of a Picarro Gas Analyzer System
  - III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
  - III.I.1. Development of a Picarro Gas Analyzer System
- IV. Modeling in Support of Field Operations

2009-2014 Strategic Plan »

Development of a Picarro Gas Analyzer System

NCAR scientists continued developing the Picarro G1301 instrument, purchased in FY 2010, into a system for use in field experiments. This gas analyzer, designed to measure water vapor, carbon dioxide, and methane simultaneously with high accuracy, has proven very useful in the study of climate change, surface-atmosphere interactions, ecology, and hydrology. Observations of these three greenhouse gases can be used directly in understanding mass budgets and canopy physiology. The gases can also be used indirectly as tracers in understanding atmospheric dynamics for weather-related phenomena.

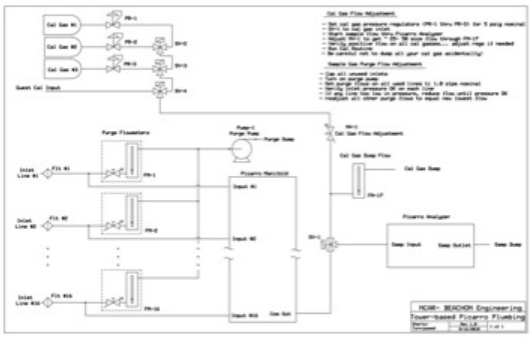

Figure: The designed gas pluming system.

In FY 2011 NCAR scientists designed a sampling system (see two figures), which can collect data from more than 16 ports using a single Picarro analyzer, to investigate spatial variations of CO_2/H_2O/CH_4. The system is designed to extract samples from a distance of ~100 m away. Scientists have purchased all the major components and the mobile shelter and are working with NCAR machine shop technicians and engineers to assemble the sampling system.

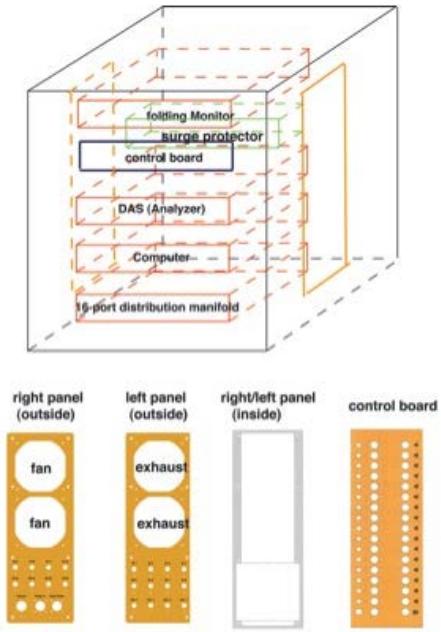

Figure: The designed sampling system, in which the analyzer, the computer, the retractable monitor, the power surge protector, the 16-poart distribution manifold, and the gas monitoring board are contained in a single enclosure for field deployment.

Due to the delay of the lab space and the technician's schedule, scientists have had to delay the field experiment until this fall or as soon as they finish assembling the sampling system. Scientists will conduct two comparison projects first: one with the manufacture calibration gases, and one with other EOL CO_2 analyzers at either Manitou Spring, the BEACHON project site, or the Marshall Field EOL test site. Analysis of the data will be carried out on the field data collected.

The analyzer with the designed sampling system will be used in the field to capture 3-D CO_2 transport. Currently EOL is working on the CentNet, which consists of about 100 remotely controlled weather stations for studying atmospheric spatial variations. The Picarro G1301 Gas Analyzer will be the "gold standard" for their CO_2 measurements.

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Log in

NESL Annual Report 2012

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
IV. Modeling in Support of Field Operations

III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight

a) Quantifying the Influence of Upwelling on Tracers In the Tropical Lower Stratosphere

The mean circulation in the stratosphere includes a global-scale overturning flow with upwelling in the tropics and descent at high latitudes, known as the Brewer-Dobson circulation. The tropical upwelling component of the circulation is important for controlling flow into the stratosphere and chemical composition, although it is a weak circulation that cannot be measured directly, but is inferred from indirect observations (such as trace constituents). Analysis of this circulation and its relationship with temperatures, ozone and the tropospheric pollution tracer carbon monoxide (CO) in the tropical lower stratosphere have been made using daily satellite observations covering several years. Observations show highly correlated variability among temperature, ozone and CO in the lower stratosphere (Figure 1), which reflects the influence of upwelling (which includes a large annual cycle, and also sub-seasonal fluctuations) acting on strong vertical gradients. The tracer variations allow quantification of the strength of upwelling over a broad range of timescales, and have improved understanding of the effects of mean circulation vs. eddy transport effects. Current studies are aimed at parallel analysis of global model simulations (based on WACCM).

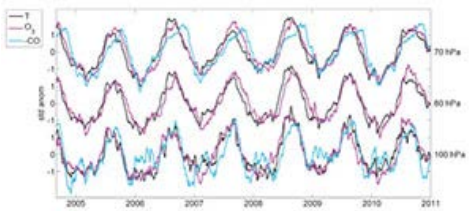

Figure 1: Time series of standardized anomalies of temperature, ozone and carbon monoxide (CO) for three pressure levels in the tropical lower stratosphere (20 N-S). The large seasonal cycles and correlated variability on sub-seasonal time scales are forced responses to variations in the mean upward circulation in the tropics (part of the global-scale Brewer-Dobson circulation). Temperatures are from ERA-Interim, and ozone and CO from Aura MLS satellite measurements.

Reference:
Abalos, M., W.J. Randel and E. Serrano, 2012: Variability in upwelling across the tropical tropopause and correlations with tracers in the lower stratosphere. Atmos. Chem. Phys. Discuss., 12, 18817-18851.

b) Impact of Convective Transport on UTLS Associated with the Asian Monsoon Anticyclone

The Asian summer monsoon (ASM) anticyclone circulation system is recognized to be a significant transport pathway for water vapor and pollutants to enter the stratosphere. The system, therefore, has a significant role in chemistry-climate interaction. The observational evidence, by far, is largely based on satellite retrievals. Satellite observations show that pollutants and trace gases of tropospheric origin have an enhanced concentration inside the anticyclone in the upper troposphere and lower stratosphere (UTLS) on the seasonal average scale. To better understand the transport pathway, the daily variability of the UTLS tracers with convective transport origin is examined together with the dynamical variability of the anticyclone location. Previous studies have shown that the ASM anticyclone, represented by the geopotential height (GPH) maximum, in the UTLS

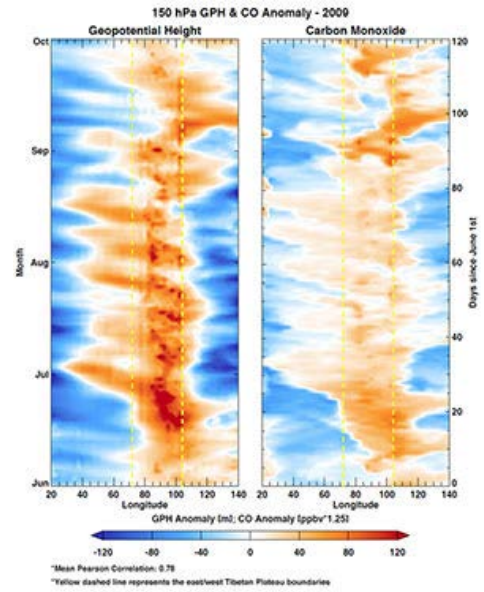

Figure 2: Hovmoeller diagrams for June 1 to September 30, 2009 (4 months period) in 20-140 W longitudinal range, for both GPH anomaly (left) and CO anomaly (right). The GPH anomalies are computed along the line of maximum GPH in each longitude within 0-70 N latitude range (the "spine" of the height field). The CO anomaly is computed in the same fashion. The yellow dash lines indicate the longitudinal range of the Tibetan plateau.

level (100 hPa) exhibits a quasi-biweekly oscillation between an eastern (Tibetan plateau) and a western (Iranian Plateau) mode. To what extent this oscillation also dictates the chemical distribution in the UTLS level is not well known. This information is especially important for flight planning of the pending field campaign SEAC^{4}RS.

This issue is investigated using a model run from the NCAR WACCM-SD (Whole Atmosphere Community Climate Model – Specified Dynamics). To examine the signature of convective transport at the UTLS level, carbon monoxide (CO) from WACCM is chosen as the tropospheric tracer. The correlation of the location of enhanced tropospheric tracer and the anticyclone, as represented by the GPH anomaly, is examined. An example is given in the figure and shown in the form a Hovmoeller diagram. These initial results indicate that the positive anomalies of the tropospheric tracer field have a strong correlation with the anticyclone at the 150 hPa level, indicating a level of strong anticyclone confinement. At 200 hPa level, the chemical tracer field is much less correlated with the GPH field, indicating a much weaker confinement. This study is still in progress.

c) Climate Impacts of Ice Nucleation

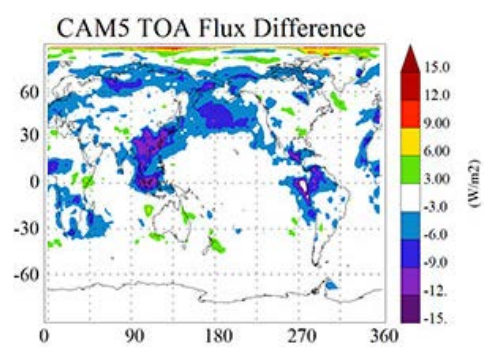

Figure 3: AIE from ice clouds estimated by change in Top of Atmosphere (TOA) radiation between 2000 and 1850.

A recent project, involving scientists from NCAR/NESL, PNNL and NASA-Goddard, looked at the impact of anthropogenic effects on ice clouds in the UTLS, focusing on changes to the nucleation of ice crystals induced by anthropogenic aerosols. Several different ice nucleation parameterizations in two different General Circulation Models were used to understand the effects of ice nucleation on the mean climate state, and the Aerosol Indirect Effects (AIE) of cirrus clouds on climate. Simulations have a range of ice microphysical states (different ice crystal number concentrations), but many simulations have higher present day ice crystal number concentrations than in-situ observations. Broadly the models can simulate the distribution, but seem to have a different balance of freezing mechanisms at low temperatures, leading to higher ice crystal numbers. These different states result from different parameterizations of the ice cloud nucleation processes, and feature different balances of homogeneous and heterogeneous nucleation. Black carbon aerosols were found to have a small (-0.06 Wm-2) and not statistically significant AIE when included as ice nuclei. Indirect effects of anthropogenic aerosols on cirrus clouds occur as a consequence of increasing anthropogenic sulfur emissions with different mechanisms important in different models, but with similar magnitude. The resulting ice AIE does not seem strongly dependent on the balance between homogeneous and heterogeneous ice nucleation. Regional effects can reach several Wm^{-2}, as illustrated in the figure. Indirect effects are slightly larger for those states with less homogeneous nucleation and lower ice number concentration in the base state. The total ice AIE is estimated at 0.27 ± 0.10 Wm^{-2}. The magnitude represents a 20% offset of the total shortwave AIE for ice and liquid clouds of -1.6 Wm^{-2}. These results are included in the latest IPCC report on anthropogenic impacts on climate change.

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Log in

NESL Annual Report 2012

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
III.A. Particle Investigations at a Norther Ozarks Tower: NOx, Oxidant, Isoprene Research (PINOT NOIR) Study
III.B. Megacities
III.B.1. Workshop on Health Impacts of Air Quality and Climate in Asia
III.B.2. Effect of Dry Deposition of Organic Vapors on Exported SOA Downwind of a Megacity
III.C. An Overview of the 2012 Deep Convection, Clouds and Chemistry (DC3) Field Campaign
III.D. NESL/ACD Contributions to 2012 TORERO Field Campaign
III.E. NDACC Highlight: The Renewed ACD/NASA FTS to Improve Remote Sensing Observations at Mauna Loa Observatory
III.F. First Deployments of the TOGA-HAIS Instrument
III.G. Convective and Microphysical Field Campaigns
III.G.1. VORTEX 2
III.G.2. The Mid-latitude Continental Convective Clouds Experiment (MC3E)
III.G.3. Mid-latitude Airborne Cirrus Properties Experiment (MACPEX)
III.G.4. Ice in Clouds Experiment-Tropical (ICE-T) Field Campaign
III.G.5. The PRE-Depression Investigation of Cloud systems in the Tropics (PREDICT)
III.H. Observations from Satellite Platforms
III.H.1. MOPPITT Highlight - Regional Trends in CO from a Decade of Satellite Observations
III.H.2. NESL/ACD Contributions to Future Satellite Missions - OCO-2 and PACE
III.H.3. HIRDLS Highlight: Development of V7 HIRDLS Data
III.H.4. UT/LS (Upper Troposphere/Lower Stratosphere) Highlight
III.I. Additional Observational Development Activities
III.I.1. Development of a Picarro Gas Analyzer System
IV. Modeling in Support of Field Operations

III.I. Additional Observational Development Activities

III.I. **Additional Observational Development Activities**

- III.I.1. **Development of a Picarro Gas Analyzer System**

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Log in

NESL Annual Report 2012

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
IV. Modeling in Support of Field Operations

III.I.1. Development of a Picarro Gas Analyzer System

During 2011 and 2012, the Picarro G1301 Gas Analyzer, which measures water vapor, carbon dioxide, and methane simultaneously with high accuracy, was assembled to measure these gases from 16 inlets.

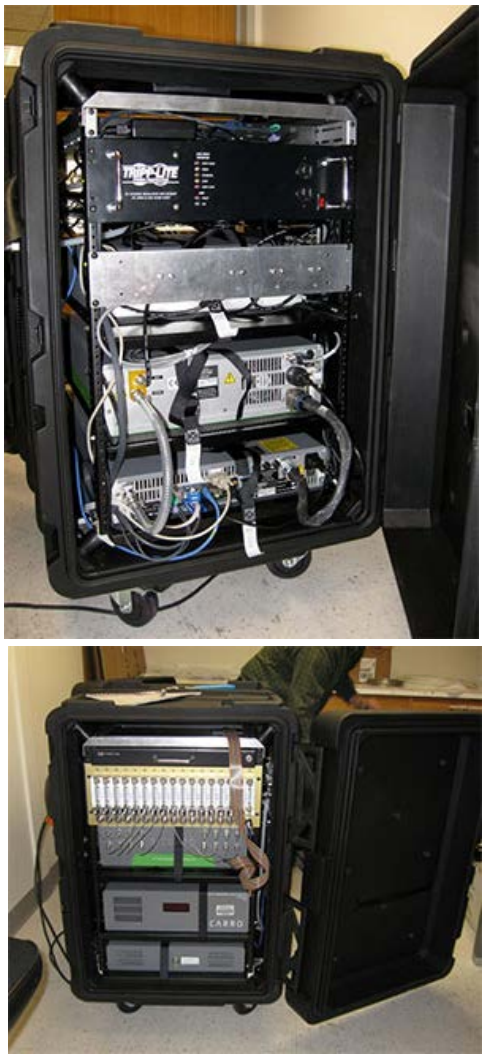

Figure: The front (top) and the rear (bottom) view of the NCAR/MMM Picarro CO2/H2O/CH4 gas measurement system, which enables data collection from 16-inlets.

During the spring and summer of 2012, the analyzer was deployed to the NCAR Marshall field site. The initial calibration with three tanks of known carbon dioxide concentrations indicates that the Picarro analyzer reaches to the accuracy of the calibration gases. Because its accuracy and stability, it was used as the standard for several other carbon dioxide analyzers in an EOL intercomparison experiment at the Marshall field site. Scientists collected about five months of the

data to test the analyzer's performance. They found that the instrument is sensitive to high temperature during the Colorado summer time. They will modify the enclosure design in which all the relevant instruments are housed to reduce the heating problem for future summer deployment.

The Picarro gas analyzer will be deployed to a university-PI led field experiment, Shallow Cold Pool SCP) Experiment at north of Colorado after the Marshall field site inter-comparison experiment (see (**http://www.eol.ucar.edu/deployment/field-deployments/field-projects/scp/shallow-cold-pool-scp-field-project**), scheduled for operation from October 1, 2012 thru November 30, 2012. The Picarro analyzer will provide information on the CO2 and H2O budget, and more importantly will provide a tracer for tracking air movement. Meanwhile, the measurement of the CO2/H2O spatial variation will provide unique observations on how small gullies affect greenhouse transport, which will have significant impacts on our understanding of land-air interactions in the long-term greenhouse gas monitoring network.

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NESL Annual Report 2012

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
IV. Modeling in Support of Field Operations
IV.A. The Hurricane Forecast Improvement Project (HFIP)
IV.B. The Antarctic Mesoscale Prediction System (AMPS)
IV.C. Wind Energy Research

IV. Modeling in Support of Field Operations

IV. Modeling in Support of Field Operations

- IV.A. **The Hurricane Forecast Improvement Project (HFIP)**
- IV.B. **The Antarctic Mesoscale Prediction System (AMPS)**
- IV.C. **Wind Energy Research**

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Log in

NESL Annual Report 2012

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
IV. Modeling in Support of Field Operations
IV.A. The Hurricane Forecast Improvement Project (HFIP)
IV.B. The Antarctic Mesoscale Prediction System (AMPS)
IV.C. Wind Energy Research

IV.A. The Hurricane Forecast Improvement Project (HFIP)

NESL is a contributor to HFIP, a NOAA-led initiative to improve hurricane forecast skill, with an emphasis on hurricane intensity and structure. HFIP involves a combination of operational and research efforts, including NCAR, universities, NOAA, and the Naval Research Laboratory (NRL). The program goals are to conduct resolution tests to determine if higher resolution models systematically improve intensity forecasts, and implement new models into a quasi-operational framework, in addition to models run operationally at NCEP. The retrospective effort is coordinated through RAL's Developmental Testbed Center (DTC).

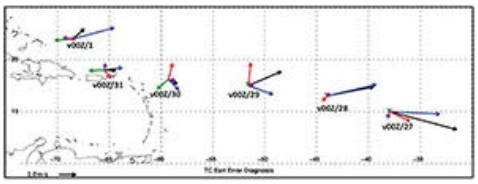

Figure: Errors in the predicted movement of hurricane Earl for 24-h forecasts made on successive days by the Advanced Hurricane WRF model (AHW). The black arrows indicate the total error; blue arrows show the error in the environmental wind; red arrows indicate errors from the depth of the storm and green arrows indicate errors from the storm size. Earl was moving toward the west-northwest, so arrows pointing to the east indicate a movement slower than observed

During FY2012, hurricane forecasts for the 2011 Atlantic hurricane season were performed. These were analyzed along with an extensive set of retrospective forecasts from 2008 to 2010. A diagnostic technique was developed to quantitatively assess the sources of forecast error. An example is given below, which shows errors in the predicted motion of hurricane Earl (2010). From these and other diagnostics it was deduced that the subtropical high was too weak, and the update model configuration that was tested in early 2012 added several modifications to address this problem. One of them was incorporating a climatology of Saharan dust which affects the temperature of the lower troposphere and hence the winds. The other was a change in the treatment of shallow clouds that mix heat and moisture in the lower part of the atmosphere. Both of these changes resulted in an improvement of the track forecasts for Atlantic tropical cyclones.

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Log in

NESL Annual Report 2012

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
IV. Modeling in Support of Field Operations
IV.A. The Hurricane Forecast Improvement Project (HFIP)
IV.B. The Antarctic Mesoscale Prediction System (AMPS)
IV.C. Wind Energy Research

IV.B. The Antarctic Mesoscale Prediction System (AMPS)

AMPS is a real-time, experimental WRF system run at high resolution over Antarctica in support of the U.S. Antarctic Program (USAP). The system provides guidance for weather forecasting for the USAP, as well as for various scientific and logistical efforts over the continent. This work is vital to USAP activities, as the weather forecasters depend on a well-maintained and advancing AMPS.

AMPS provided NWP guidance to the USAP forecasters through the 2011–2012 field season. This was delivered through the AMPS web page (http://mmm.ucar/edu/rt/amps) as well as the Antarctic IDD (internet data distribution). High-resolution products were produced for the Pine Island Glacier field campaign. For this, a special 5-km forecast grid was set up for the region and special products were generated for it.

AMPS also supported the NSF research vessels R/V Nathaniel B. Palmer and R/V Laurence M. Gould as they cruised the Ross Sea and Southern Ocean for the 2011–2012 season. AMPS provided a ship-following window to provide tailored WRF forecast information to the vessels daily. The figure below shows an example, an AMPS forecast of sea level pressure, surface wind, and 3-hourly precipitation for the region around the Palmer (marked "NBP) in the Ross Sea. Related to this, AMPS also provided similar support to the Italian Antarctic Program vessel M/V Italica during a fuel transfer with the Palmer in the Ross Sea.

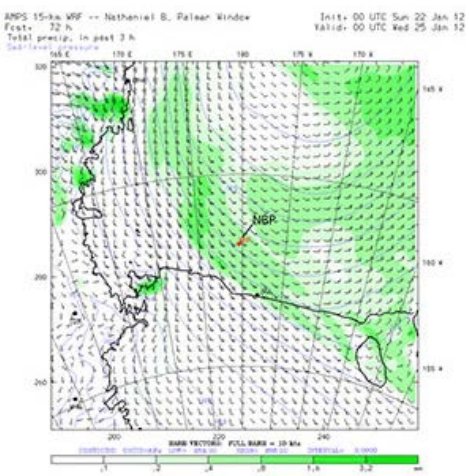

Figure: AMPS forecast for R/V Nathaniel B. Palmer from 0000 UTC 22 Jan 2012 run. Sea level pressure (contours, interval= 2 mb), surface winds (barbs, full barb= 10kt), and 3-hourly precipitation (shaded, scale at bottom) for hr 72 (valid 0000 UTC 25 Jan 2012) shown. Location of Palmer (in Ross Sea) marked "NBP".

In FY2012, the AMPS team worked with CISL on the setup and testing of the new computer for AMPS. This machine, Erebus, was acquired, installed at the NWCS, and tested. The team is now in the process of porting AMPS to the new platform.

Over the past year, the polar modifications in WRF were updated. This was done under special funding from the NSF Office of Cyberinfrastructure and in collaboration with The Ohio State University. The polar modifications better capture conditions unique to the high latitudes, such as sea ice and glacial ice. Two areas were addressed. First, the polar code was restructured into new modules separated from the land surface models. Second, the porting of the latest polar modifications from Ohio State to the most recent WRF release, V3.4.1, was begun.

NCAR organized and hosted the 7th Antarctic Meteorological Observation, Modeling, and Forecasting Workshop in July 2012. This workshop brought together those with research and operational/logistical interests in Antarctic meteorology and weather forecasting. Attendance was about 50, and there was international participation from the UK, Australia, Finland, New Zealand, and Germany. NCAR also hosted the Workshop on Atmospheric Model Parameterizations in the Polar Regions in July. This workshop covered current ideas on model verification in the Polar regions, improvement of parameterizations, and observations useful for model improvement.

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Log in

NESL Annual Report 2012

NESL Director's Message
Table of Contents
I. Scientific Discovery
II. Prediction Across Scales
III. NESL Observational Science
IV. Modeling in Support of Field Operations
IV.A. The Hurricane Forecast Improvement Project (HFIP)
IV.B. The Antarctic Mesoscale Prediction System (AMPS)
IV.C. Wind Energy Research

IV.C. Wind Energy Research

In collaboration with a number of outside and NCAR/RAL collaborators, major activity within NESL/MMM this year on wind energy research focused on offshore winds. NCAR scientists surveyed, collected, and acquired a wide range of already available offshore wind and wave data sets. In addition to several data sets from episodic experiments carried out off of the East Coast (including: The Shoaling Waves Experiment (SHOWEX) which took place near Duck, North Carolina during Spring 1997, Spring 1999, and Fall 1999, and CBLAST (Coupled Boundary Layers/Air-Sea Transfer) carried out in Summer 2001 and 2002 south of Martha's Vineyard), scientists also acquired the FINO data set which is a comprehensive data set consisting of multiyear measurements of lower-boundary layer structure over North and Baltic Sea from three offshore platforms. The utility of the FINO datasets lies in the fact that FINO1 has been collecting data since 2003 and that FINO3 platform has been operating since 2009. The first objective has been to determine which offshore data sets are suitable for the analysis required to determine the effects of swell and atmospheric stability on the structure of marine boundary layer over the rotor plane of a modern turbine.

Our analysis of the East Coast data sets from the CBLAST field study reveals frequent cases of warm air advection over colder water leading to stable stratification in the marine boundary layer and partial collapse of the surface wind and wave field, decoupling, and forming low-levels jets in the range of heights coinciding with the modern wind turbine rotor plane. Such common low-level jets complicate assessment of wind climatology at hub height as well as operationally forecasting winds at hub heights.

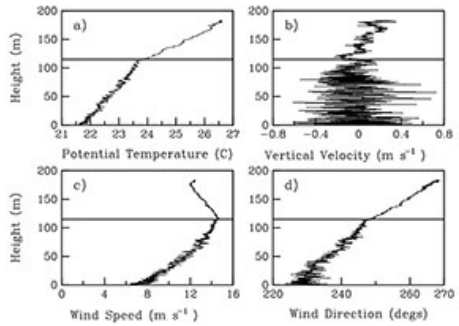

Figure: An example low-level wind maxima and associated potential temperature profile near Martha's Vineyard during offshore flow from an aircraft sounding during the CBLAST Experiment in August 2001.

The height at which the low-level jet occurs depends on the wind speed and therefore atmospheric stability. Under weaker winds or stronger stratification (~5 ms-1), the low-level wind maximum occurs below 50m. While under stronger wind conditions and weaker stratification low-level wind maximum occurs above 100m (Figure). In both cases, the wind maxima coincide with the height of the elevated thermal inversion as can be seen from observations of potential temperature (depicted in panel 'a' in the Figure). The low-level jet results in strong shear below and above the wind maximum. These offshore low-level jets can occur at a range of heights spanning the turbine rotor plane, potentially leading to substantial stress on wind turbine blades. From this analysis, we purport that the data from the episodic East Coast field studies will be suitable for studying stratification effects on wind and turbulence profiles in the marine boundary layer.

Analysis of the FINO datasets is ongoing, but the most important aspect of the FINO datasets is that they include information on the wave state, so using these datasets NESL/MMM scientists will be able to connect surface wave conditions to hub-height winds. Initial analysis of the data from the FINO towers suggests that a wide range of wind directions persist over a relatively predominant wave direction (not shown). The key outcome of this overall effort is that our data analysis has demonstrated the utility of these data sets for our stated purpose to establish the effects of thermal stratification and swell on hub height winds and shear over turbine rotor plane.

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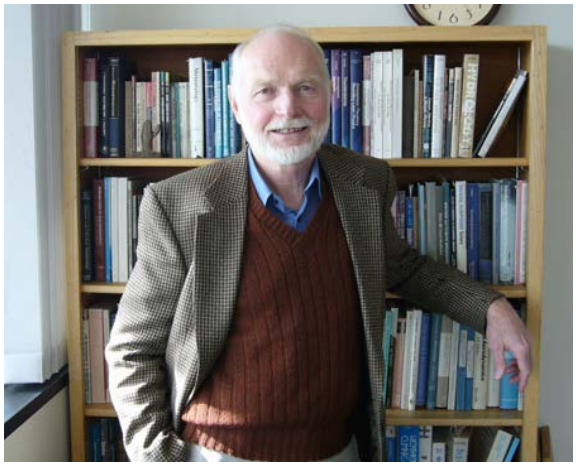
Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Director's Message



Brant Foote - RAL Director

Welcome to the Research Applications Laboratory's Annual Report for FY2012. Our goal is to conduct directed research that contributes to the depth of fundamental understanding of the atmosphere and its interaction with society, and to develop and transfer knowledge and technology that expands the reach of atmospheric science and contributes to the betterment of life on Earth. We are, at present, an organization with annual expenditures of approximately $32M and a staff comprised of about 200 scientists, software engineers, and management/administration personnel.

I hope you will enjoy reading this year's Annual Report. As in the past, it follows the outline of our strategic plan, providing details on our many accomplishments over the past year and our plans for the future. I would like to highlight here the successful conclusion of an important aviation program in Juneau, Alaska, as well as the significant expansion of two programs in renewable energy and water resources. Both were cast as research "frontiers" in our 2009 Strategic Plan, but are now clear imperatives for the Laboratory as we move forward.

Juneau: In 2012 we successfully concluded a long-term effort on behalf of the FAA to develop an operational wind warning system for the Juneau, Alaska airport. Over the life of this program, our staff made important scientific and technical advances that improved our understanding of turbulent flows over complex terrain; devised new approaches to siting, deploying, and maintaining instruments in extreme weather conditions; and developed new methods for analyzing data from meteorological sensors. This system for Juneau is the first FAA-approved operational, terminal-area turbulence warning system to be deployed in the U.S., and I was pleased to nominate the team that created it for UCAR's Outstanding Performance Award for Scientific and Technical Advancement in 2012.

Renewable Energy: In 2011 we successfully delivered an advanced wind power forecasting system to Xcel Energy, with improved capabilities that are estimated to save many millions of dollars per year for the power utility. In 2013 we will expand the system's capabilities by integrating the Variational Doppler Radar Analysis System (VDRAS) to allow real-time analysis and forecasting for wind power ramps, improve forecasting of extreme events, and add a new probabilistic forecasting capability to the system to provide better uncertainty estimates for predictions. We will also, for the first time, be developing new methods and techniques for incorporating solar energy prediction capabilities into the Xcel forecast system.

In late 2012 we were also notified of the award of a major new solar energy forecasting program from the Department of Energy. RAL will lead a public-private partnership of national laboratories, utilities, and universities focused on creating better forecasts of when, where, and how much solar power will be produced at U.S. solar energy plants. Enhanced solar forecasting technologies will clearly be important in integrating cost-competitive, reliable solar energy into the electricity grid and ultimately providing clean, renewable energy to U.S. consumers.

Water Resources: For more than a decade, RAL scientists have made major contributions to Water System research at NCAR, particularly with regard to the impact of changing climate on the Colorado Headwaters. In 2012, this base-funded work was augmented by complementary programs funded by the Bureau of Reclamation and the Army Corps of Engineers, as well as by private and non-governmental organizations in the U.S. and Europe. I am particularly pleased with advances that have been made in developing the WRF-Hydro model which combines a state-of-the art, community-developed numerical weather prediction model, WRF, and a flexible and extensible distributed hydrological modeling framework into a unified, computational architecture. The code is freely available to the community and is

supported, in part, by NCAR. The WRF-Hydro model is now being used in more than ten countries around the world by research groups and operational prediction agencies. With a growing network of model users and increasing record of improved model skill, it is becoming clear that WRF-Hydro is poised to become an essential community resource for hydrometeorological and hydroclimatological prediction.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
  - Icing: InFlight, Ground and Engine
  - Prediction of Storm Hazards for Aviation
  - Turbulence
  - Ceiling and Visibility Research and Development
  - Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact
  - Dissemination of Aviation Weather Information
  - Oceanic Weather: Convection and Turbulence
  - Avian Radar Performance
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Next Generation Air Transportation

Play a leadership role within the atmospheric research community to provide the necessary scientific underpinning and technology to support the weather and climate–related needs of the Next Generation Air Transportation System (NextGen).

- **InFlight, Ground and Engine**
- **Prediction of Storm Hazards for Aviation**
- **Turbulence**
- **Ceiling and Visibility Research and Development**
- **Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact**
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Log in

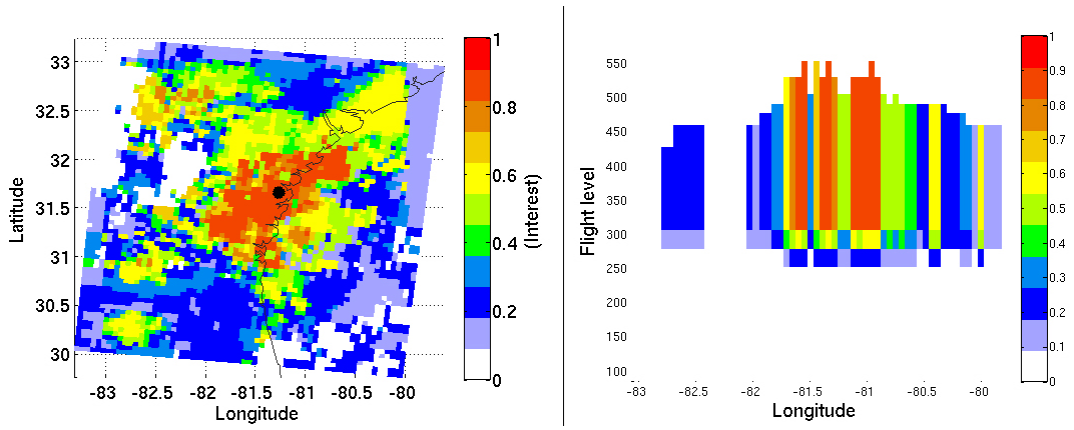
RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
  - Icing: InFlight, Ground and Engine
  - Prediction of Storm Hazards for Aviation
  - Turbulence
  - Ceiling and Visibility Research and Development
  - Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact
  - Dissemination of Aviation Weather Information
  - Oceanic Weather: Convection and Turbulence
  - Avian Radar Performance
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Icing: InFlight, Ground and Engine

FAA-Sponsored Activities

For the past two decades RAL scientists have worked to improve diagnoses and forecasts of icing conditions that impact aviation. Our largest program is the FAA's Aviation Weather Research Program, which is focused on providing operationally-available, automated in-flight icing forecasts over the CONUS and Alaska. At this time, the Current and Forecast Icing Products (CIP and FIP), developed at RAL, are running at the National Weather Service's Aviation Weather Center and are approved for unrestricted supplementary use. The outputs include expected icing severity, probability of encounter, and potential for supercooled large drop (SLD, those drops with diameters exceeding 50 microns) at 20-km resolution over the CONUS for 0-12 h.



Preliminary ALPHA output displayed in plan-view (left) and vertical cross-section (right) format. Scale is on the right and represents the likelihood of encountering high ice water content (HIWC) regions; warmer colors convey higher likelihood. The black dot is the location of an aircraft encounter with a HIWC region.

In 2012 RAL transferred CIP and FIP to the new Weather and Forecast Rapid Refresh (RAP) Numerical Weather Prediction (NWP) model, which became operational in May 2012. Improvements in the model's microphysical parameterizations were developed by RAL staff working under the FAA's InFlight icing and Model Development and Enhancement teams. During the summer of 2012 the Icing Team rewrote the CIP and FIP codes to make them more portable to different platforms and more easily upgradable for new data inputs or revised data formats. The output fields are also being changed to 13-km resolution to match that of the RAP model. We also began work on new projects within the FAA program: 1) MICRO (Model for Icing Conditions in Real-time Operations), which will incorporate a high-resolution NWP model and improved use of sensor data to output the full drop size distribution (DSD) for icing prediction and severity calculations and 2) IPA (Icing Product-Alaska) which will revise CIP and FIP for the Alaska weather and data environments.

An initial version of ALPHA, the Algorithm for Prediction of High Ice Water Content (HIWC) Areas, was developed and tested on cases over the CONUS and during last year's PREDICT project in the Caribbean. The concept uses NWP output combined with satellite and radar data to diagnose cold cloud tops, warm atmosphere (compared to a standard sounding), high radar reflectivity below typical flight cruise altitudes, and other factors to determine regions conducive to the HIWC hazard.

We completed a preliminary Icing Hazard Level (IHL) algorithm under a program funded by the FAA NEXRAD Project Office. The IHL algorithm uses NEXRAD and NWP data to find likely icing conditions that are related to freezing drizzle and mixed-phase cloud conditions using radar reflectivity and polarization parameters now available on the radar network. This algorithm will be implemented on a test version of the NEXRAD Open Radar Products Generator (ORPG)

in fall 2012 and will be tested on live and archived data sets.

Work continued with United Airlines to make improvements as needed to the Weather Support for Deicing Decision Making (WSDDM) systems deployed at Denver, Cleveland, and Minneapolis. This is being funded by United Airlines. The Liquid Water Equivalent (LWE) system is being evaluated for operational use through testing funded by Vaisala, Inc. The FAA continues to support anti-icing fluid testing through panel tests using the snow machine at the FL3 laboratory and at the Marshall test site.

A new project, Terminal-Area Icing Weather Information System (TAIWIS) was initiated to provide high-resolution detection, diagnosis and forecasting of icing conditions in the near-airport area. This system should include elements of our ground icing (WSDDM, LWE) and inflight icing (MICRO) work. In 2012 the tasks are to establish TAIWIS requirements, baseline capabilities for detecting and forecasting icing conditions in the terminal area, describe research that could lead to capabilities available for testing in the next several years, and work with the FAA on a thorough gap analysis and research plan.

NOAA-Sponsored Activities

We completed our installation of the Interactive Correction in 4 Dimensions (IC4D) workstation software and are using it as a platform for storm case study analysis. The IC4D workstation is used extensively by the Alaska Aviation Weather Unit and is valuable for helping us understand their working environment. Work began on a Global Forecast Icing Severity algorithm evaluation. NCEP's Meteorological Development Laboratory modified our operational version of FIP to ingest Global Forecast System (GFS) model data to produce a world-wide icing forecast. Our role is to work with them to evaluate the quality of the output by comparing with our RAP-based FIP and to adjust fuzzy logic maps within the algorithm to provide the best map to that product's output.

NASA-Sponsored Activities

Analysis of winter storm data collected from the NASA Icing Remote Sensing System (NIRSS) and the CHILL S-band radar during the winter of 2010-2011 continued. Radar and radiometer measurements are being examined for times when pilots flying near the facilities reported icing conditions. Additionally, a new balloon-borne instrument for detecting supercooled liquid water (and thus potential icing conditions) was tested in flights over north Boulder. The instrument package was developed by Anasphere, Inc. and RAL. NOAA's Physical Science Division; NASA Glenn Research Center; Radiometrics, Inc.; and Anasphere worked together to launch the sondes and evaluate the results.

Plans for 2013

In 2013 we will continue to improve our icing algorithms and move them forward toward operational deployment and use. This not only involves scientific and engineering effort but also a good deal of interaction with the FAA and NWS to prepare Concepts of Use and Operations documents and to demonstrate preliminary versions to potential future users.

The HIWC field program is now scheduled for Spring 2014 in Darwin, Australia. A virtual field program will be conducted in spring 2013 during which ALPHA will be deployed in Darwin to test communications and data availability at the project site. This is an opportunity to work with the local forecasters to better understand the weather conditions that will be present during the field campaign and to incorporate those forecasters into the research.

We will also evaluate a winter Hydrometeor Detection Algorithms (HCA) on live and archived NEXRAD polarization data from Cleveland and Denver and complete the GFIS evaluation.

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Log in

https://nar.ucar.edu/2012/lar/ral/prediction-storm-hazards-aviation Go

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
  - Icing: InFlight, Ground and Engine
  - Prediction of Storm Hazards for Aviation
  - Turbulence
  - Ceiling and Visibility Research and Development
  - Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact
  - Dissemination of Aviation Weather Information
  - Oceanic Weather: Convection and Turbulence
  - Avian Radar Performance
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Prediction of Storm Hazards for Aviation

Background

The Next Generation Air Transportation System (NextGen) is a national priority designed to meet the air transportation needs of the United States in the 21st century—in particular, a significant growth in demand for air traffic services, possibly on the order of two to three times today's demand levels. Since weather conditions can seriously restrict aircraft operations and levels of service available to system users, the manner by which weather is observed, forecast, disseminated, and used in decision-making is of critical importance.

For the past several years, RAL has been engaged in multiple FAA-funded research and development efforts geared toward improved convective weather support for air traffic management en route and in/out of terminals (e.g., CoSPA) and, more recently, for airport operations safety for outdoor workers (i.e., lightning hazard). In addition, efforts have continued in terms of enhancing our understanding of numerical weather prediction model performance, which enables effective harvesting of model predictions for convective storm initiation and probabilistic forecasting.

FY2012 Accomplishments

The 0 – 8 hour CoSPA forecasts - jointly developed and maintained by MIT Lincoln Laboratory, NOAA Earth System Research Laboratory, and NCAR RAL - continue to be made available to aviation planners (i.e., select FAA and airline industry partners) via a web-based display during the convective weather season (April through October). The display allows users to overlay airports and associated arrival and departure fixes, route structures, and sectors on current and forecast weather facilitating the product's utility (Figure 1). This past summer, like the previous year, only a reduced operational evaluation was conducted by the FAA that primarily relied on surveys and interviews with select groups of users. The analyses convey sustained interest in and usage of the CoSPA forecast products by the aviation planners. An initial version of CoSPA is currently undergoing acquisition by the FAA's NextGen Weather Processor.

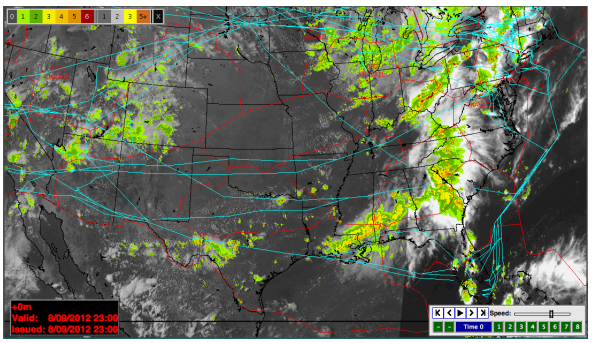

Figure 1. Analysis and forecast products made available to aviation planners via a web-based display.

Another, more recent research effort has been concerned with the safety risks of personnel working outdoors at airports (e.g., baggage handlers, food and fuel suppliers) when thunderstorms are in the vicinity that may generate cloud-to-ground lightning strikes. In collaboration with airport stakeholders, we have been evaluating current procedures, as well as weather data sources used in the decision making. This task includes observations on-site with airport and airline stakeholders along with development of enhanced monitoring and nowcasting capabilities of lightning at airports. Preliminary findings from the observations at Denver International Airport suggest that there is substantial uncertainty associated with the decision-making process for ramp closures (i.e., pulling people inside for safety reasons) due to thunderstorms and lightning in close proximity of

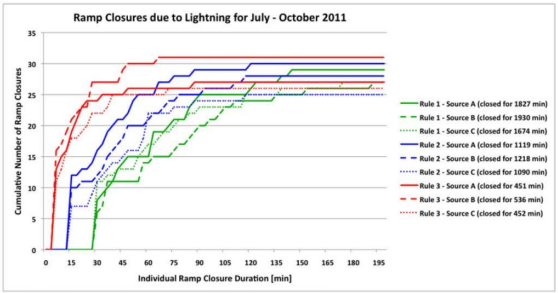

Figure 2. Ramp closure variations due to stakeholder safety

procedures and lightning data sources.

concourses/gates (Figure 2). This uncertainty is caused by the various sources of lightning information, differences in procedures applied by the various stakeholders, human factors, and the way information is communicated.

Unexpected initiation of large-scale convective storms can have substantial impacts on air traffic. Using data mining approaches and ensemble forecasts, our research this past year has been geared toward early identification of areas prone to develop large-scale storms, including assessment of how well numerical weather prediction models capture those storm initiation areas. Unfortunately, numerical weather prediction models continue to experience difficulty in determining whether a storm will initiate or not in a particular area and if it does, how it will evolve and whether it will become an organized, lightning producing storm system. We observed notable regional differences in model skill.

This substantial prediction uncertainty has prompted us to develop probabilistic convective storm guidance products using ensemble forecasts. Two probabilistic prediction efforts are underway: one focused on developing a probabilistic storm impacts product based on ensemble forecasts for the United States while the other aims at mounting a probabilistic convection guidance product based on global ensemble forecasts for strategic transoceanic air traffic planning. Both these tasks include a close collaboration with the NWS Aviation Weather Center (AWC).

FY2013 Plans

Research and development will focus on improving the CoSPA forecast system, particularly with regard to the calibration of model storm intensity, correction of model storm position errors, and treatment of storm initiation in the blending algorithm. CoSPA forecasts will be provided again to aviation planners during the next convective summer season.

It is expected that new capabilities and products will be episodically demonstrated to users as technologies mature. An enhanced lightning nowcasting capability will likely be evaluated during the next year. Development of ensemble-based probabilistic storm impact predictions will continue for both domestic and international flight domains.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
  - Icing: InFlight, Ground and Engine
  - Prediction of Storm Hazards for Aviation
  - Turbulence
  - Ceiling and Visibility Research and Development
  - Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact
  - Dissemination of Aviation Weather Information
  - Oceanic Weather: Convection and Turbulence
  - Avian Radar Performance
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Turbulence

Background

Turbulence encounters by general and commercial aviation pose significant safety and flight efficiency concerns. Almost anyone who has flown commercially has had an unpleasant experience with turbulence and has a tale to tell about it. In fact, turbulence encounters account for well over 75% of all weather-related injuries on commercial aircraft and amounts to at least $200M annually in costs according to some estimates. Consequently, there is an urgent need to provide better turbulence information to pilots and route planners so that the number of encounters can be minimized, or at least provide adequate warnings so that passengers and crew will have time to fasten their seatbelts before an expected encounter.

For more than fifteen years, scientists and engineers at the National Center for Atmospheric Research's Research Application Laboratory (NCAR/RAL) have led efforts to address these needs. Working under the sponsorship of the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA) and in collaboration with several universities, the team has conducted research aimed at improving our fundamental understanding of the nature and causes of turbulence. Additionally, the team has developed new techniques for better observing and forecasting turbulence.

Efforts have been focused on three areas: (1) development and implementation of new techniques for obtaining automated *in situ* reports of turbulence encounters from commercial aircraft, (2) development of an automated detection system of in-cloud turbulence using the national NEXRAD radar network, and (3) development and implementation of an automated turbulence forecasting system called Graphical Turbulence Guidance or GTG. While R&D efforts continue in each of these areas, the products that are being developed have reached a level of maturity that allow them to be used operationally by pilots and route planners in tactical and strategic planning for avoiding turbulence or mitigating encounters.

A fourth long-term effort, developing and implementing an operational turbulence and windshear warning system for the Juneau, Alaska airport, is also discussed in this report.

Automated *In situ* Measurements

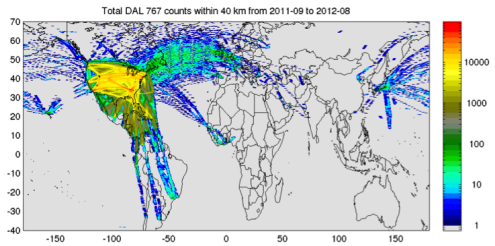

Figure 1. Tracks of several Delta Air Lines 767-300ER and 767-400ER aircraft. The color scale is the frequency of occurrence along particular tracks.

Despite the continued reporting of the frequency and severity of turbulence encounters, our understanding of the nature and genesis of this complex atmospheric phenomenon remains limited. Turbulence research has been limited in part by a lack of reliable data. Verbal pilot reports (PIREPs) have typically been the only source of information for the location and severity of turbulence at flight levels. These reports are, unfortunately, incomplete (reporting is voluntary), and highly subjective (what one pilot views as moderate might be light or severe to another). Recent investigations into the accuracy of PIREPs have indicated an average position error of about 46 km, or several grid points with current operational numerical weather prediction (NWP) grid spacings. While computer models are very useful in forecasting other atmospheric hazards, they are of limited value here given that turbulence exists for short periods of time and in small geographical areas. In order to improve the detection and forecasting of turbulence, it is clearly essential to upgrade the turbulence observation and reporting system and to create empirical means for obtaining more abundant, reliable data. In pursuit of this goal, we are in the process of augmenting, and eventually replacing, the PIREPs with *in situ* observations from selected commercial aircraft. These observations and their dissemination are completely automated, and provide a measure of atmospheric turbulence intensity levels as quantified by the eddy

dissipation rate (EDR, m $^{2/3}$/s).The *in situ* EDR system consists of a simple software upgrade to the aircraft's ACMS (Aircraft Condition and Monitoring System), and no hardware changes are required.

FY2012 Accomplishments:

Currently the *in situ* EDR software package is implemented on about 90 United Airlines 757-200 aircraft and about 90 Delta Airlines 737-700 and 737-800 aircraft. This year, initial implementation of the algorithm on Delta's 767 (-300ER and -400ER) fleet began. This will provide measurements globally as indicated by flight tracks shown in Figure 1. Implementation on about 100 aircraft is expected to be completed in 2013.

FY2013 Plans:

We are currently in discussions with Southwest Airlines to implement the algorithm on their entire 737 -700 fleet. Discussions with United Airlines to implement the algorithm on their 767 fleet have also been initiated.

Remote Sensing Measurements

In order to give pilots better information about potentially hazardous regions of turbulence in thunderstorms before they encounter them, RAL scientists have developed a product that uses ground-based Doppler radars to remotely detect turbulence within clouds. The algorithm runs on data from each NEXRAD, processing each "tilt" or "sweep" independently to obtain estimates of eddy dissipation rate (EDR). The results can then be merged with measurements from other radars, mapped at chosen flight altitudes, and displayed for interested users. The initial version of this product, the NEXRAD Turbulence Detection Algorithm (NTDA), was adopted by the National Weather Service and implemented on all of its radar systems in 2007 and 2008. Since then, a number of advancements have been made to the NTDA to increase its coverage and accuracy. A prototype radar data ingest, processing, and mosaic system using the latest version of the NTDA continues to run in real-time at NCAR, using a real-time data feed from 133 NEXRADs in the Continental US and generating 3-D maps of in-cloud turbulence every 5 minutes at a resolution of 2 km horizontally and 3,000 ft vertically. A sample horizontal cross-section with other relevant information overlaid is shown in Figure 2.

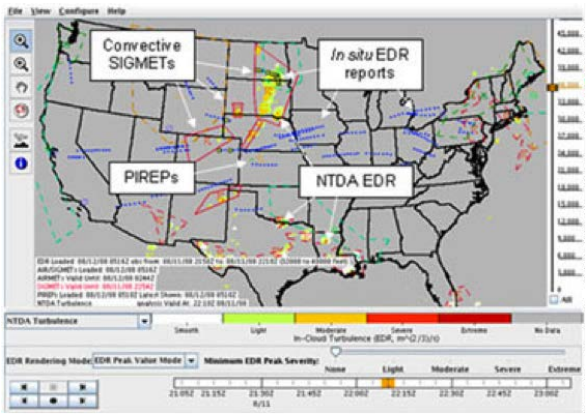

Figure 2. Experimental ADDS display of the NTDA turbulence mosaic, with convective SIGMETs and turbulence reports overlaid.

In 2012, work began on modifying the NTDA to run in Taiwan on four Doppler weather radars, including three Gematronik radars and one NEXRAD, for integration into the Advanced Operational Aviation Weather System that supports the Taiwan Civil Aeronautics Administration (CAA). Several modifications have been required and are still underway.

FY2012 Accomplishments:

The latest version of the NTDA, NTDA-2.5, accommodates the recent NEXRAD dual-polarization upgrade and increases coverage via a more refined quality control procedure. The primary improvement has been the development and implementation of a dynamic signal-to-noise ratio (DSNR) interest map for assessing the quality of spectrum width measurements, which are used by the NTDA to determine turbulence intensity. These interest maps are now computed dynamically for each radar sweep or tilt based on that sweep's operational parameters using a table of numerous radar measurement simulations. NTDA-2.5 has been verified by statistical comparisons with *in situ* EDR data and by examining its performance for a number of turbulence accident cases. For example, on 13 June 2012, United Airlines Flight 1632 appears to have flown over or into a developing convective cell and encountered severe turbulence - an accident that was investigated by the National Transportation Safety Board. NTDA EDR estimates indicated severe turbulence (0.5+) at the encounter location in the 5.0° elevation scan that

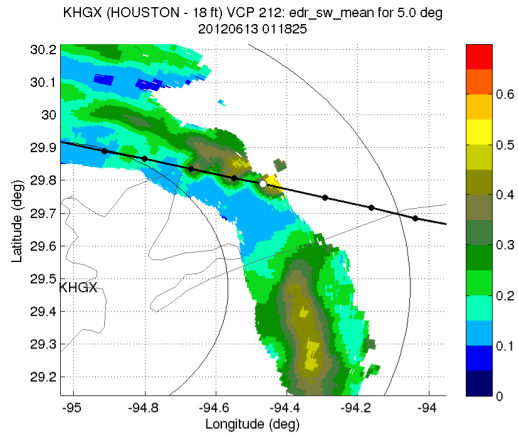

Figure 3. EDR produced by NTDA operating on the 5.0° sweep from KHGX (Houston NEXRAD) at 1:18 UTC 13 June 2012. The white circle shows the location of a severe turbulence encounter by United Airlines flight 1632 at about 1:17 UTC that was investigated by the National Transportation Safety Board.

intersected the aircraft flight track near the time of the encounter.

The NTDA detected severe turbulence at the encounter location.

NTDA data were also used to analyze the development of turbulence inside thunderstorms and relate turbulence volumes to the occurrence of lightning. The correlation between these quantities may be used in conjunction with future geostationary satellite lightning mapping data to help diagnose likely regions of turbulence in regions not served by Doppler radar.

FY2013 Plans:

NTDA will continue to run as a real-time prototype over the CONUS, providing data used for the development of turbulence nowcast products. NTDA will continue to be modified for use on Doppler weather radars in Taiwan as part of the Advanced Operational Aviation Weather System (AOAWS) Phase 3 project.

Nowcasting/Forecasting Turbulence

RAL has been developing and testing aviation-scale turbulence nowcast and forecast algorithms that provide forecasts out to 12 hours. These algorithms are based on operational NWP model output and are updated hourly. The version that is used over the Continental U. S. (CONUS) is termed the GTG (Graphical Turbulence Guidance) product. It relies on the WRF RAP (**http://rapidrefresh.noaa.gov/**) model output and provides what amounts to an ensemble weighted mean of various turbulence diagnostics output as EDR ($m^{2/3}$ /s) on flight levels between 10,000 ft MSL and FL450. The output is available to interested users on NOAA's ADDS web site (http://www.aviationweather.gov/adds/).

In addition to the GTG *forecast* system (forecasts updated hourly), we are currently developing a *nowcast* system, GTG-N, which will provide rapid (every 15 min) updates and make heavy use of the latest available turbulence observations from the *in situ* EDR estimates, PIREPS, NTDA, and other sources (e.g., satellite-based inferences) on a GTG background. This will greatly enhance pilot situational awareness, especially for turbulence associated with thunderstorms (convectively-induced turbulence or CIT). Special diagnostics (termed "DCIT", Diagnose Convectively-Induce Turbulence) are being developed to predict areas of likely near-cloud turbulence.

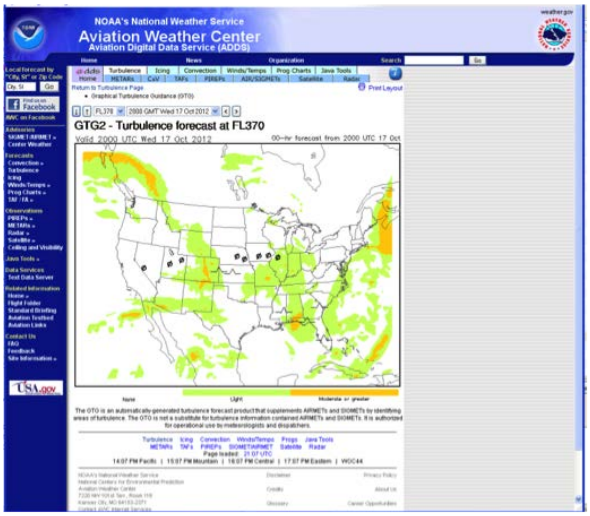

Figure 4. Example GTG2.5 output as it appears on NOAA's Experimental ADDS website.

FY2012 Accomplishments:

The Graphical Turbulence Guidance version 2.5 (GTG2.5), which provides WRF RAP–based forecasts of turbulence, became "operational" on 1 May 2012 when the WRF-RAP replaced RUC at NCEP. An example image of the WRF RAP-based GTG as it appears on the ADDS website to on-line users is provided in Fig. 4. Other algorithms that make use of GTG output (GTG-N and DCIT) have been updated to use the WRF RAP as well.

Substantial effort has been invested in developing a better physical understanding of the mechanisms responsible for CIT and CAT (three papers were published last year on this subject) with the long-term goal of providing better operational CIT forecasts. These studies make use of high-resolution nested numerical simulations that are large enough to capture the relevant large-scale processes and fine enough to capture the turbulence generating mechanisms.

FY2013 Plans:

A third version of the WRF RAP-based guidance, GTG3, will begin formal evaluation sometime near the end of FY2013. GTG3 will provide turbulence forecasts from the surface to FL450 and include explicit mountain-wave induced turbulence. A first version of GTG-N will be part of the GTG3 package. A global GTG based on the GFS model will also be developed and tested. Investigations of clear-air turbulence events using high-resolution WRF simulations will continue with emphasis on the relation to gravity waves and gravity wave breaking.

Juneau Airport Winds System (JAWS)

Although Juneau is the capital of Alaska, the city is only accessible by air or sea. Safe, reliable air transportation is therefore critical, but difficult to achieve given Juneau's location at the end of the Gastineau Channel with mountains on either side of the water. Severe turbulence induced by this complex

Figure 5. Sheep Mountain anemometer site in April 2012.

terrain has led to a number of incidents and near-accidents at the airport and frequently resulted in the closure of runways when wind speeds were judged to be hazardous. In response to concerns for safety and the need for greater operational efficiency, the Federal Aviation Administration sought help from NCAR in 1996 to determine the feasibility of creating and implementing a wind hazard warning system. When early studies showed that significant improvements could be made, a full-scale research, development, and technology transfer program was initiated. Early efforts focused on understanding local meteorology, as well as the specific nature of turbulence in the airport environment. Observational data were critical to this effort; thus, anemometers and wind profilers were acquired and deployed, and instrumented research aircraft were flown to collect data in three field programs. Field project data were used to develop algorithms which turn sensor data into real-time warnings, which were then provided to users in displays specifically designed to help them make decisions regarding safe flight. The graphical display was designed for a variety of users including Automated Flight Service Station specialists, airline dispatchers, and pilots. It contains information that depicts current alerts and conditions as well as conditions during the past hour.

FY2012 Accomplishments

Following extensive evaluations by the FAA, the agency certified the Juneau Airport Winds System (JAWS) as a fully operational turbulence warning system in June 2012. This is the first FAA-approved operational terminal-area turbulence warning system to be deployed in the U.S. The prototype warning system is now used every day by airlines and pilots flying in and out of Juneau to assess current turbulence hazards in the vicinity of the airport. The FAA now owns and operates the system. The National Weather Service in southeastern Alaska is using data from the JAWS system in the forecasts it delivers to the public. Data is also now available for direct download by the public on smart phones and tablets.

RAL nominated the team responsible for the development of JAWS for UCAR's 2012 Outstanding Performance Award for Scientific and Technical Advancement.

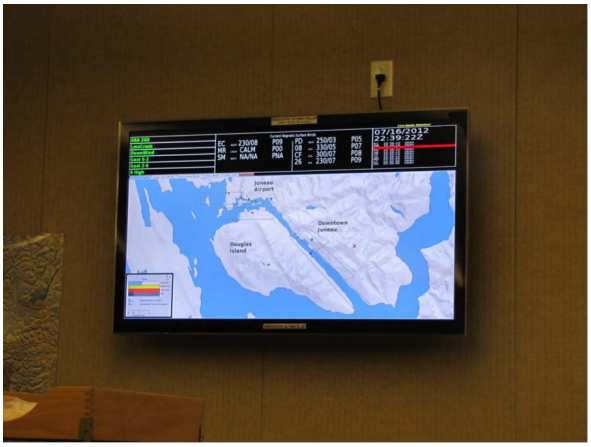

Figure 6. Geographic display of Juneau Airport Wind System. Hazard warning areas are outlined as boxes.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
  - Icing: InFlight, Ground and Engine
  - Prediction of Storm Hazards for Aviation
  - Turbulence
  - Ceiling and Visibility Research and Development
  - Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact
  - Dissemination of Aviation Weather Information
  - Oceanic Weather: Convection and Turbulence
  - Avian Radar Performance
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Ceiling and Visibility Research and Development

Impacted ceiling and surface visibility (C&V) conditions represent a costly source of flow capacity reduction for air terminals servicing high-volume commercial traffic. Further, these conditions pose a major safety risk for general aviation (GA) operations and critical operational limitations for helicopter-based emergency medical services and off-shore oil production facilities. RAL's work toward automated real-time C&V diagnoses and probabilistic forecasts will help address the human-based decisions made in these applications today and will provide the quantitative forecast grids needed by the automated decision support systems that are critical to future operations under NextGen.

FY2012 Accomplishments

C&V Analysis Product Reaches Operational Status

In past years, RAL has worked to develop a web-based CONUS C&V analysis product targeted to improve users' visualization of local and regional-scale ceiling and visibility conditions – a high priority for the general aviation and helicopter emergency medical service communities. FAA evaluation of the analysis product was successfully completed in FY2011, yielding final approval for operational use by pilots, dispatchers, and others as a supplement to primary observations and forecasts. RAL's work in FY12 aided NOAA's Aviation Weather Center in bringing the analysis code to operations-ready status. The product was implemented for operational use in July of 2012 and is updated every five minutes. See **http://www.aviationweather.gov/adds/cv/**.

RAL C&V Forecast Method Builds on Current Forecast Skill

Under funding provided by FAA and NOAA, RAL is developing a 1-10 hr automated C&V forecast system for hourly production of both probabilistic and deterministic (yes/no) forecasts for CONUS airports. Our approach seeks to make best practical use of existing operational forecast resources such as NOAA's Localized Aviation MOS Program (LAMP) and Rapid Refresh model (RAP). Both resources show forecast skill for C&V, but neither utilizes the skill of the other to boost performance. Thus, they serve today as separate and unrelated guidance sources for aviation weather forecasters.

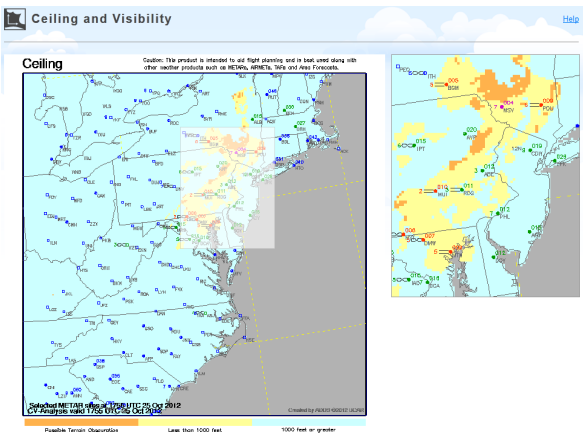

Figure 1: Left: Regional view of current ceiling conditions as shown by RAL's newly-operational Ceiling and Visibility Analysis product. Right: Magnified sub-regional view indicating possible terrain obscuration (orange) in southern New York and eastern Pennsylvania. Yellow areas warn of widespread ceilings less than 1000' above ground level.

RAL's approach seeks to bridge LAMP and RAP through a unique blending method, yielding a net gain in forecast skill over either element taken alone. By embedding RAL's resource blending approach within the current operational production cycle for hourly LAMP forecasts, the improved forecasts would be distributed across the existing NOAA network as an improved LAMP product, without need for costly new data streams or forecaster visualization tools. Our work toward this forecast approach proceeds in partnership with LAMP and RAP developers and is yielding improved forecast skill in prototype tests. One important finding of this work in FY2012 is outlined below:

Probability Thresholds: For weather forecasting, a probability threshold acts like a filter. We want to pass high probabilities as 'yes' forecasts marking cases that are most likely to identify a low C or V occurrence. Similarly, we want to mark low probabilities as 'no' forecasts unlikely to correspond to such events. As we have sought to develop an algorithm to dynamically find optimum thresholds, we have found that slight changes in the underlying character of the probability data stream confound the thresholding process, leading to errant yes/no forecasts. Importantly, changes in

the fractional mix of LAMP and RAP are sufficient to produce this negative effect. Thus, we find that the conventional thresholding criteria outlined above are unlikely to succeed within our blended resource method. As a result, current work examines the advantage of a possible role reversal – *(i)* deriving the best possible deterministic forecast through blending of LAMP, RAP, and other resources, and *(ii)* then estimating a corresponding probabilistic forecast through new methods. We believe this approach may best serve users of both the probabilistic and yes/no forecasts.

FY2013 Plans

Forecasting of Ceiling and Visibility

FY2013 work on RAL's C&V forecast system will focus on the following:

- Refinement of the techniques used to optimize the skill of related probabilistic and deterministic forecasts of ceiling and visibility across the CONUS.
- In partnership with NOAA's Meteorological Development Laboratory, analysis of the feasibility of implementing RAL's CONUS C&V forecast system within NOAA's operational LAMP forecast product. This work will transition to development of a detailed implementation plan.
- Initiation of work toward an Alaska-domain C&V forecast product patterned after the methods used in the CONUS C&V system.

Forecasting of Runway Visual Range

FY2013 work will also open a new line of investigation related to runway visual range (RVR). RVR is defined as the distance over which the pilot of an approaching aircraft can visually identify the markings or lights delineating the target runway or its center line. As such, it is a highly specific characteristic of the near-surface visibility within an airport area. RVR plays a critical role in a pilot's decision to maintain or abort an instrument landing, and thus has a strong influence on airport landing rates and resulting impacts on the efficiency of the national airspace.

RVR work will begin with an assessment of the current state of science and operational procedures as applied to RVR determination and reporting. Based upon that assessment, RAL will begin work to develop 1) a plan for future improvements in RVR reporting; and 2) a strategy for development of techniques for automated short-term (1-12 hr) RVR forecasting.

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  - Turbulence
  - Ceiling and Visibility Research and Development
  - Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact
  - Dissemination of Aviation Weather Information
  - Oceanic Weather: Convection and Turbulence
  - Avian Radar Performance
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact

Background

Since weather conditions can seriously restrict aircraft operations and levels of service available to system users, the manner by which weather is observed, forecast, disseminated, and used in making air traffic management (ATM) decisions is of critical importance to the operation of the United States' National Airspace System (NAS). As the United States moves toward significantly increasing the capacity of the NAS through implementation of the Next Generation Air Transportation System (NextGen), it becomes critical to integrate weather (and associated uncertainty) information into ATM decision-making process. RAL has been a significant contributor to this effort of developing advanced concepts of weather translation and integration.

Methodologies for estimating probabilistic Weather-related Impacts on Aviation

Daily ATM planning utilizes weather predictions with forecast horizon of 12 hours and longer for high-impact weather systems, such as hurricanes and winter storms, and transoceanic flights. Strategic ATM planners look for detailed information about weather systems, including storm structure, intensity, organization, location and timing, and associated forecast uncertainty.

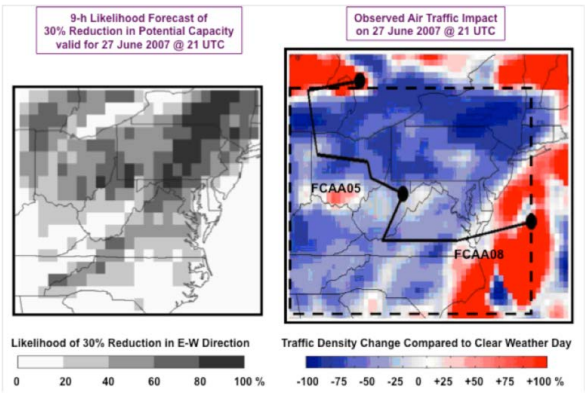

Figure 1. Prediction of likelihood to encounter a 30% reduction in potential capacity (left) and observed traffic impact on 27 June 2007 at 21 UTC (right).

RAL has been developing advanced concepts of using ensemble model forecasts to create probabilistic weather-related impact predictions for both today's consumption by ATM planners and future incorporation into largely automated decision support tools. One novel approach that was developed under NASA sponsorship utilizes storm characteristics (e.g., intensity and depth) and observed pilot behavior to deviate around storms to create a convective weather avoidance field (a technique developed by MIT Lincoln Laboratory), which subsequently is subjected to Metron's MinCut technique (a method to compute flow bottlenecks) that determines an expected capacity reduction due to the presence of storms. These procedures are applied to every ensemble forecast member in order to generate a probability distribution of potential capacity reduction for each spatial domain of interest (e.g., sectors or centers) that can be visualized as likelihood to loose a certain fraction of available airspace due to the presence of hazardous weather (Figure 1). This approach was presented by Steiner et al. (*Air Traffic Control Quarterly*, 2010).

FY2012 Accomplishments

During the summer of 2012 the 10-member ensemble forecasts generated by the Air Force Weather Agency (AFWA) have been accessed in real time and subjected to the capacity reduction estimation procedure outlined above. The resulting likelihood forecasts of losing a fraction of the potentially available capacity (Figure 2) have been sent to the NWS Aviation Weather Center (AWC) for

use as a first guess convective storm impact prediction utilized during the Aviation Weather Testbed exercises.

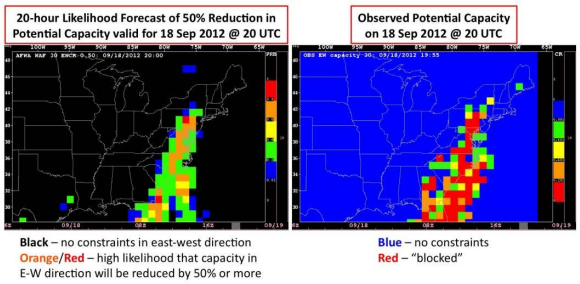

Figure 2. Prediction of likelihood to encounter a 50% reduction in potential capacity (left) and observed potential capacity on 18 September 2012 at 20 UTC (right).

FY2013 Plans

The likelihood predictions of potential capacity reductions based on using the AFWA ensemble forecasts will continue and be made available again to the AWC Aviation Weather Testbed next summer as first-guess impact predictions for development of the daily Aviation Weather Statements.

A new effort is gearing up to explore use of ensemble-based approaches to provide improved guidance of convective weather hazards for transoceanic flights. This effort might explore the above concept as well to highlight potential capacity impacts due to convective storms in oceanic airspace.

ATM – Weather Integration Planning

Version 3.0 of the NextGen Concept of Operations (2009) provides an overall, integrated view of NextGen operations in the 2025 timeframe, including key transformations from today's operations. It serves as a steering vision for the ultimate form of the NextGen end state, guiding the latest version of the NextGen Implementation Plan released in March 2012. RAL's foundational research and transition of aviation-specific weather continues to impact planning for performance-based measures that make NextGen work—i.e., navigation, collaboration, reduced horizontal and vertical separation, traffic flow management, terminal efficiencies such as low visibility operations at airports, and separation management. RAL has taken the initiative to lead part of the effort to consolidate promising tools and methods that have potential for translation of weather constraints into ATM impact; integration into NextGen systemic representations; evaluation for system performance and feedback; and simulation of traffic flows in the presence of weather constraints for cost-benefit analyses of alternative solutions. This effort focuses on near-term R&D needed for IOC while ensuring these early steps are consistent with mid-term NextGen implementation goals. It also assures input plus feedback into the aviation weather R&D being defined for the FAA's Aviation Weather Research Program (AWRP) and Reduce Weather Impact (RWI) programs, both part of the FAA's Aviation Weather Division.

FY2012 Accomplishments

RAL's accomplishments fall into three top-level areas: The AWRP, the NextGen Network-Enabled Weather (NNEW), and the Weather Technology in the Cockpit (WTIC) Program. Many of the accomplishments have been in the standards and performance-based metrics definitions—through the RTCA, SAE, and various international data format, management, and communications bodies (weather data exchange model definition, WXXM). The AWRP continues to showcase RAL technology transition expertise through internet dissemination such as Aviation Digital Data Service (ADDS).

Figure 3. A photo of the RCS during the simulation. Airbus A-320/330 flight deck.

The fledgling WTIC program in RAL had many significant accomplishments. In 2012, the RTCA Special Committee 206 published two new documents—one a Concept of Use for uplink of Weather and Aeronautical Information, and the other a Concept of Operations, or Operational Services and Environment Document (OSED), for weather data downlink and crosslink. RAL is a charter member of this body, interfacing with academia, industry, and government while significantly contributing to the preparation and review of these guidance documents. RAL also began a program that is defining a concept of use and infrastructure for portable device dissemination of aviation weather. And in 2012, RAL led a significant simulation study of the use and

display of oceanic weather information in the FAA William J. Hughes Technical Center (WJHTC) Research Cockpit Simulator in Atlantic City (Figure 3). This effort will lead to further oceanic weather R&D with uplink of information to actual passenger flights (Figure 4). Finally, the RAL-led NNEW program transitioned to a procurement action for the FAA and assumed a new moniker, the Common Support Services – Weather (CSS–Wx) Program. RAL continues its interface with the JPDO and other government-industry forums to update JPDO planning on an annual basis.

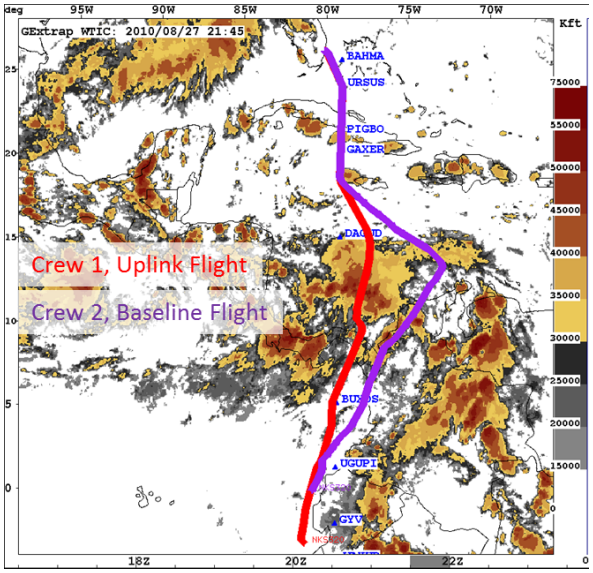

Figure 4. Graphical depiction of the GOES-East derived cloud top heights (30Kft and 40Kft contours) from 27 Aug 2010. Crew 1 (uplink) and Crew 2 (baseline) flight tracks for the entire route are shown. This shows the flight route efficiency gained through uplink/update of strategic oceanic weather information.

FY2013 Plans

Future integration planning and implementation for the mid-term NextGen vision will take the form of meaningful collaboration with recognized leaders in national airspace system performance and flow constraint impact. RAL is pursuing a joint effort with the Mitre Center for Advanced Aviation System Development (CAASD) that will potentially conduct laboratory evaluations of one or more weather translation-to-impact capabilities, integrated with prototype ATM decisions support tools. Other initiatives through FAA sponsorship will explore first-order integration of weather information to support decision making on the flight deck as well as collaboration with air traffic managers and controllers. We will document the results of the investigated translation capability algorithms and of the integration of the information into ATM decision support algorithms, in the context of the NextGen mid-term vision contained in the NextGen Implementation Plan.

Optimizing Sensors and Platforms to Meet the Needs for NextGen

Optimization of relevant weather observation and forecasting capabilities are essential for conducting safe and efficient flight operations in the NAS. It is imperative, therefore, to ensure that the FAA's current and future weather observing and forecasting capabilities are adequate to satisfy NextGen requirements. Under the RWI program, the FAA has been conducting an assessment of relevant weather sensors on the ground, and on airborne and space platforms. This sensor assessment is also known as "Right Sizing" effort.

FY2012 Accomplishment

The FAA Right Sizing effort is geared toward assessing the FAA's sensor network for its readiness to support the requirements and needs of NextGen's Final Operating Capability (FOC) in 2025. During the past year the focus was reduced to supporting the FAA's Technical Center in Atlantic City, New Jersey to develop a Flexible Terminal Sensor Network (FTSN) capability. NCAR's role was primarily to provide the FAA with detailed information (code, examples, set-up instructions, etc.) about the Low-Level Windshear Alert System (LLWAS) for a capability demonstration that will take place later this year (Figure 5).

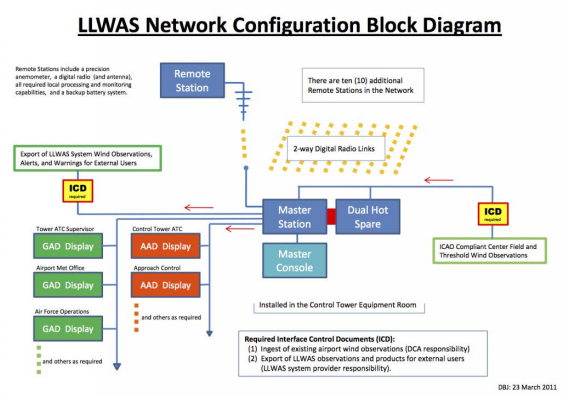

Figure 5. LLWAS Network Configuration Block Diagram.

FY2013 Plans

NCAR will continue to support the FAA in this effort with a focus specifically on the integration of the Low Level Windshear Alert System (LLWAS) capability into the FTSN. A FTSN demonstration experiment is planned for late in 2012 that will showcase potential improvements that can be achieved toward meeting NextGen requirements.

ATM – Weather Integration Activities within NOAA

An Aviation Weather Cooperative Agreement (AWCA) with NOAA continues to facilitate collaborative work on weather

integration and to transition that work from research to operations across federal agency lines for NextGen interim capabilities. The collaborative effort has been defined in general terms to include turbulence, convection (specifically, Autonowcaster deployment and use), ceiling and visibility, and in-flight icing with a specific focus on developing and using human-over-the-loop (HOTL) forecast techniques.

FY2012 Accomplishments

For In-Flight Icing: Activities centered on advances surrounding the Interactive Correction in 4 Dimensions (IC4D) system. IC4D runs on a workstation at NCAR and is monitored to ensure it is operating properly and that the output looks correct. We update the system as needed to keep in pace with that being used at AAWU. Additionally, work has continued to improve the Forecast Icing Product (FIP), the output of which is input into IC4D for analysis and adjustment.

For Storm Forecasting: Results of the Forecaster-Over-the-Loop demonstration conducted from 2005 – 2010 at the Ft. Worth/Dallas WFO were documented in the following paper, "Impacts of Forecaster Involvement on Convective Storm Initiation and Evolution Nowcasting", by Roberts et al. that is scheduled to be published in the October issue of *Weather and Forecasting* .

For Turbulence: Support was provided for the development and testing of a global turbulence forecast product based on the CONUS GTG for eventual WAFC implementation. A collaborative article was published in *Geophysical Research Letters* reviewing the state-of-the-art understanding of the nature and sources of atmospheric turbulence for aviation.

For Ceiling and Visibility: R&D was directed toward forecast methods that could be used in an automated ceiling and visibility forecast system (CVF), including work focused on development of a self-adjusting method to determine optimal probability thresholds needed to derive deterministic forecasts from probabilistic forecast data. The advantage of such an algorithm will be its ability to self-adjust to accommodate seasonal and year-to-year variability. Better thresholds are expected to yield better deterministic forecasts.

FY2013 Plans

The NOAA Aviation Weather Cooperative Agreement will continue the collaboration between RAL and the NWS; activities will remain within the general areas described above.

ATM/Weather Integration Outreach Activities

RAL participated in many of the outreach venues available to further weather R&D, harmonization, and integration into ATM decision support tools. Notable events included new technology workshops sponsored by the FAA, NASA, and the Air Traffic Control Association (ATCA).

FY2012 Accomplishments

Presentations that were specifically focused on the weather integration problem were given by RAL staff at the FAA/NASA/ATCA New Technologies Workshop in Atlantic City, NJ in May 2012, and the AMS ARAM Conference at Atlanta, GA in January 2012. RAL also participated in FAA and industry advisory committees such as the RTCA, SAE G-10 (weather displays on the flight deck), and the Friends and Partners of Aviation Weather (FPAW). We provide expertise on weather technologies as well as receive feedback from industry and government on how we are meeting respective user needs.

FY2013 Plans

RAL will participate in the 2013 ATCA/NASA/FAA New Technologies Workshop and the ATCA Annual Meeting, plus has a funded and critical role in RTCA and SAE forums RAL will continue to participate in as many team partnerships as feasible to ensure and support a comprehensive transfer of our technology to the NextGen IOC and subsequent implementation.

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Log in

https://nar.ucar.edu/2012/lar/ral/dissemination-aviation-weather-information Go

Research Applications Laboratory | RAL
2012 ANNUAL REPORT

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
  - Icing: InFlight, Ground and Engine
  - Prediction of Storm Hazards for Aviation
  - Turbulence
  - Ceiling and Visibility Research and Development
  - Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact
  - Dissemination of Aviation Weather Information
  - Oceanic Weather: Convection and Turbulence
  - Avian Radar Performance
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Dissemination of Aviation Weather Information

Background

The Next Generation Air Transportation System (NextGen) is now taking shape on the design boards of several federal agencies. NextGen has been parsed into several components, each with its own associated R&D and acquisition effort. One such effort is dedicated to developing the weather information needs of NextGen and providing common weather-related decision information to all stakeholders within the system. The NextGen System is a national priority to meet the expanding air transportation needs of the U.S. in the 21st century. Since weather conditions can seriously restrict aircraft operations and levels of service available to system users, the manner by which weather is observed, forecast, disseminated, and used in decision–making is of critical importance.

RAL's activity in dissemination of aviation weather information is concentrated in three areas:

1. Common Support Services – Weather (CSS-Wx) (formerly NNEW),
2. Aviation Digital Data Service (ADDS), and
3. Weather Technology in the Cockpit (WTIC).

CSS-Wx is a program to develop next generation technology and infrastructure for dissemination of weather data to US Government and other users. ADDS uses web pages and data services to deliver weather data to today's aviation community. WTIC is developing methods for making the best weather information available to pilots for decision-making in the cockpit.

Common Support Services – Weather (CSS-Wx) Program *(Formerly NNEW)*

For the past few years RAL has been engaged in developing standards and technology for the NextGen Network Enabled Weather (NNEW) Program. NNEW has been the FAA portion of a joint program with NOAA to develop next generation technology and infrastructure for dissemination of weather data to US government and other users. NNEW's goal has been to enable ubiquitous access to aviation weather data anywhere an appropriate network connection is available. NNEW has transitioned into the FAA's acquisition process, and become part of a larger related program called Common Support Services, and has been named CSS-Wx.

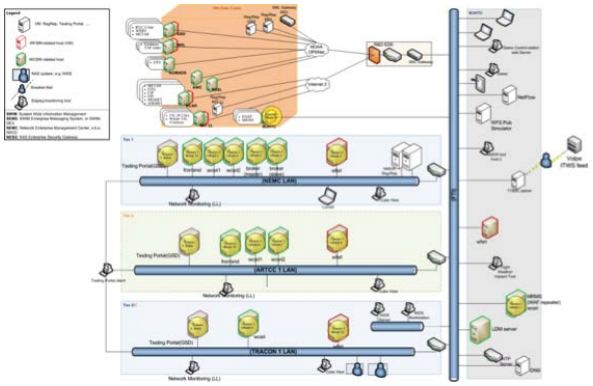

Figure 1. Diagram of Capability Evaluation with tiered data distribution.

CSS-Wx achieves its goal by using a service-oriented architecture (SOA) approach in which existing internet technology is leveraged to build weather data directory and delivery services that conform to international standards. CSS-Wx is combining a data directory service using OASIS ebXML Registry/Repository (Reg/Rep) standards with data servers based on the Open Geospatial Consortium (OGC) Web Feature Service (WFS) and Web Coverage Service (WCS) standards. Using thesetechnologies, it is possible to build complex, dynamic weather systems where data sources and clients can be developed and modified independently but remain compatible while data latency and network bandwidth are optimized. RAL's participation in CSS-Wx is sponsored by the FAA CSS-Wx Program Office and work is conducted collaboratively with the FAA's William J. Hughes Technical Center, MIT/Lincoln Laboratories, the MITRE Corporation, and NOAA.

FY2012 Accomplishments

In FY2012, RAL updated the WCSRI capabilities to reflect the new OGC WSC 2.0 standard. RAL also assisted the FAA in

preparing technical materials for a Request for Proposal for a commercially provided CSS-Wx system. The 2012 activities culminated in the preparation for a Capability Evaluation for FY2013 that will showcase additional abilities and applications for CSS-Wx technologies

FY2013 Plans

The focus for FY13 is supporting the FAA's acquisition process for CSS-Wx, including the completion of the various components of the Reference Implementation to be provided to the successful vendor as a basis for their development.

Aviation Digital Data Service (ADDS) Program

ADDS is a dissemination program that uses web pages to distribute aviation weather data. There are two instances of ADDS web pages: Experimental ADDS which is run at NCAR and Operational ADDS which runs at the NWS Aviation Weather Center in Kansas City. RAL uses Experimental ADDS to expose new prototype weather products to aviation users and gather feedback on the products' utility. Operational ADDS provides weather products that have been through the full review and approval process for operational use in aviation.

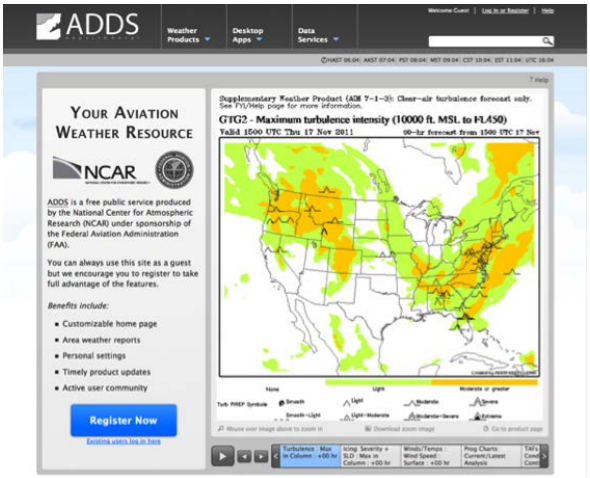

Figure 2. The Experimental ADDS Web site.

FY2012 Accomplishments

In FY2012 ADDS continued to provide critical weather information to a broad cross-section of the aviation community, 24 hours a day, 7 days a week. Final testing and transition of ADDS to the WRFRR was completed.

FY2013 Plans

In FY2013, RAL will develop a 5-year roadmap for ADDS development, in close collaboration with the FAA and NWS. In addition to on-going, routine activities in support of the system, a major convergence effort will bring experimental and operational ADDS into closer alignment in order to make the transition of new capabilities more efficient.

Weather Dissemination to the Flight Deck - Weather Technology in the Cockpit (WTIC) Program

One of the programs led by the FAA's Aviation Weather Office (AWO) is Weather Technology in the Cockpit (WTIC). RAL took the initiative several years ago to create a government and industry consensus document that became an initial version of the WTIC Concept of Operations. The WTIC Program Office now uses this document to build the NextGen WTIC Program, one of the legs of the future Air Traffic Control (ATC) system's collaborative triad (the others being ATC/ATM and airline dispatch or flight operations control). Throughout 2012, RAL was a working member of two joint industry/government committees under the auspices of the RTCA and SAE G–10 that are chartered to establish data link and cockpit weather display standards and requirements for NextGen. European consensus through Eurocae and Eurocontrol is a prime focus for these efforts as plenary meetings alternate between Europe and the USA and include high–level representatives from the European FLYSAFE and SESAR programs. Certain SAE and RTCA/Eurocae document development efforts will continue through 2014. The goal of these joint working committees is to ensure that these capabilities are harmonized between North America and the European Union and to promote the use of standard weather information on all aircraft flying between the two continents. In a new WTIC effort started in 2012, RAL is studying the requirements and technologies that would enable pilots to gain the advantages inherent in the rapidly emerging world of mobile technologies, including both tablets and phones.

FY2012 Accomplishments

- RAL continued to be a lead participant in the WTIC Concept of Operations and weather requirements/specifications development associated with uplink and downlink of weather data and information. This included RAL participation on two RTCA committees in addition to the SC206, relating to uplink, downlink, and crosslink of meteorological information supporting the new capabilities contained in the NextGen vision.
- RAL planned and conducted evaluations of human over the loop (HOTL) concepts and collateral benefits associated with weather updates to airline flights on trans-oceanic trips. This initial set of evaluations was conducted in the NextGen Integration and Evaluation Capability (NIEC) flight simulator at the William J. Hughes Technical Center (WJHTC). *Airline* trips to South America were the simulated scenarios, using experienced airline pilots as test subjects. Updated convection information was simulated to better understand its impact on pilot decision making while operating in a remote/oceanic flight environment.
- In a new WTIC effort, RAL developed a 5-year roadmap for the use of mobile devices in the cockpit to provide pilots with improved weather awareness and decision-making.

FY2013 Plans

- Uplink of weather updates to actual trans-oceanic airline trips. These evaluations will further our understanding of the HOTL concept, and enhance the science of aviation weather diagnosis/forecasting in data-sparse regions.
- Continue support of national and international activities to develop standards for cockpit dissemination and use of weather information.
- Provide a comprehensive technology assessment of mobile devices for use in delivery of weather information to the cockpit. We will also conduct a broad survey of the needs and expectations of users in relation to mobile devices for aviation weather delivery.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
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  - Prediction of Storm Hazards for Aviation
  - Turbulence
  - Ceiling and Visibility Research and Development
  - Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact
  - Dissemination of Aviation Weather Information
  - Oceanic Weather: Convection and Turbulence
  - Avian Radar Performance
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Oceanic Weather: Convection and Turbulence

Background

The Next Generation Air Transportation System (NextGen) is a national priority to meet the air transportation needs of the U.S. in the 21st century – in particular, a significant growth in demand for air traffic services, possibly on the order of three times today's demand lev-els. Since weather conditions can seriously restrict aircraft operations and levels of service available to system users, the manner by which weather is observed, forecast, dissemi-nated, and used in decision-making is of critical importance. Aviation users operating within oceanic and remote regions have limited access to high-resolution (temporal and spatial) weather products that depict the current and future locations of deep convection and turbulence.

To address these needs, RAL scientists have been developing weather products related to the oceanic/remote occurrence of deep convection and turbulence from clear air (CAT) and convectively-induced (CIT) sources. For convection, the Oceanic Convection Diagnosis and Nowcasting system has been under development for the past few years to detect and fore-cast deep convection using satellite-based methodologies in combination with numerical model results. These methods have been implemented both regionally (i.e., the Gulf of Mexico/Caribbean area), as well as globally. Another effort that is underway, the Storm Forecasting Project, blends numerical weather prediction results with observations to pro-duce extrapolation forecasts from 1 – 12 hours of the rain rate and the cloud top height. For turbulence, the Global Turbulence Decision Support System (DSS) for Aviation has been under development for the past few years. This effort uses a methodology developed for the continental U.S. (CONUS) Graphical Turbulence Guidance (GTG) product with modifica-tions to produce estimates of CAT over a global domain. A global convection diagnosis and forecasting system was developed as part of the Global Turbulence DSS for Aviation. A new investigation into the utility of global ensemble forecasts to provide probabilistic guidance for convective storms is underway. Accomplishments and plans related to the ongoing convection and turbulence weather products are discussed below.

Storm Forecasting Project

This feasibility study produced 0–12 hour blended convective forecasts over the Gulf of Mexico and global domains to be used for aviation planning and situational awareness. Blended forecasts of extrapolated satellite data (rain rate) and Numerical Weather Predic-tion (NWP) results were created. Collaborators in this effort include the Naval Research Laboratory, Monterey, and the Northern Gulf Institute.

FY2012 Accomplishments

Seamless, blended 0-12 hr forecasts were created for satellite-derived rain rate data and Global Forecasting System (GFS) NWP results using two methodologies: "fixed weights" and "dynamical weights". In the fixed weight scheme, a simple weighted average of the two forecasts, based on prior performance scores, was used to create the blended forecast. In the dynamical weighting scheme, weights were calculated according to the most recent performance scores and could change daily and/or regionally. Using data from March 2011, preliminary validation results compared extrapolation method, model results, and blended forecasts for a rain rate threshold of 0.5 mm/hr (Figure 1). Results for both the Gulf of Mexico and global domains had similar performance. The dynamical weighting scheme resulted in a slight performance improvement over fixed weights in the 2-6 hr lead times. The bias suggested blending forecasts are over-forecasting at the lower threshold,

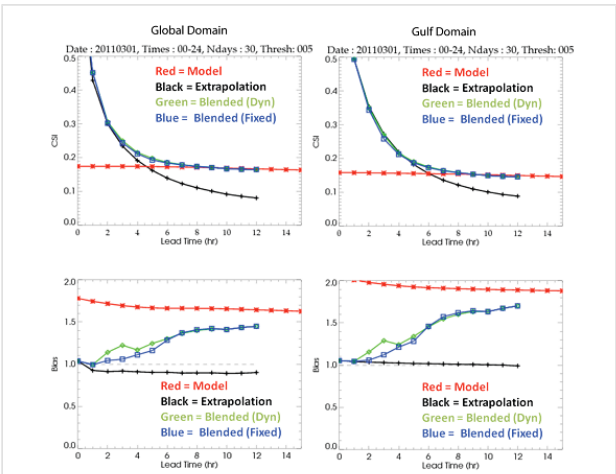

Figure 1. Critical Success Index (CSI) and bias of global domain

but under-forecasting at the higher threshold.

(left column) and Gulf of Mex-ico domain (right column) for GFS model (red), extrapolation (black), dynamical blending (green) and fixed weight blending (blue) rain rate forecast based on one month of data (March 2011). The rain rate threshold is 0.5 mm/hr.

FY2013 Plans

Validation of the blended forecasts from fixed and dynamic weighting schemes will con-tinue for additional cases. The cloud top height field from extrapolated and model forecasts will be evaluated to ascertain if blended forecasts are achievable.

Global Turbulence Decision Support System (DSS) for Aviation

This project adapted the GTG algorithm and software previously developed for use in CO-NUS airspace by the FAA Aviation Weather Research Program to utilize GFS model data and create turbulence forecasts for use in global turbulence decision support. Additionally, it investigated the use of satellite-based diagnostics and convective nowcasts to develop a global turbulence nowcast capability.

FY2012 Accomplishments

The real-time Global Turbulence DSS for Aviation turbulence forecast ("Global GTG") proto-type was updated to use the latest GTG version 3.0 diagnostics and infrastructure. This included incorporating diagnostics developed specifically for forecasting mountain wave turbulence (MWT). Additionally, GTG3.0 uses an improved software infrastructure that should permit easy, future adaptation to other NWP models such as ECMWF or the UK Met Office. Figure 2 shows the prototype Global GTG forecast for 25 May 2010, when a severe turbulence encounter over western Greenland injured 10 people aboard United Flight 935, causing a diversion to Montreal. The prototype Global GTG forecast captured both the tur-bulence associated with the accident and turbulence experienced by numerous transatlan-tic flights near the same time.

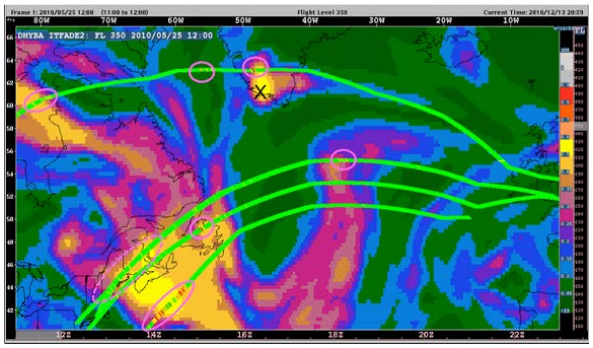

Figure 2: Global Graphical Turbulence DSS forecast at flight level 350 (35,000 ft.) valid at 1200 UTC 25 May 2010; "warmer" colors denote greater turbulence. The "X" marks the location where United Flight 935 encountered turbulence over southern Greenland, injuring 10 people and causing the flight to divert to Montreal. The colored flight tracks denote turbulence experienced by transatlantic flights as recorded in the Global Aircraft Data Set (GADS) around the same time, with significant events circled in pink. With one exception (near 55W, 63N), the turbulence forecast shows excellent correspondence with the turbulence encountered.

As part of this project, several satellite-derived turbulence prediction fields were devel-oped in conjunction with the University of Wisconsin-Madison SSEC/CIMSS and imple-mented to run in the NCAR software infrastructure. These fields included the tropopause fold identification algorithm (TFA), objective identification of convective overshooting tops (OTs), and a downslope wind diagnosis intended to help determine likely mountain-wave turbulence (MWT) locations. Satellite–derived convection diagnoses and nowcasts from the global CDO and CNO were also utilized. The satellite-based products show promise in complementing the short-term GTG turbulence forecasts to create skillful nowcasts.

The prototype real-time global turbulence forecasts were demonstrated to operational In-ternational Desk forecasters at the Aviation Weather Center in February via a web-accessible Java display (Figure 3), and a real-time feed of the prototype forecasts to the AWC was provided to facilitate forecaster evaluation via N-AWIPS. The forecast lead times were increased to encompass 0-48 hours at the AWC's request. NCAR staff attended a World Area Forecast System (WAFS) coordination meeting and are collaborating with NOAA and UK Met Office personnel to facilitate the further development and ultimate tran-sition to operations of this technology.

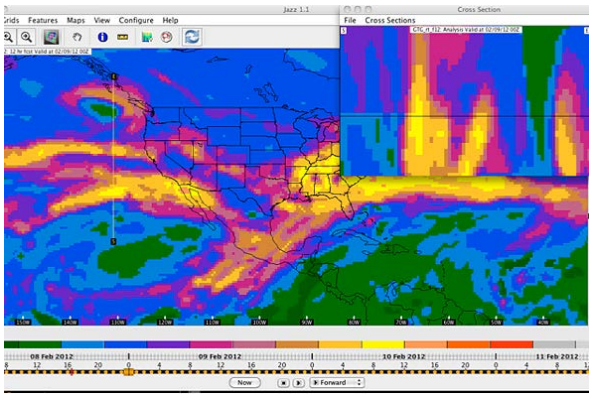

Figure 3: Prototype Global GTG 12-hour forecast valid 9 February 2012 00 UTC, displayed via a web-accessible Java display tool. A vertical cross-section along the north-south transect depicted in the western Pacific appears in a separate window and is overlaid in the upper right.

FY2013 Plans

The goal in FY2013 is to complete development of the Global GTG system and prepare it for deployment in support of the WAFS, using both the GFS and UKMET global NWP models. The resulting turbulence forecasts will address clear-air, mountain-wave and convectively-induced turbulence sources in a unified fashion for global aviation users, providing a re-placement of the current WAFS gridded turbulence product, which is produced from only the Ellrod Index.

Global Convection Diagnosis and Forecasts

As part of the Global Turbulence Decision Support System (DSS) for Aviation, convection extrapolation forecasts over a global domain have been developed. The system detects convection via a data fusion of satellite products that include cloud top height and channel differencing to infer updraft location; while hourly, gridded forecasts out to 8 hours are ac-complished using an object tracker merged with model wind fields. The forecasts are up-dated at 3 hr intervals.

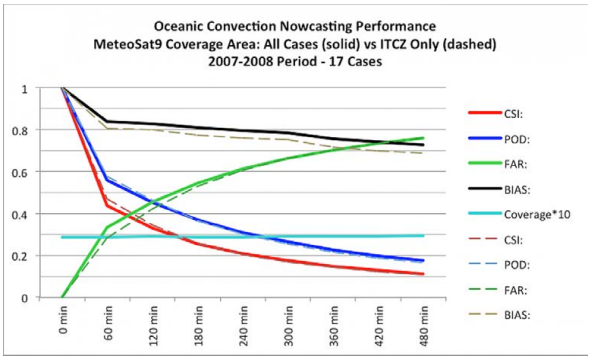

Figure 4. Statistical performance measures (CSI; Probability of Detection, POD; False Alarm Ratio, FAR; and bias) are shown for the 17 cases from 2007 and 2008. Solid lines denote skill scores for the domain between +60 deg latitude while dashed lines denote results for the ITCZ region. Areal coverage (x10) of convection is indicated by the cyan line.

FY2012 Accomplishments

Global convection extrapolation forecasts were evaluated for 0-8 hrs for selected case stud-ies from 2007 and 2008. The evaluations were done for regions between +60 degrees lati-tude and for the InterTropical Convergence Zone (ITCZ; Figure 4) within MeteoSat9 cover-age. Results show slight improvement in skill scores within the ITCZ for early lead times. An automated validation methodology for the convection detection product was devised where measurements from the Tropical Rainfall Measuring Mission (TRMM) formed the validation data set. Results were compared to a manual methodology.

For a limited domain (i.e., coverage of GOES-East and GOES-West), the convection forecasts are available in real-time and can be viewed online at: (http://www.rap.ucar.edu/projects/ocn/realtime_sys/global_extrap/).

Probabilistic Guidance of Convective Hazards

Prediction of convective storms into the future is burdened with significant uncertainty. Use of ensemble forecasts is one way of trying to characterize forecast uncertainty. A re-cently initiated effort aims to develop a forecast product that provides probabilistic guid-ance on convective storm hazards for transoceanic flights with lead times of 24 – 36 hours. This product will be based on methodology that utilizes global ensemble forecasts and ex-tracts relevant information to identify convective storm hazards.

FY2012 Accomplishments

Efforts during this past year have been focused on the development of an initial methodol-ogy to characterize oceanic convection based on global ensemble forecasts. Various model output fields were evaluated for their ability to portrait convection and possible regional dependencies. The Total Column Water (TCW) anomaly field was selected as a candidate field (Figure 5). Moreover, roadmap and prototype system designs were developed.

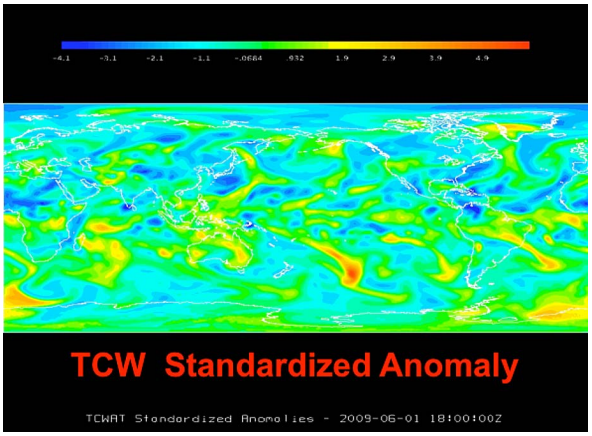

Figure 5. Total Column Water (TCW) Standardized Anomaly field is shown for 1 June 2009 at 18 UTC. Outlines of the continents are shown (white lines) over the global domain.

FY2013 Plans

During the coming year, an initial prototype capability will be developed to characterize the likelihood of convective storms in the northern Pacific airspace based on harvesting multiple global ensemble forecasts. Moreover, additional work will be carried out to better define the "truth field" used for calibration of the probabilistic forecast products.

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  - Turbulence
  - Ceiling and Visibility Research and Development
  - Integration of Weather Information Into Air Traffic Management Decisions for Reduced Weather Impact
  - Dissemination of Aviation Weather Information
  - Oceanic Weather: Convection and Turbulence
  - Avian Radar Performance
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Avian Radar Performance

Background

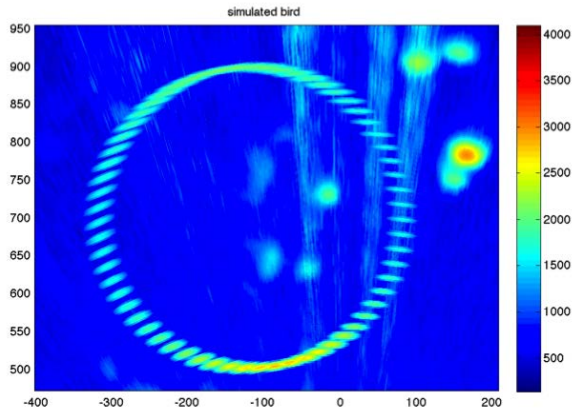
The US Airways Flight 1549 accident on 15 January 2009 was the result of a collision with a flock of Canada geese shortly after takeoff from New Your City's La Guardia Airport. Upon failure of both engines and with insufficient time to return to the airport, the pilot was forced to ditch the aircraft in the Hudson River. Due to the skill of the pilot, no lives were lost, but the aircraft was damaged beyond repair. As this accident shows, bird strikes are a significant threat to flight safety as the impact can result in injuries and fatalities for passengers and crew as well as substantial damage to the airframe. Bird and other wildlife strikes cost U. S. civil aviation more than $600 million per year. Since 1988, more than 219 people have been killed worldwide after their aircraft collided with birds. The United States Department of Agriculture (USDA) has the authority to regulate wildlife management at U.S. civilian airports. Because of commercial development of avian radar tracking systems, the USDA is evaluating their potential for use at airports for wildlife management and by the air traffic control system. One such system, the DeTect, Inc. Merlin avian radar system, is being evaluated by NCAR RAL and EOL.

Figure 1. The DeTect, Inc., Merlin radar system deployed at the Marshall Field Site.

In FY2010, RAL and EOL scientists and engineers began to assess the performance of the DeTect, Inc. Merlin avian radar system. The USDA purchased a Merlin avian radar system and it is on loan to NCAR. The unit is currently located at the Marshall Field Site for data collection (Figure 1). The evaluation has consisted of measurements of the radar system characteristics, examination of radar data characteristics and evaluation of the performance of the bird detection and tracking software via simulation.

FY2012 Accomplishments

To test the performance of the bird detection and tracking algorithm, the radar cross sections of bird targets are being simulated in the Raleigh, mie and optical regions. The bird targets are inserted into the radar data and the resulting, merged file is input into the detection and tracking algorithm. Results are statistically analyzed to measure performance (Figure 2). Testing protocols have been devised and include a stationary bird, a circling bird, a bird moving in a straight line, a bird moving in an arc and along a radial. Multiple birds can also be input. Various altitudes of the bird are used in the protocols.



Measurement of the antenna beam pattern was completed by Nearfield Systems Inc.

A ball launcher was used to test the radar's ability to detect projectiles since bird targets cannot be

controlled. Tennis balls were filled with water prior to launch. The golf balls were painted with metallic paint. The softball was not modified. The test was successful and the radar could detect the balls.

FY2013 Plans

Completion of the simulation study and evaluation of the tracking performance.

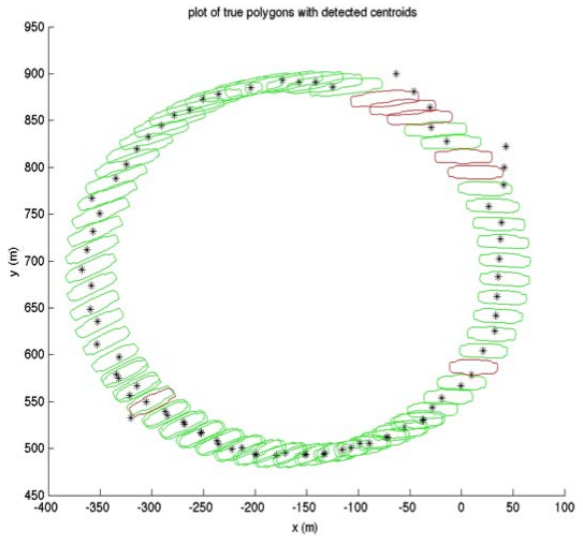


Figure 2. In a), a simulated, circling bird is inserted into the radar data (expressed as counts). Multiple scans have been combined into this plot to show the path of the bird with time. In b), the statistical results are shown after the simulation is input into the detection and tracking algorithm. The algorithm position centroids are indicated by an asterisk. The simulated bird is contoured with green polygons (successful detection) and with purple polygons (missed detection) where the asterisk is either inside or outside the polygon, respectively

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
  - Surface Transportation Weather
  - Renewable Energy
  - Weather Prediction Statistical Optimization
  - Advanced Operational Aviation Weather System
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

New and Emerging Applications

Identify, explore, develop and implement advanced weather decision support systems for new and emerging user sectors.

- **Surface Transportation Weather**
- **Renewable Energy**
- **Weather Prediction Statistical Optimization**
- **Advanced Operational Aviation Weather System (AOAWS)**

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  - Weather Prediction Statistical Optimization
  - Advanced Operational Aviation Weather System
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Surface Transportation Weather

Background

RAL is a key contributor to the research and development of the weather component of the Federal Highway Administration's wireless **Connected Vehicle** program. RAL also continues to support the adoption of the winter **Maintenance Decision Support System (MDSS)** technology across the nation.

In the coming year, RAL will continue to expand efforts by developing transportation decision support systems focusing on traffic, incident, and emergency management and maintenance beyond snow and ice control by seamlessly blending the strategic prediction components of the system with tactical short-term weather and road condition technologies.

FY2012 Accomplishments:

Vehicle Data Translator

The **Connected Vehicle** program has three main goals: to increase safety, mobility, and environmental efficiency. This program will ultimately provide vehicle probe data (including weather data) from millions of vehicles that will be available to the weather community to support the diagnosis and short-term prediction of weather and road conditions (Figure 1). With funding and support from the USDOT Research and Innovative Technology Administration (RITA) and direction from the Federal Highway Administration's (FHWA) **Road Weather Management Program**, RAL conducted research in FY12 to continue development of the prototype Vehicle Data Translator (VDT). The VDT incorporates vehicle-based measurements of the road and surrounding atmosphere with other, more traditional weather data sources, and creates road and atmospheric hazard products for a variety of users. Analysis in FY12 focused on three key areas: obtaining mobile data from Minnesota and Nevada State Department of Transportation (DOT) plows and supervisor trucks; developing the third version of the VDT; and publishing prior research in peer-reviewed journals.

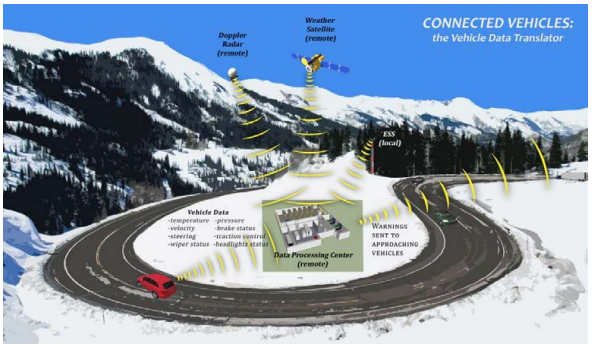
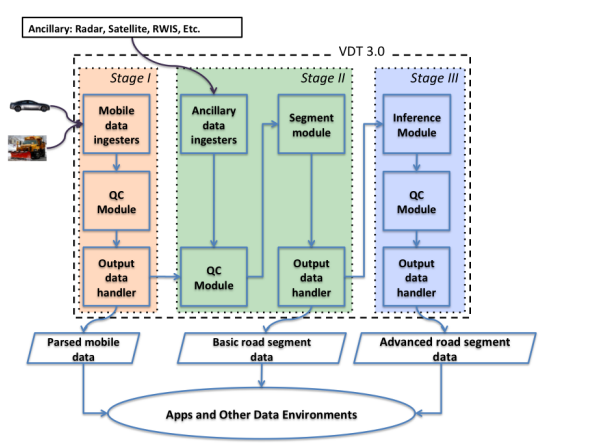


Figure 1. Schematic of the connected vehicle concept.

RAL partnered with the Minnesota and Nevada DOTs to obtain mobile data. In Minnesota, data (e.g., brake data and ambient air temperature) from the Controller Access Network Bus (CANBus) as well as external data (e.g., pavement temperature) were collected from over 100 snowplows and supervisor trucks across the state. In Nevada, similar data were obtained along I-80.

RAL also refined the VDT in three stages, as shown in Figure 2. The initial stage of the VDT ingests mobile data. If the data are already pre-processed in some way, such as by the *Clarus* System, then the VDT can simply read the metadata and data from the *Clarus* output. However, the VDT also has routines to directly ingest mobile data from the CANBus or a data collection and forwarding facility, parse them,



and then sort them by time, road segments, and grid cells (the road segments and grid cells are user-defined via configuration files). This stage also reads any extra data sent from the vehicle that originates outside of the CANBus, such as readings from add-on sensors. These data are then passed through a *QC Module* that tags data that contain invalid geospatial or temporal information (e.g., latitude values greater than 90°N or time of day greater than 23:59:59). All data are passed through the *Output Data Handler*, which outputs the "parsed mobile data" for use in applications, and also for use in Stage II of the VDT.

Figure 2: VDT 3.0 Data Processing. Images courtesy iStockPhoto (**http://www.istockphoto.com/stock-photo-1285117-snow-plow.php** and **http://www.istockphoto.com/stock-photo-9272930-aluminium-supercar.php**)

Stage II analyses provide the road segment data using QC'd mobile data. The *QC Module* examines individual mobile data (CANBus and some add-on sensors) and flags each data point for relevant QC tests. Ancillary data, such as *Clarus* surface station data and radar data, are also ingested by the *Ancillary Data Ingesters*, which perform the same functions as the Stage I *Mobile Data Ingestors module* (except in this case for ancillary data), including time stamping and geolocating. These ancillary data are then used in some of the QC processes, but they are not QC'ed themselves; however, the ancillary data used in the VDT 3.0 is all QC'd by other means before being incorporated into the VDT. All data are passed through to the *Statistics* component, where the mobile data that pass QC are used to compute road segment statistics. Examples of these data would include the mean air temperature over an individual road segment for a given time step, or the percentage of windshield wipers activated over an individual road segment for a given time step. All mobile data with QC flags and the statistical data for the "Basic road segment" data are output from Stage II.

Stage III analyses provide additional added value for mobile data. In the *Inference Module*, fuzzy logic algorithms, decision trees, and other data mining procedures are used to produce the "Advanced Road Segment" data. Examples of these include combining mobile data with radar, satellite, and fixed surface station data to compute a derived 'road precipitation' product over an individual road segment for a given time step. These data are then run through a *QC Module* that assigns a confidence value to the "Advanced road segment" data assessments.

In FY13, NCAR will continue to refine the VDT and use it as a base in developing road weather applications, such as a traveler information system (Figure 3).

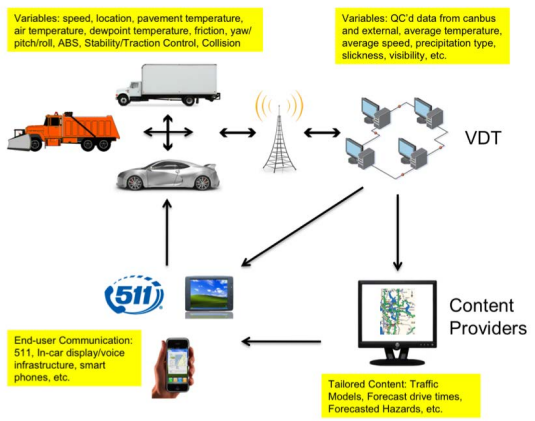


Figure 3. Conceptual schematic of VDT-enabled traveler information system.

Maintenance Decision Support System (MDSS)

Since 1999, RAL has led a team of national laboratories in the development of the Federal prototype winter Maintenance Decision Support System (MDSS), a unique decision support system that provides real-time snow and ice control guidance (e.g., treatment times, chemical choices, rates, and locations) for user-defined roadway segments. Other highlights included continuing to work with Denver International Airport and supporting the FHWA's annual Road Weather Management Meeting.

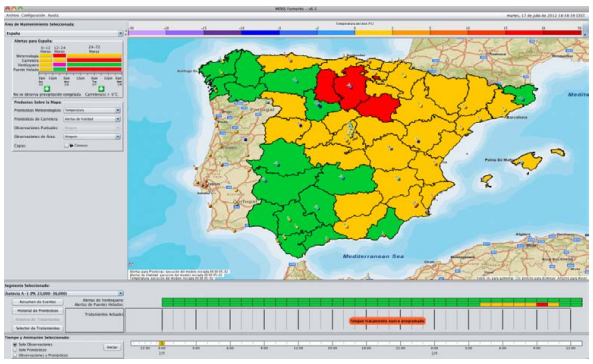


Figure 4. Spanish MDSS Display.

In FY12, NCAR completed development for a prototype Spanish MDSS for roads near Madrid, Spain (Figure 4). The Spanish version maintains the functionality of the U.S. prototype, while incorporating new research aimed at changes in Spanish maintenance practices. The road temperature forecast, as generated by the Model of the Environment and Temperature of Roads (METRo), was altered to include post-processing. This led to a noticeable improvement in the road temperature forecast.

In FY13, NCAR will partner with Alaska DOT to develop a new MDSS Display and enhanced high-latitude functionality.

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Log in

RAL Annual Report

- Director's Message
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- New and Emerging Applications
  - Surface Transportation Weather
  - Renewable Energy
  - Weather Prediction Statistical Optimization
  - Advanced Operational Aviation Weather System
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Renewable Energy

Background:

For the past three years RAL has collaborated with university researchers, DOE labs, commercial partners, and other NCAR entities to develop methods to more accurately analyze and predict wind energy in support of the renewable energy industry. Projects have focused on resource assessment, real time forecasting to improve operations and economics of incorporating wind energy into the power mix, and characterization and quantification of variability in wind energy.

Xcel Energy Wind Power Prediction Project

In FY2012, RAL completed a 2.5 year collaborative project with **Xcel Energy Services, Inc**.to increase the amount of wind energy in its energy generation portfolio. New wind prediction technologies help operators make critical decisions about powering down traditional coal- and natural gas–powered plants when sufficient winds are predicted, enabling increased reliance on alternative energy while still meeting the needs of customers.

The Wind Energy Forecasting System developed by RAL incorporates observations of current atmospheric conditions from satellites, aircraft, weather radars, ground-based weather stations, and even sensors on the wind turbines. The information is then utilized by a number of powerful tools: the Weather Research and Forecasting (WRF) model; the Real-Time Four-Dimensional Data Assimilation System (**RTFDDA**), which continuously updates the WRF model simulations with the most recent observations; the Dynamic Integrated Forecast System (**DICast®**), which statistically optimizes the forecasts based on current observations, climatological data, and real-time validation of the model predictions; an ensemble of numerical weather prediction forecasts based on both WRF and the MM5 (Penn State/NCAR) mesoscale models; NCAR calibration tools that improve the probabilistic forecast, specifically the Analogue Kalman Filter combined with Quantile Regression to remove bias, sharpen the forecast, and increase statistical reliability; the Four Dimensional Variational Doppler Radar Analysis System (VDRAS), which combines Doppler radar data with a cloud scale model to predict short term weather events; an NCAR-developed expert system that uses field observations to fine-tune predictions when wind ramps are most likely to impact the wind plant; and customized Graphical User Interfaces to provide grid operators with a best forecast that includes error estimates as well as meteorological GUIs to visualize the weather graphics (Figure A). The team who developed this system for Xcel won UCAR's Outstanding Performance Award for Scientific and Technical Advancement in December 2011.

Off-Shore Wind Energy Projects

A new DOE-funded project focus on enhanced understanding of the interactions between the ocean and the atmosphere in order to better predict winds for both locating wind plants and for forecasting power for plant operations. A second project, in collaboration with Penn State, is developing a "Cyber Wind Facility", a computational facility akin to a field wind turbine test facility that blends models across scales. These projects will lead to better modeling capability to reduce market barriers to developing offshore wind energy.

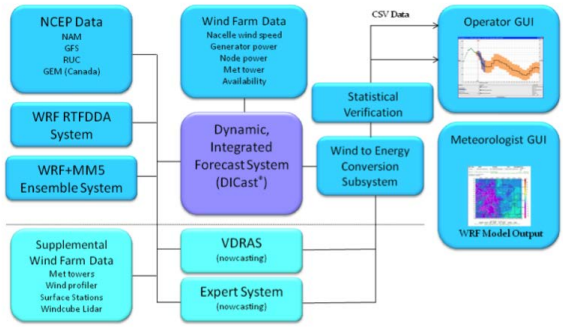

Figure A: Conceptual diagram of the wind energy prediction technology components incorporated into the system configuration.

Quantifying the Wind and Solar Resource and its Interannual Variability

In 2012, NCAR collaborated with the National Renewable Energy Laboratory (NREL) to produce a new database of annual means and interannual variability of wind

and solar resources. The goal was to produce a reliable dataset that is useful for assessing the inter-annual variability of wind and solar power over the continental U.S. (CONUS) for NREL's Regional Energy Deployment System (ReEDS). The end result is a database of expected future climate wind and solar resource values and their interannual variability, quantified by season and by time of day. An example of projected changes for the summer season appears in Figure B.

Wind Turbine and Turbine Array Wake Characterization

The effects of operating wind turbine rotors on atmospheric flows can be represented using a generalized actuator disk model. To further study these effects, RAL scientists have implemented a generalized actuator disk model in the Weather Research and Forecasting (WRF) model to examine wind turbine wakes, their structure and interaction in wind turbine arrays, as well as their effect on transport processes in atmospheric boundary layers using the large-eddy simulation (LES) approach. In collaboration with the Lawrence Livermore National Laboratory (LLNL), RAL scientists are working to validate the generalized actuator disk model in WRF-LES using the data from the Turbine Wake and Inflow Characterization Study (TWICS) experiment that took place at the National Wind Technology Center (NWTC) test site of the National Renewable Energy Laboratory (NREL) in the spring of 2011. The validated generalized actuator disk model implemented in WRF will advance the capability to model details of flow through wind turbine arrays under a wide range of atmospheric conditions and thus will become an advanced tool for wind resource assessment and wind turbine array performance evaluation as well as turbine load calculations.

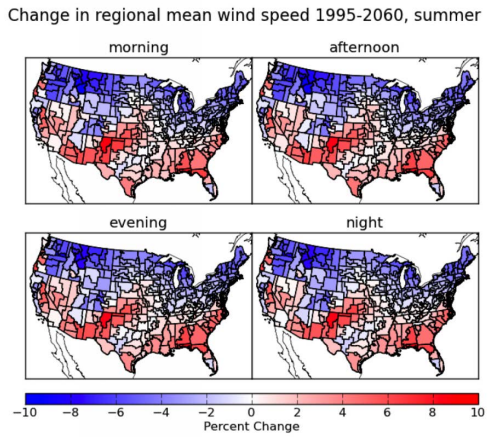

Figure B. Projected future changes in hub-height wind speed from current summer means for different time periods.

Using Analog Methods for Renewable Energy

A successful and economically feasible integration of a large portion of wind power into the electrical grid requires accurate wind power forecasting, as well as reliable quantification of the state-dependent uncertainty associated with the wind power forecast. To accomplish this, RAL scientists are combining real-time and historical data from state-of-the art numerical weather prediction models and extensive records of wind power observations to provide reliable quantification of the forecast uncertainty and accurate power forecast of day-ahead lead times. The approach, called the analog ensemble, is being tested on an off-shore wind park. Predictions are evaluated in terms of spread error consistency, normalized mean absolute errors, and in terms of value score in a simple cost/loss model for a range of users' cost/loss profiles, and compared to a conventional deterministic power forecasting approaches. The analog method has shown great value for improving both the best prediction and in quantifying its uncertainty.

Using Typhoon Modeling to Design Better Wind Turbines

In 2012, RAL collaborated with Taiwan's Industrial Technology Research Institute (ITRI) to enable wind energy development in Taiwan. Most of this energy is expected to be developed off-shore, and thus the impact of typhoons on wind turbine performance under extreme conditions is a major concern. A secondary concern is how to best deploy arrays of wind turbines to optimize their performance. A third issue emphasizes the operation of wind turbines in the marine environment, including forecasting wind power. NCAR and ITRI are planning an applied research program that will integrate observations, model output, and design criteria to advance wind energy capabilities in environments that experience extreme wind events.

Plans for FY2013:

DOE has recently selected RAL's proposal, "A Public-Private-Academic Partnership to Advance Solar Power Forecasting" for funding. This new three-year program will feature partnerships with the National Renewable Energy Laboratory, Brookhaven National Laboratory; a number of universities; independent system operators (ISOs); and commercial forecast providers, as well as with NOAA scientists. This program will develop a solar power forecasting system that advances the state-of-the-science through cutting edge research, test it in several high penetration solar utilities and ISOs, and disseminate the research results widely to raise the bar on solar forecasting technology.

Other plans include:

- Continued collaboration with Xcel Energy to enhance the Wind Power Prediction System, including predicting icing, high speed cutouts, load forecasting, enhancing power conversion algorithms, etc.
- Collaboration with NREL and the University of Colorado to deploy a vertically pointing lidar to study wind turbine wakes and to model those wakes using LES techniques.
- Expansion of wind forecasting capability into new areas, including mountainous and coastal sites.
- Assist NREL with resource assessment and developing measurement programs in developing countries.
- Work with partners at Colorado State University to quantify how wind power can be integrated with pumped

storage to supply reliable power

- Work with colleagues at Penn State University to assess the feasibility of integrating wind turbines into buildings
- Work with partners at Colorado School of Mines to analyze how wind power forecasting can help smooth the demand/variable energy balance when applying smart grid concepts
- Work with partners at the University of Colorado to study the impact of atmospheric stability and shear on wind power production
- Work with partners at Penn State to include mesoscale model data in a coupled multi-scale cyber wind facility
- Expand calibration of the uncertainty in wind forecasting systems in conjunction with other laboratories and with commercial partners
- Downscale model solutions for resource assessment
- Apply new artificial intelligence techniques to wind prediction problems
- Work on improving offshore hub-height wind speed and wind shear prediction
- Improve marine boundary layer parameterization to better account for the interaction between sea surface and the atmosphere.

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Log in

RAL Annual Report

- Director's Message
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  - Renewable Energy
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  - Advanced Operational Aviation Weather System
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Weather Prediction Statistical Optimization

Background

RAL is a leader in the development of intelligent weather prediction systems that blend data from numerical weather prediction models, statistical datasets, real time observations, and human intelligence to optimize forecasts at user–defined locations. The Dynamic Integrated Forecast System (DICast®) and Location Optimized Gridded & Integrated Forecast System (LOGICast™) are examples of such technology. DICast® is currently being used by three of the nation's largest commercial weather service companies. There is a growing desire in industry to have fine–tuned forecasts for specific user–defined locations. This trend is clear in the energy, transportation, agriculture, and location–based service industries. RAL's expertise in meteorology, engineering, and applied mathematics and statistics, is being utilized to address society's growing need for accurate weather information.

FY2012 Accomplishments

A number of new models have now been added to the DICast system to contribute to the consensus forecast. In particular the European Centre for Medium-Range Weather Forecast (ECMWF) deterministic model has now been incorporated. Here development was required to ingest the ECMWF meteorological variables such as precipitation accumulation. Other similar developments include incorporation of the ECMWF ensemble mean; addition of the GFS and CMC ensembles; and replacement of the Rapid Update Cycle (RUC) model with the Rapid Refresh model.

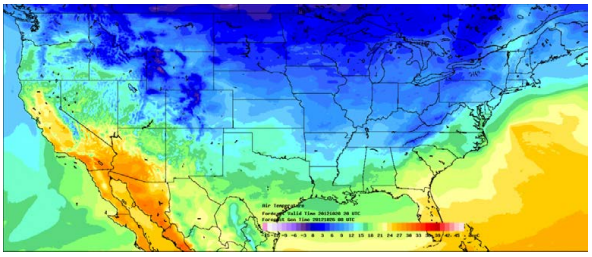

Figure 1: 4-km LOGICast forecast of air temperature over CONUS at 60 hr lead time.

DICast is continuing to play a significant role in wind energy forecasting. In addition to being used for forecasting wind speeds and wind energy production for Xcel Energy, it is now being utilized to forecast wind power production for a number of other utilities in the United States and in Europe. This year additional 80m and 100m wind speed predictors were added to DICast to improve its wind speed forecast. DICast now incorporates the ECMWF model in its wind speed consensus forecast. This particular model is playing an important role in reducing the overall forecast error. In order to improve the power forecast made using DICast wind speed forecasts, enhancements were made to the wind to power conversion module. Here the data mining procedure utilized for power conversion was improved and fully automated. This new procedure is now utilized to estimate turbine power as well as connection node power. It is also able to quality control spurious wind/power data that are generated when wind farm power output are experiencing manually imposed transmission constraints.

DICast's temporal interpolation at longer lead times was improved this year. A new algorithm for probability of thunder was added and the forward error correction of the probability of thunder is now based on lightning observations. Hourly quantitative precipitation forecasts are now extracted from the North American Model (NAM) and incorporated in the DICast product suite. Decoding changes have been made to extract time average model data as opposed to instantaneous model data. Also the site addition and removal process in DICast has been simplified to improve DICast's usability.

RAL's gridded forecast system, Logicast, also saw significant development and improvement this year. Here the entire system architecture was generalized and restructured to support different model configurations and multiple regions. In order to improving processing speed and disk utilization, Logicast's data store was optimized to allow for the processing of larger regions. Existing modules were tested more thoroughly in order to support making Logicast suitable for operational use.

Logicast was also extended to support Europe. In the European Logicast a new temperature climatology capability was incorporated. Logicast is now using a global model at higher resolution (1/8th deg). The time range was extended to 15

days and the time resolution was extended to hourly. Logicast was also extended to utilize the ECMWF model.

FY2013 Plans

RAL staff will work in the following areas to improve the predictive capability of DICast and LOGICast in 2013:

- Improve precipitation forecasts through model evaluation and incorporation of nowcast system output
- Improve longer-range (10-15) day forecasts
- Evaluate LOGICast interpolation techniques at mesonet sites
- Evaluate and incorporate solar radiation forecast data
- Incorporate new high resolution models to improve regional forecasts (eg UK-met model for Europe) or short term precip forecasts (eg HRRR)
- Make extensions and improvements to LOGICast to support road weather forecasting.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
  - Surface Transportation Weather
  - Renewable Energy
  - Weather Prediction Statistical Optimization
  - Advanced Operational Aviation Weather System
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Advanced Operational Aviation Weather System

Background

Since 1998, RAL and MMM have collaborated in the development of an **Advanced Operational Aviation Weather System (AOAWS)** for the **Civil Aeronautics Administration (CAA) of Taiwan**. The AOAWS provides the CAA, the airlines, and the flying public with state-of-the-art aviation weather technology to detect and forecast hazardous weather phenomena that affect aviation operations, airspace efficiency, and capacity and safety at Taiwan's major hub airports. In 2010, NCAR's local Taiwan technology partner became **International Integrated Systems, Inc** (IISI)

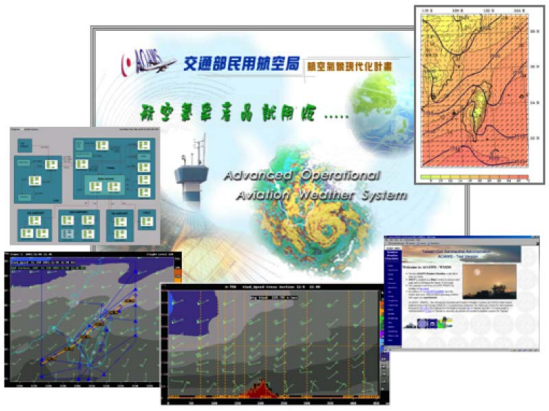

Figure 1: Composite image showing several AOAWS end-user display screens.

Major components of the AOAWS include: Low-Level Wind Shear Alert Systems (LLWAS Phase III) at Songshun and Taoyuan International Airport (formerly known as Chiang Kai-shek International); the WRF model which provides regularly-updated forecasts on two domains with grid spacing of 20km, and 4km; the Multi-dimensional Display System (MDS), which integrates all available real-time observational data and displays the information automatically to aviation forecasters and flight planning specialists; a JAVA-based version of the MDS; a web-based display system (WMDS) that displays most of the data available on the MDS on a CAA website for users (e.g., pilots and dispatchers) to view the AOAWS weather products remotely; and an AOAWS System Monitor Display (SMD) that provides system and networking activity information and alerts to the operators if any one of the sub-systems is not running smoothly. Since 2010, the WRF modeling enhancements are being developed by NCAR/MMM under a separate research agreement with the Taiwan Central Weather Bureau (CWB).

FY2012 Accomplishments

The AOAWS program began a new phase of research and development in January 2012 that includes the development of a radar-based turbulence product similar to the NEXRAD-based **NEXRAD Turbulence Detection Algorithm (NTDA)**, and the **Current Icing Potential Algorithm (CIP)** product, that will complement the **Forecast Icing Product (FIP)** product; this work leverages research being conducted by RAL for the FAA's Aviation Weather Research Program. A sample image of the NTDA and turbulence at flight level FL110 (11,000 ft.) is shown in Figure 2.

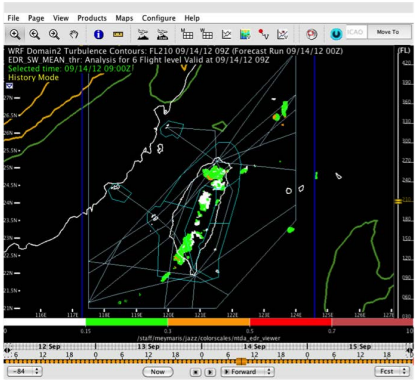

Figure 2: Diagnosed turbulence from the NTDA merged with the predicted turbulence at FL100 (11,000 ft.).

In 2012, we also explored several statistical data mining techniques (e.g., Random Forest, and Cubist) and error correction schemes that would improve the model's post-processing algorithms to improve the skill of airport specific wind, temperature, relative humidity, wind, ceiling, and visibility forecasts.

RAL is also collaborating with its IISI partners in Taiwan to capture user requirements for integrating aviation weather hazard products (e.g., thunderstorm, turbulence, and icing) into a new CAA Air Traffic Management System (ATMS) developed by Thales. We will work with air traffic controllers, managers, and supervisors in a user group setting to capture and document their needs.

FY2013 Plans

The development of the CIP, NTDA, and display application upgrades will be completed and the new capabilities will be integrated, tested, and become operational in the AOAWS in 2013. As part of this effort, we will conduct verification studies of the new turbulence and icing products and refine the algorithms as necessary. Rigorous testing of the entire AOAWS system will be conducted to ensure a high level of serviceability for the end users.

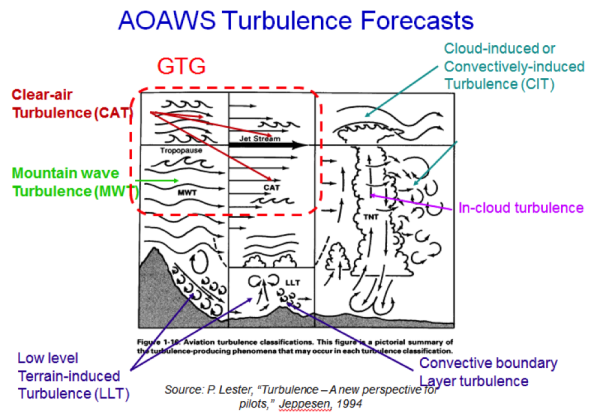

Figure 3: Illustration of different turbulence generation mechanisms (courtesy of Robert Sharman). The AOAWS turbulence enhancements for 2013 will include upgrades to the Graphical Turbulence Guidance (GTG) algorithm and the development of a radar-based turbulence diagnostic product.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

National Security Applications

Significantly advance our understanding of mesoscale and urban-scale weather and climate processes, especially in the boundary layer, and our ability to forecast these atmospheric conditions operationally for the purpose of providing forecasters, decision makers, and emergency managers with accurate information to save lives and property.

- **Operational Numerical Weather Prediction and Improved Data Assimilation**
- **Mesoscale Climate Downscaling**
- **Atmospheric Transport and Dispersion of Hazardous Materials Research and Development**

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Operational Numerical Weather Prediction and Improved Data Assimilation

Background

Over the past several decades, RAL has developed and deployed complex computer-based operational systems for analyzing and forecasting climate and weather at high resolution worldwide. This development is built upon the Laboratory's deep foundation of applied scientific research and engineering. Systems and their products are tailored to each project to maximize the benefit to the sponsors and end-users. For example, improved analyses and forecasts at Army test ranges saves millions of tax dollars by identifying when weather suitable for testing will occur, and improves safety by predicting conditions that would be hazardous to personnel and materiel. Other domestic and international projects include forecasting for wind farms at resolutions that can approximate large eddies within the atmosphere's boundary layer; new, innovative ways to supply models with current observations from radar ; and exploring how urban development affects the weather, and how that weather in turn affects the health of people living in urban areas. In this section of the Annual Report, we describe our work in the following areas:

- **Four-Dimensional Weather System**
- **Real-time Microscale FDDA Forecasting System for Korea**
- **MAGEN RTFDDA and 3DVAR Hybrid System**
- **Xcel Energy NWP for Wind Power Forecasting**
- **AirDat CONUS and North America RTFDDA Forecasting System**
- **The RTFDDA-3DVAR Hybrid Radar Data Assimilation System**
- **Fine-Scale Precision Forecasting with WRF-RTFDDA-LES**
- **4D-REKF Ensemble Data Assimilation and Forecasting**
- **Real-time Ensemble-RTFDDA Wind Energy Forecast for China**
- Real-time FDDA and WRF3DVAR Hybrid Weather Prediction System for PME
- **Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction**
- **Mesoscale Ensemble Prediction**
- **High Performance Computing for Operational Modeling**

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
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- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Four-Dimensional Weather System

Since the middle 1990s, the U.S. Army Test and Evaluation Command (ATEC) has sponsored RAL to conduct on-going research, development, and technology-transfer of the Four-Dimensional Weather (4DWX) system. 4DWX is an advanced numerical weather prediction (NWP) system that analyzes current weather and makes detailed predictions of weather over the next several days. 4DWX's NWP core is the Weather Research and Forecasting (WRF) Model, the current industry standard. 4DWX ingests observations into the NWP core through NCAR's Real-Time Four-Dimensional Data Assimilation (RTFDDA) scheme. 4DWX is used by ATEC forecasters at eight test ranges (Fig. 1) across five major climate zones. RAL improves 4DWX regularly, updating software and/or hardware for ATEC one or more times per year.

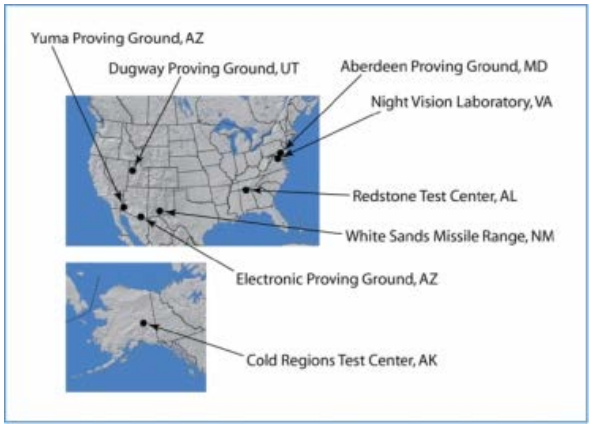


Figure 1. Army test ranges that use 4DWX.

The project's overarching goal is to provide to forecasters at the ATEC ranges the technology and expertise they require in order to match the scales and utility of their forecast guidance to the scales and weather sensitivity of the ranges' testing operations, and 4DWX is one of RAL's chief means of meeting that goal.

FY2012 Accomplishments:

Advanced Data Assimilation

4DWX continues to rely on RTFDDA as one way to ingest a multitude of observations from common and specialized sources. RTFDDA involves modifications to an NWP model's predictive equations so the model can be gently adjusted, or nudged, toward observed conditions during the model's analysis stage, before the forecast stage begins. The scheme is computationally efficient and preserves the precise timing of observations, which gives 4DWX a more accurate depiction of the weather at any instant. RTFDDA has recently been upgraded to improve how the influence of complex terrain is approximated and to increase the sophistication and flexibility of spatial weighting functions, which now are anisotropic and tuned for specific locations and weather.

RAL is also in the final stages of developing a hybrid approach to data assimilation, 4D-REKF (4-Dimensional Relaxation Kalman Filter), which incorporates the cutting-edge ensemble Kalman Filter data assimilation scheme into the RTFDDA framework. 4D-REKF inherits all advantages of RTFDDA but with much better algorithms that will lead to optimal use of observations—especially observations from remote-sensor platforms—and to better accuracy and reliability. A research version of this new, advanced hybrid scheme continues to be refined in anticipation of prototypical deployment in 2013.

In 2012, RAL deployed a prototypical system for ingesting observations from radars into 4DWX and other NWP modeling systems. The method is based on coupling RTFDDA and 3DVAR with NCAR's Variational Doppler Radar Assimilation System (VDRAS), and it includes the effects of the latent heating that can be inferred from radar reflectivity. VDRAS assimilates series of real-time radar observations (radial velocity and reflectivity) from single or multiple Doppler radars, then uses a fast numerical model to make frequently updated short-term forecasts of dry flow in the planetary boundary layer.

Ensemble Forecasting

Since 2007, Dugway Proving Ground (DPG) has used an ensemble four-dimensional weather system (called E-4DWX) developed by RAL. E-4DWX provides a suite of 30 forecasts valid at the same place and time, each producing slightly

different but similarly realistic forecasts. Differences among ensemble members are induced by varying initial conditions, boundary conditions, model physics, and model cores, which contain the probability information of the model forecasts that varies with changes in weather regime.

Output from E-4DWX is calibrated—that is, made statistically accurate, or realistic, so that the probability of E-4DWX's forecasts being realized represents the true, natural probability. By using a method known as quantile regression, the distribution of ensemble forecasts (i.e., the mean, spread, and higher moments) is adjusted to match the actual probability distribution of weather as determined through observations. The benefits of calibration include: 1) reducing forecast error and biases, producing a calibrated ensemble mean that has on average one half the error variance of any single ensemble member; 2) predicting accurate likelihoods of extreme and potentially devastating weather; and 3) providing a measure of forecast uncertainty through the dispersion among ensemble members. Calibration is performed on moments of the overall probability distribution function, no matter the size of the ensemble membership from which the distribution is created, as opposed to calibrating output from specific ensemble members. This makes E-4DWX particularly robust, even if individual members of the ensemble fail at some point during the forecast.

E-4DWX was the first operational high-resolution ensemble to be used by the U. S. Department of Defense. Since E-4DWX went into operation, not a single test at DPG has been canceled due to unpredicted adverse weather. Enhancements to E-4DWX in 2012 include new weather maps and graphics for the forecasters and improvements in the calibration sub-system. The schemes used to generate perturbations among ensemble members were also improved. The Canadian GEM model was added to the sources of boundary conditions, which increases the independence of the various ensemble members.

RAL is also developing a method of ensemble prediction based on searching for past forecasts that are similar to the current forecast, then finding what conditions were actually observed in the cases of those past forecasts. That collection of observed conditions is an ensemble of a kind, and it can be used for making predictions just as any other ensemble is used. Predictions from such an analog ensemble are inherently calibrated, so an extra calibration step is not required. In 2012, RAL began testing how to achieve the best overall probabilistic forecasts from a marriage between the analog and the dynamical E-4DWX technologies. Development will continue in FY2013 and beyond.

Experimental Very Large-Eddy-Scale (VLES) Simulations

On several projects, including this one funded by ATEC, RAL is experimenting with VLES simulations in an operational framework. Our current experiments are focused on Granite Peak at DPG, where the local winds driven by complex terrain are notoriously difficult to forecast. Advances in 2012 include 1) acceleration of the current VLES model by ~65% over original versions of the model, and 2) more skillful forecasts of near-surface temperature and wind compared with standard mesoscale simulations.

Forecasts of Severe Weather

The 4DWX system has components that predict severe weather on two scales: the next few hours, based on both observations and model predictions blended via the AutoNowcaster, and the next few days, based on model predictions alone. In 2012, the short-term, radar-based lightning potential forecasts were upgraded to use predicted freezing-level heights from the NWP core of 4DWX. The AutoNowcaster was also upgraded to employ the dual polarization data newly available from the NEXRAD network. Two new predictor fields are being developed and tested: frontogenesis and Q-vectors.

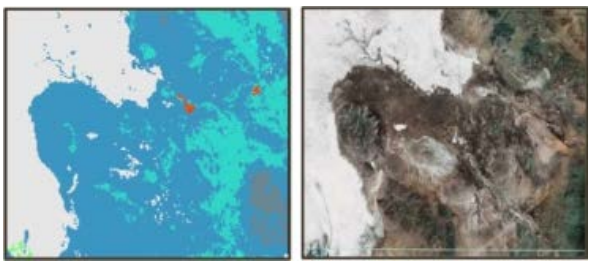
Coupled Applications

Direct weather analyses and predictions from 4DWX and E-4DWX are the core of the weather information used by forecasters at the ATEC ranges, but that information can be made even more valuable when it is supplied to decision support systems (DSSes) that simulate how the weather affects other processes and conditions, such as sound propagation and the transport and dispersion of airborne hazards. Examples of DSSes that have been linked to 4DWX and/or E-4DWX include:

- Noise Assessment and Prediction System (NAPS)
- Second-order Closure Integrated Puff (SCIPUFF) model
- Lewis Rocket Trajectory Model
- Open Burn / Open Detonation Model (OBODM)

New geographic datasets for 4DWX

In 2012, RAL implemented in 4DWX a newer, higher-resolution dataset of land cover (30-m pixels) and terrain elevation (90-m pixels). The dataset is derived from the National Land Cover Database 2006 (NLCD 2006), a 16-class classification scheme based on Landsat imagery, and distributed by the Multi-Resolution Land Characterization (MRLC) consortium. Implementation included converting the data to a format that 4DWX (that is, the WRF Model) can use, and adding customized depictions of playa, white sand, and lava for the intermountain West.



4DWX is now using land-cover data finer than previously used by any operational forecasting system for the conterminous U.S. (Fig. 2).

Figure 2. derived from the National Land Cover Database 2006 (left panel) compared to satellite images from Google Earth (right) at Dugway Proving Ground (DPG). Developed land is in orange. Even DPG's runway is represented in the new land cover (western of the two orange areas). The white regions in both panels are the salt flats, or playa, that can strongly affect the weather at DPG.

Web Portal

The primary interface to the 4DWX system at all ATEC ranges is the 4DWX Portal (Fig. 3). The portal's flexibility, accessibility, modularity, and extensibility are ideally suited to the customized weather support that RAL provides to forecasters. Weather maps and related graphics from 4DWX include optional color palettes that can be seen by the color-blind (Fig. 4). By using web forms designed in RAL, forecasters can more efficiently customize their weather maps. The Portal's dashboard has a flexible, configurable layout, with streamlined access to portlets for coupled applications. The list of output formats that the Portal supports includes the third-party BUFKIT and RAOB applications. In 2012, a portlet was added that displays climatographies of lightning observed by the National Lightning Detection Network (NLDN). These climatographies show forecasters typical monthly and hourly patterns of severe weather at the ranges. Improvements were also made to many of the 4DWX Portal's other portlets.

Figure 3. Front page of the 4DWX Portal at three ranges: Electronic Proving Ground in AZ, White Sands Missile range in NM, and Dugway Proving Ground in UT. From each page, forecasters can access model output, current and historical observations at the stations shown in red on the maps, a tool for issuing weather warnings, radar displays, and more.

Integrated Data Viewer (IDV)

RAL collaborates with Unidata to include among 4DWX's displays capabilities the Integrated Data Viewer (IDV), which is a sophisticated, flexible, Java-based application for analyzing and displaying geophysical data. IDV is the primary means by which range forecasters explore in greater depth the weather analyses and forecasts from 4DWX. This more complex and flexible exploration complements the "virtual map wall" that is available through the 4DWX Web Portal, whose purpose is to provide the easiest and quickest interface to a standard suite of pre-generated weather maps. IDV is also a research tool and is employed by scientists and engineers during their testing, development, and refinement of 4DWX.

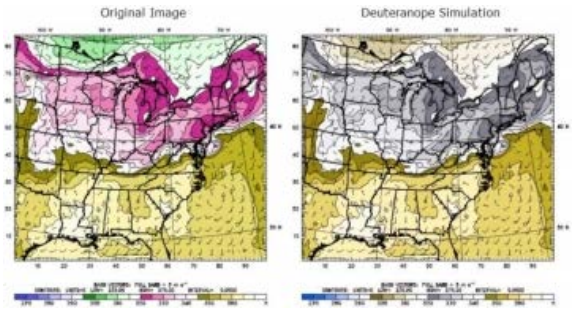


Figure 4. Examples of the two color palettes available through the 4DWX Portal. Each panel is a map of near-surface potential temperature. The left panel shows the map's appearance to those with no color-blindness. The right panel simulates how the map appears to those with deuteranope color-blindness (courtesy of vischeck.com).

Selected Key Plans for FY13:

In collaboration with the University of Utah, RAL will implement in 4DWX an algorithm for creating daily high-resolution composites of skin temperature of inland lakes from satellite data. The composites will be more accurate than what is currently run operationally by national forecast offices.

Because ATEC lacks the computing resources to run a dynamical ensemble for all test ranges, RAL will continue to find and test innovative approaches to generate probabilistic forecasts that do not require large, expensive computers. More generally, RAL will accelerate the design and deployment of technology that permits ATEC forecasters to frame their guidance in terms of probabilities, which will allow more cost-effective risk assessments by test directors.

Development of sophisticated yet user-friendly methods of model verification, which will include tools that can aid forecasters during operations, will continue. One such tool, the 4DWX Verification GUI, was demonstrated to forecasters in pre-prototypical form in late 2012. The initial operational version of the GUI will be delivered in the first part of 2013, then development of a more advanced version 2 will commence.

The hybrid radar data assimilation scheme described above will become fully operational at Aberdeen Proving Ground in Maryland.

One of the most attractive elements of the 4DWX project is that the ATEC test ranges serve as natural laboratories for atmospheric research, complete with dense observing networks and specialized data that permit study of mesoscale and microscale phenomena in complex terrain. Continual improvements to 4DWX and to community numerical weather prediction models, such as the WRF Model, are made possible through this collaboration. Accordingly, in FY2013 and the several years that follow, RAL will continue its involvement in the MATERHORN field campaign, providing data and

advice to investigators and, in return, receiving datasets and other material from the field campaign before they are made available to the general public. This work will aid model development and technology transfer to ATEC.

Finally, outreach and training will continue to be a core component of the 4DWX project through the Forecaster Training that RAL hosts, and through teleconferences, on-line documentation, and visits to ranges.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
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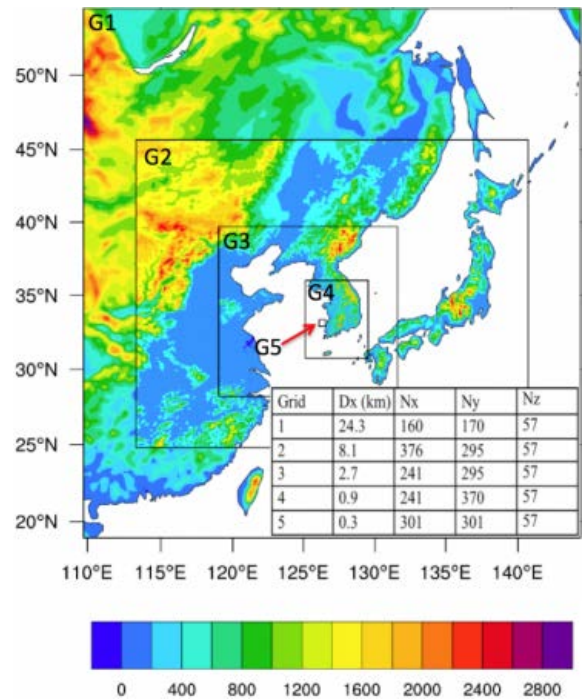
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Real-time Microscale FDDA Forecasting System for Korea

Background

With the recent and continued increase in market penetration of wind power, the energy industry requires accurate, fine-scale, and up-to-date weather information to support decision makers in making critical judgments on a daily basis with regard to energy generation, dispatch, demand, storage, and integration. Wind forecasting for the energy industry is even more challenging than normal weather forecasting. Turbulent and chaotic processes are more important for the wind prediction; local topography and its underlying features can have strong influence on wind speed, turbulence and wind shear. In collaboration with the Korean Meteorological Administration (KMA), RAL is developing a real-time multi-scale simultaneous-nestdown operational wind power forecasting system for wind power prediction in Korea. The system downscales the WRF-based mesoscale Four-Dimensional Data Assimilation (FDDA) forecasting system with coarse grid domains to a large eddy simulation (LES) scale fine grid covering a major offshore wind farm (Fig. 1). The system provides weather analyses and forecasts from synoptic-scale numerical weather predictions (NWP) to regional weather predictions, and even further down to small- and micro- scale weather modeling. The RTFDDA utilizes land use and topography data down to 90-m pixel size from KMA with the finest WRF nest at 300 m grid spacing.



Grid	Dx (km)	Nx	Ny	Nz
1	24.3	160	170	57
2	8.1	376	295	57
3	2.7	241	295	57
4	0.9	241	370	57
5	0.3	301	301	57

Figure 1. RTFDDA five-nested domain setup for the offshore wind farm.

FY2012 Accomplishments

Refinements have been made to the real-time modeling system and post-processing; these include:

- Adjusting the adaptive time step parameters to increase efficiency;
- changing the Lin microphysics to WSM6 microphysics for more realistic representation of cloud microphysical processes;
- using the NASA Goddard shortwave radiation scheme to better represent solar flux and the removal of trace cloud mixing ratio to reduce daytime cold bias; and
- adding products for solar power: downward solar flux; cloud top temperature, column-integrated total hydrometeor water content (Fig. 2)

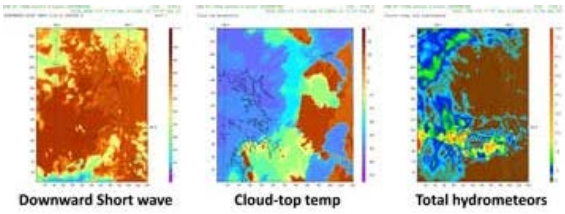


Figure 2. Sample web product : downward shortwave flux (left), cloud top temperature (middle) and column-integrated total hydrometeor water content (right).

Analysis of the July 2011 Korean Flood

An ensemble of NWP forecasts that samples and propagates the uncertainties in the model and data presents exceptional benefit to providing a more reliable forecast, along with highly needed probabilistic forecasts and estimate of forecast uncertainties. If the different ensemble members agree on the forecast, the event will likely happen. If not, there is much uncertainty in the forecast. Usually, the ensemble means perform better than an individual deterministic forecast. We ran the July 2011 Korean flood case with a 15-member ensemble with the RTFDDA in ensemble mode with perturbations in physics: microphysics, cumulus parameterization schemes, and radiation schemes. Convection is extremely sensitive to model physics because model physics can affect melting/freezing/condensation, updraft/downdraft strength, atmospheric stability which in turn can affect the outflow boundaries of convective storms and their subsequent interaction with the environment which can generate new convection. Figure 3 shows the 1-h precipitation accumulation valid at 2300 UTC 26 July 2011 for various ensemble members. The model results were sensitive to the different physics schemes with some members clearly distinguishing the two precipitation bands in the north and south and some members not being able to distinguish the two precipitation bands in the north and south.

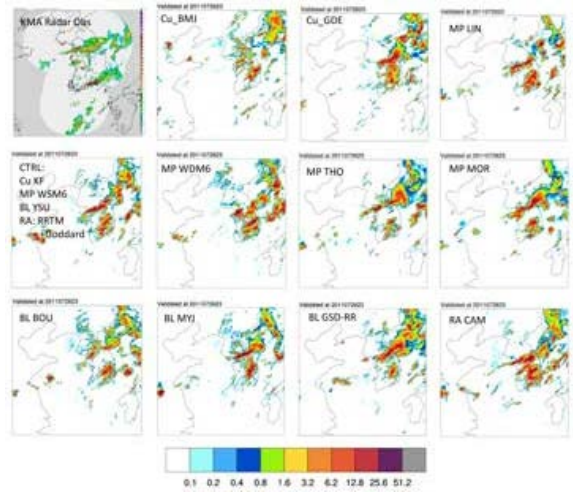


Figure 3. 5-h forecast: 1-h precipitation accumulation (mm) valid at 2300 UTC 26 July for different ensemble members and radar-derived precipitation rate (mm/h).

Terrain Impact Study

As computing power increases, mesoscale models are being run at higher and higher resolution. Naturally, the user wants to represent the underlying terrain in the mesoscale model as realistically as possible by matching the terrain resolution to that of the model. However, from a theoretical standpoint, this may not be the best option. For example, it has been shown by Skamarock (2004) that the effective resolution of ARW WRF is 7 Dx. Terrain features of 7 Dx or smaller may impose forcings on the WRF model that are unphysical, generating noise or instability. One way to alleviate this problem is to apply smoothing to the terrain. However, there is a drawback in this procedure. Smoothing decreases the realism of the terrain and defeats the purpose of running a high-resolution model. So, we conducted a study to systematically investigate the effects of terrain smoothing on the flow in the Korean Peninsula. A case study corresponding to a cold frontal passage in December 2011 was run using the RTFDDA system. To smooth the terrain, we used discrete wavelet analysis (DWT) to remove certain features from the original terrain (Fig. 4). Although more smoothing reduced more numerical noise, as the terrain became smoother, the mountain peaks became lower and the nighttime temperature at mountain peaks became too warm (Figs. 5 and 6). Two-pass DWT (4 Dx removal) appears to be a good compromise between maintaining realistic topographically-driven weather and reducing small-scale numerical noise.

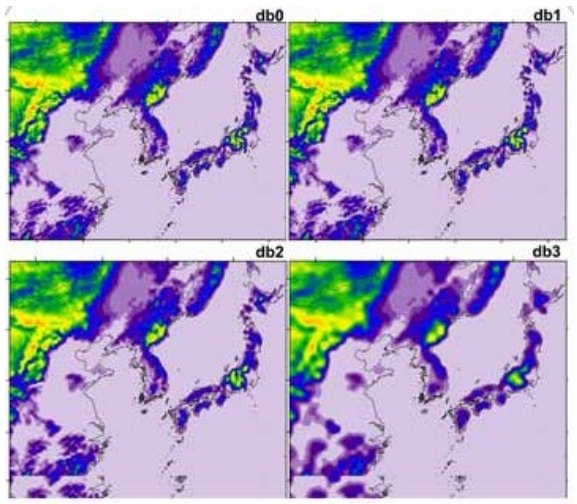


Figure 4. D2 WRF terrain (Dx = 12 km) with different passes of DWT.

IMAGE PLACEHOLDER

Figure 5. 0-1.5 km AGL kinetic energy spectrum from D2.

IMAGE PLACEHOLDER

Figure 6. D2 2-m temperature analysis (contours) superposed with terrain (shading) from WRF-RTFDDA valid at 1200 UTC, 25 December 2010.

Plans for FY2013

We will continue to work on the 2011 Korean flood case focusing on SST sensitivity and studying the impact of radar data assimilation (reflectivity) and additional observational datasets from KMA (e.g., satellite wind, radar radial wind, and dense surface observations across the Korean Peninsula). In addition, we will continue the terrain impact study

with simulations at higher resolution (down to Dx = 0.9 km).

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

MAGEN RTFDDA and 3DVAR Hybrid System

MAGEN (Model for Advanced GENeration of 4D Weather) is a three-year project that aims to apply and improve the NCAR/RAL WRF-based Real–Time Four–Dimensional Data Assimilation (RTFDDA) and forecasting system for providing high-resolution weather guidance over the Eastern Mediterranean region at 3.3km grid intervals. The project goal is to use the WRF-RTFDDA system to provide improved forecasts of prevailing, high–impact mesoscale weather processes, including land–sea breezes, dynamically and thermodynamically induced topographic flows, low–level jets and wind shear, coastal clouds, localized fogs, and severe weather and precipitation associated with low pressure systems during the wet seasons. To meet these requirements, an ambitious research effort has been undertaken to enhance the RTFDDA system with several improvements that are applicable to local weather regimes, data availability, and the operational needs of the sponsor in this unique geographical region that is characterized by mountainous terrain and intricate land-water contrasts.

The WRF-RTFDDA system has been running semi-operationally over the Eastern Mediterranean since July 2009 with 4 cycles a day and 6 h continuous data assimilation and 72 h forecasts each cycle. The model forecasts are accessed and viewed by local forecasters in their daily weather forecasting. NCAR provides continuous development and enhancement of the WRF-RTFDDA system with incorporations of new achievements from the broad research community.

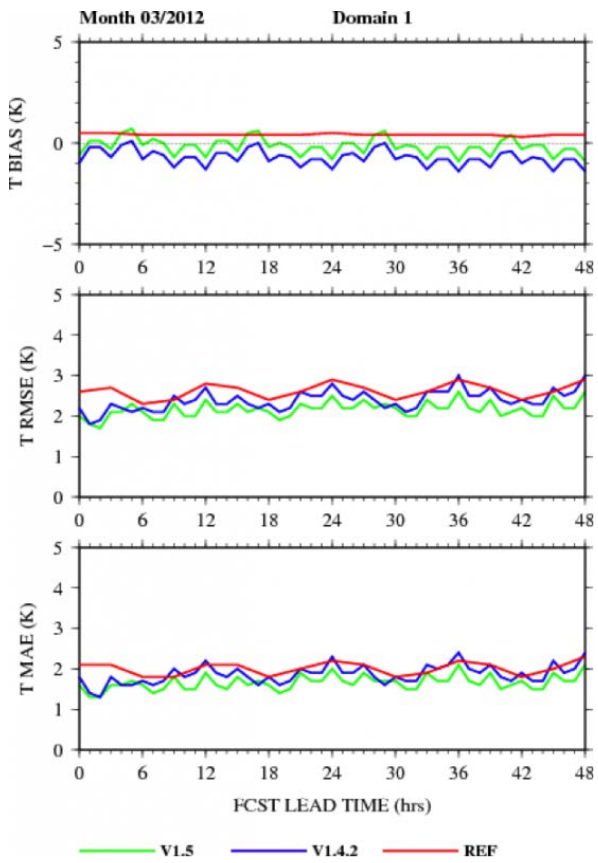
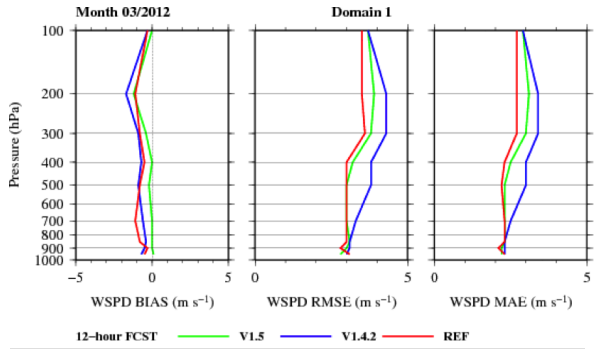


Figure 1. Bias, RMSE and MAE of Domain 1 2-m temperature (K) as a function of forecast lead time averaged over the two-week period for MAGEN V1.5 (green), MAGEN V1.4.2 (blue) and GFS (red).

FY2012 Accomplishments:

During FY2012, the MAGEN RTFDDA-3DVAR hybrid data assimilation system was extensively tested and evaluated both in the semi-operational mode and in the research mode. The final system, MAGEN V1.5, incorporates all of the new features and improvements in the community WRF 3.3.1, WRFDA 3.3.1 and WRF-based RTFDDA 3.3.1. Detailed evaluation of the final MAGEN system as compared to its immediate predecessor (V1.4.2) was conducted for a two-week period of March 24 through April 6, 2012. As shown in Fig. 1 that depicts the bias, RMSE (root-mean-square-error) and MAE (mean absolute error) of Domain 1 2-m temperature as a function of forecast lead time averaged over the two-week



period, V1.5 consistently exhibits the least errors when compared to V1.4.2 and the driving GFS data. V1.5 also shows consistent improvement in upper-air wind speed (Fig. 2), geopotential height (Fig. 3) as well as other variables except for wind direction at the lowest vertical levels (not shown). MAGEN V1.5 is not only capable of assimilating satellite radiance data but also represents the best system in the MAGEN series.

One question that often confronts the numerical weather forecasting community is the model spin-up issue in association with cold-starts. There has been constant trade-off between needs for more accurate and very short-range forecasts and the issue of "spin-up" adjustments. In climatologically semi-arid places such as the Eastern Mediterranean where the only source of moisture is evaporation over the Mediterranean Sea, the "spin-up" issue may become important due to the time it takes for the model to initiate, accumulate and transport enough moisture from the sea to the land. Using the MAGEN system and focusing on the Feb. 24, 2012 rainfall case over Israel, we demonstrated that both the cold-start time and the model spin-up have significant impact on the simulations of rainfall events over the region. We demonstrated the benefit of continuous cycling in RTFDDA that helps to efficiently spin up and localize moisture.

Another fundamental modeling issue is associated with the model's vertical resolution. The MAGEN modeling systems have been showing warm biases at and around 100 mb (Fig. 4) for all domain areas. This attracted great attention from end-users. During FY2012, extensive analyses and numerical experiments have been conducted to investigate the causes. The results show that the warm biases are mainly caused by insufficient MAGEN model vertical levels at and around the 100-mb level where the tropopause is generally located. The tropopause is characterized by a vertical thermal structure with a change in the environmental lapse rate from positive to negative (warming with height). It appears that the lack of vertical resolution near the tropopause in the GFS model, which provides the boundary conditions for the MAGEN model, cuts off the top of the temperature inversion at the upper levels of the tropopause. This cut-off leads to warm biases when the GFS temperature profile is interpolated onto the WRF model levels. It has been found that increasing the model vertical levels just below and just above the 100-mb level can significantly reduce the warm biases (Fig. 5).

FY2013 Plans:

The final MAGEN system has been delivered to Israel and is now running in its own operational environment. NCAR/RAL will continue to help forecasters understand, use, and maintain the MAGEN system. Research toward enhancing the operational MAGEN WRF model resolution to 1.1 km grid has been planned for FY2013. Research will also be conducted to optimize the WRF model physics and the MAGEN data assimilation schemes for this new high-resolution modeling system.

Figure 2. Vertical distributions of bias, RMSE and MAE of Domain 1 12-h wind speed (m s-1) averaged over the two-week period for MAGEN V1.5 (green), MAGEN V1.4.2 (blue) and GFS (red).

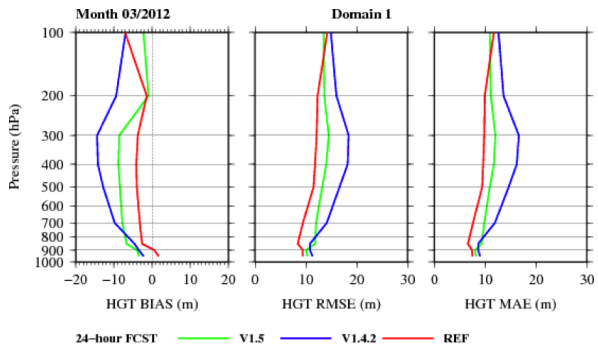


Figure 3. Vertical distributions of bias, RMSE and MAE of Domain 1 24-h geopotential height (m) averaged over the two-week period for MAGEN V1.5 (green), MAGEN V1.4.2 (blue) and GFS (red).

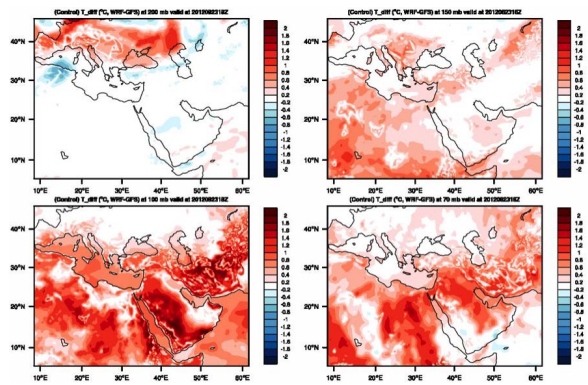


Figure 4. Temperature differences between the MAGEN V1.4.2 analysis and the driving GFS data valid at 18Z Aug. 23, 2012 at 200 mb (top left), 150 mb (top right), 100 mb (bottom left) and 70 mb (bottom right). MAGEN V1.4.2 was run with 57 vertical levels.

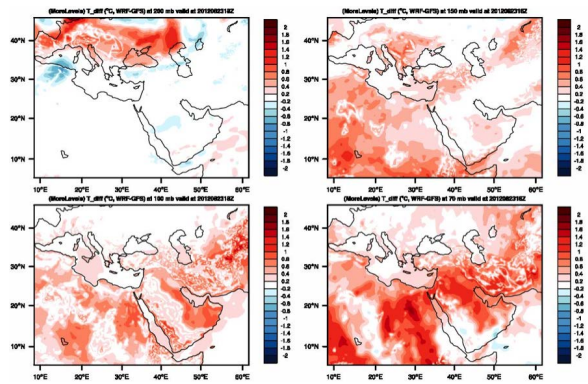


Figure 5. Same as Figure 4 except that MAGEN V1.4.2 was run with 61 vertical levels with 2 additional levels added just below and just above the 100-mb level, respectively.

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https://nar.ucar.edu/2012/lar/ral/xcel-energy-nwp-wind-power-forecasting Go

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Xcel Energy NWP for Wind Power Forecasting

Background

Accurate weather forecasting is critical for wind energy production and management because the wind speed can change rapidly in a short time period. Furthermore, the associated wind power variability represents a challenge with respect to managing the power grid. Operational forecasting for wind energy faces many challenges. First, the forecast accuracy requirements are much higher than those of typical weather forecasts. Second, surface and lower–level winds are highly variable in space and time due to many factors including the multi–scale interactions, and complex terrain can greatly magnify this challenge. Third, there is very limited understanding of the modeling requirements for representing the wind at turbine hub height and across the turbine blades.

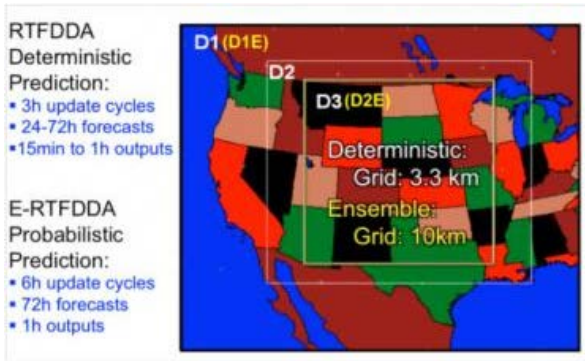

Figure 1. Grid setup of the Xcel RTFDDA and E-RTFDDA forecast systems.

Achievements in FY2012

In collaboration with Xcel Energy Inc., RAL developed a wind power forecasting system for predicting wind at more than 40 wind farms in Colorado, Minnesota, New Mexico and Texas. To better resolve the terrain effects of the Rocky Mountains on the atmospheric circulation in the Front Range area where some of the major Xcel wind farms are located, an operational Real-Time Four-Dimensional Data Assimilation (RTFDDA) system based on the Weather Research and Forecasting (WRF) model was set up with a large fine mesh, at 3.3 km grid increment, to cover the major forcing of the Rocky Mountains (Fig. 1).

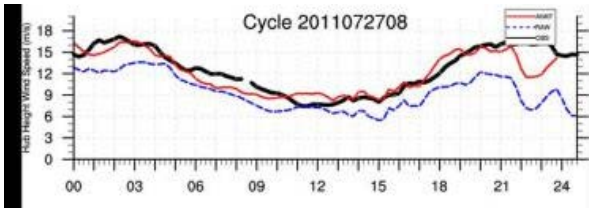

Figure 2. Sample hub height wind speed forecast.

In addition, a 30-member ensemble RTFDDA (E-RTFDDA) system has also been set up at 10-km grid spacing in the finest mesh covering the same region as the deterministic model. The E-RTFDDA system provides an alternative to the high-resolution deterministic forecast model to sponsors interested in probabilistic forecast. Finally, we explored the possibility of additional setup by introducing a small third domain in the E-RTFDDA configuration at 3.3 km grid spacing. This domain was small but covered some of the major wind farms in northern Colorado. We were pleased that this additional domain did not slow down the forecast by much. Using a 3.3 km grid for the E-RTFDDA system is certainly a practical possibility and would help increase the spread of the forecast.

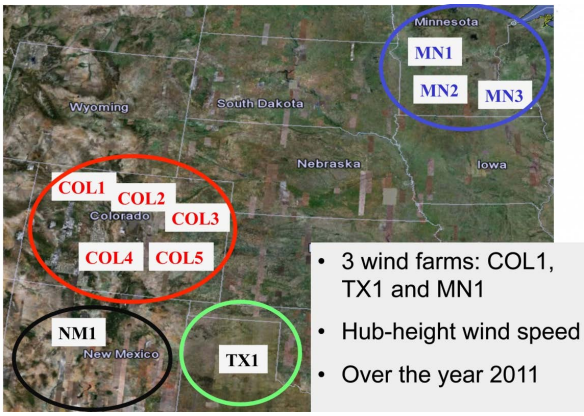

Figure 3. Wind farm locations.

Both the deterministic and ensemble forecast

systems were transferred to Global Weather Corporation which maintains the real-time systems on behalf of Xcel Energy in the summer of 2011 at the conclusion of this project. Both of these systems provide meteorological forecast at 15-min intervals which is crucial for Xcel Energy operations (example in Fig. 2).

By the end of the project, we have accomplished the following besides the aforementioned accomplishments:

i. improvements to RTFDDA and E-RTFDDA including upgrading WRF to the newest community version; improving WRF's adaptive time-step algorithm; modifying the QNSE PBL height computation; making code changes to WRF to output sub-hour interval model sounding profiles; improving assimilation of surface temperature observation; and improving assimilation of met-tower and wind turbine hub height wind data with adjusted terrain heights to take account of model terrain and station elevation inconsistencies.
ii. further refinement and utilization of the model output post-processing using Kalman filter (KF), analog Kalman filter (ANKF) and quantile regression (QR).
iii. improvements to the WRF planetary boundary layer (PBL) scheme using concepts from intermittent turbulence to target deficiencies of most PBL schemes under stable clear sky nighttime conditions.
iv. verification of model performance.

Evaluation of Post-processing Methods and Model Performance

After the Xcel project ended, we evaluated the performance of the 0-24 h forecast of the E-RTFDDA system for the year 2011 as well as the post-processed model output from the E-RTFDDA system: QR, KF, and ANKF for wind farms in Colorado, Minnesota and Texas (Fig. 3). KF and ANKF can correct systematic model biases. Quantile regression was used to calibrate the ensemble to provide more spread.

The rationale of using an ensemble forecast system is to capture the probabilistic nature of weather forecast. Ideally, the larger the spread of the ensemble, the better is the ensemble forecast system. Figure 4 shows the results of the rank histogram of the hub height wind speed forecast of the 30-member ensemble for the Colorado wind farm to diagnose the spread of the ensemble. The spread for the Colorado wind farm was too small. After application of QR, the spread of the ensemble forecast for the Colorado wind farm became larger (Fig. 5). Figure 6 shows the root mean square error (RMSE) of the ensemble mean hub-height wind speed forecast for the Colorado wind farm. Post-processed forecast generally fared better than the raw model forecast with the rankings as follows: QR+ANKF, ANKF, KF, and raw ensemble mean. QR+ANKF had the lowest RMSE during 0-9 h forecast but then had the same RMSE as ANKF after 9 h forecast.

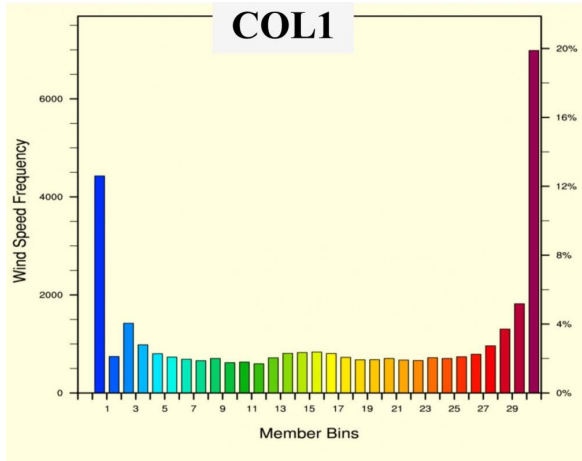

Figure 4. Rank histogram of Colorado wind farm forecast from uncalibrated ensemble forecast.

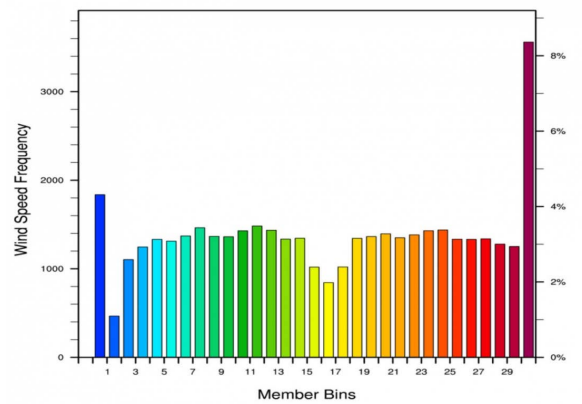

Figure 5. Rank histogram of Colorado wind farm forecast from calibrated ensemble forecast using quantile regression.

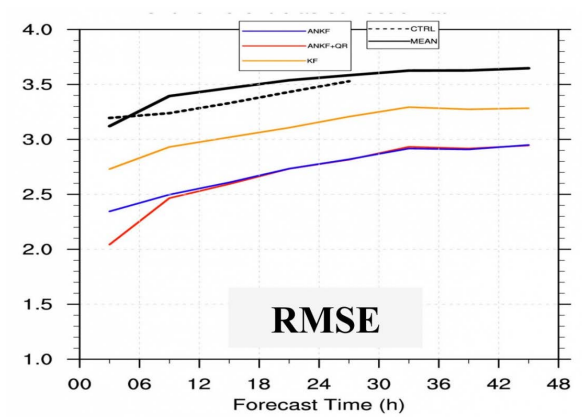

Figure 6. Root mean square error of hub height wind forecast from Colorado wind farm.

Plans for FY2013

Xcel Energy has planned to provide new funding for FY2013. Research will be conducted to assimilate nacelle wind direction data into deterministic WRF, evaluate boundary conditions from other global models (other than just GFS) to

improve ensemble configuration, reconfigure the Deterministic WRF to have a longer forecast horizon, and upgrade the WRF core with new community WRF advances/releases.

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RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
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  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

AirDat CONUS and North America RTFDDA Forecasting System

Background:

Since 2008, NCAR and AirDat have successfully installed and customized the WRF-based RTFDDA system on AirDat's Linux clusters for real-time operation. This system is the first explicit cloud modeling system running operationally and continuously over the CONUS domain. The system is routinely upgraded to incorporate the latest advances made by the WRF development community and NCAR/RAL's RTFDDA modeling groups. Implementation of a Kalman Filter based bias-correction scheme for online statistical processing of the RTFDDA forecasts at selected 524 surface sites has resulted in a significant reduction of the model forecast biases, depending on station locations and variables examined. Positive impacts in reducing the RMSE and increasing correlation coefficients of temperature, humidity and wind speed have been achieved through the assimilation of AirDat's TAMDAR data. Observed warm-season coherent pattern and diurnal cycles over CONUS are being reasonably well-resolved by the high-resolution CONUS domain.

FY2012 Accomplishments:

As AirDat continues to expand its operation, the TAMDAR observations over traditionally data-sparse areas such as Alaska, Mexico, the northeastern Pacific Ocean, the western Atlantic Ocean, and the Gulf of Mexico have become available. In order to make use of these new and valuable observations, an advanced hybrid RTFDDA and WRF-3DVAR data assimilation system (Fig. 1) has been designed and implemented for the North America (NA) domain that now encompasses the entire CONUS, as well as the aforementioned data-sparse regions. This hybrid system adequately imposes synoptic weather controls for the NA domain both by employing the GFS analyses and by assimilating all available observations including the TAMDAR data.

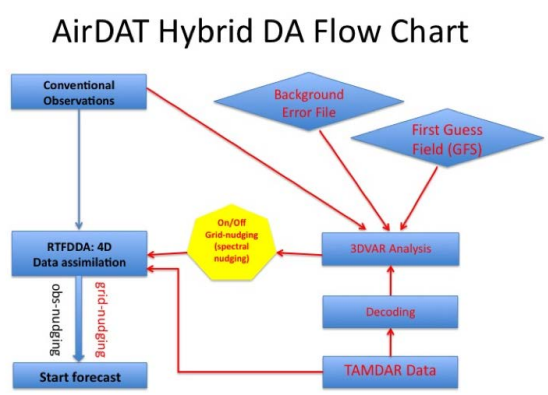

Figure 1. Schematic diagram of the NCAR-AirDat RTFDDA-3DVAR hybrid data assimilation system./div>

The NA domain was implemented and installed on AirDat's clusters at the beginning of 2012. The results from several weeks' experimental runs were compared with the CONUS domain operational model outputs. Preliminary evaluation of the NA domain's simulated precipitation against the current CONUS RTFDDA system and the NSSL composite precipitation (gauge+radar) shows that 1) the North America RTFDDA System has been performing reasonably well in comparison with the observations in that it captures almost all of the observed major precipitation events in terms of both spatial distribution and rainfall amount, and 2) there is no apparent degradation in performance in spite of the use of a much large mother domain (in comparison to that of the current CONUS RTFDDA System). As a matter of fact, there is evidence showing that the North America System exhibits improvements over the current CONUS RTFDDA system. As an example, Figures 2a and 2b present comparisons between the NA domain and the CONUS RTFDDA simulated

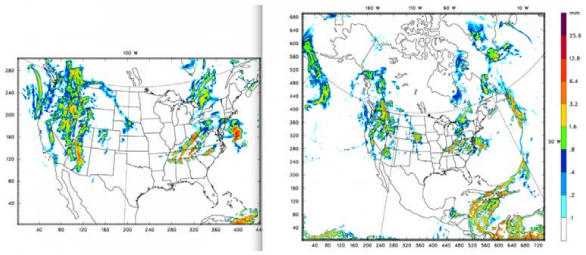

Figure 2a. 6-hour forecasted hourly precipitation from 12-km RTFDDA valid at 18Z April 26, 2012 (left: CONUS domain, right: North America Domain)

rainfall. Figure 2a shows that both model systems resolve the two major rain bands over the Continental U.S. in their 12-km mother domains. In Figure 2b, three major rain bands are identified in the observations: the first one over the US-Canada border in the Northwest, the second one extending from the Gulf of Mexico to the Great Lakes, and the third one in south Florida. Both model systems capture the three observed rain bands. While the NA system produces a closer match to the observations for the first two rain bands, it underestimates the areal extent of the rain band over south Florida.

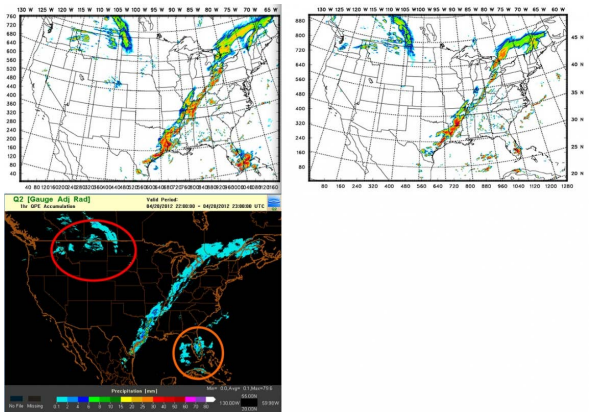

Figure 2b. 5-hour forecasted hourly precipitation from 4-km RTFDDA valid at 23Z, April 20, 2012. (top left: current CONUS RTFDDA system: CONUS; top right: North America RTFDDA system: NA;bottom center: gauge+radar).

Another focus in FY2012 is the continued development of the RTFDDA-based TAMDAR data quality-control (QC) system. The improved QC system allows for the incorporation of AirDat's expanded instrumentation, operations and services, as well as expanded coverage within the CONUS and Alaskan domains. This QC system adds new, improved algorithms to the earlier version of the system. Unlike the earlier system that was based on an RTFDDA offline data QC module, the new online QC system is embedded within RTFDDA and uses the "at the observation time" quasi-final-analysis as a reference. The new QC system is expected to significantly improve the credibility, functionality and accuracy of the quality control results. The new online QC system is already in operation for the 12 km CONUS domain. A post-processing package based upon previous work has also been developed to monitor the QC results and the working conditions of the sensors installed on the airplanes. A sample real-time TAMDAR QC output is shown in Fig. 3. The result is proving to be very useful for filtering out bad TAMDAR data and (or) instruments that are not functioning properly.

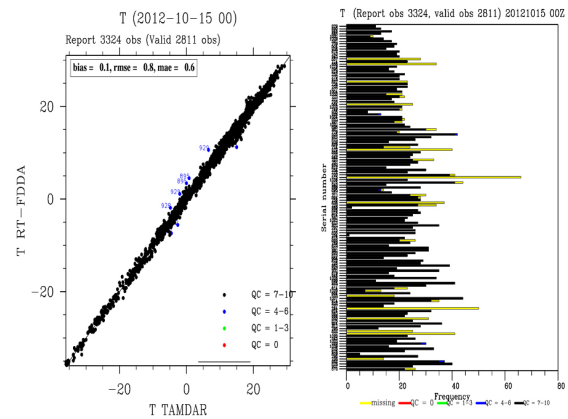

Figure 3. Scatter plot of the TAMDAR observed temperature versus RTFDDA analysis (left), and histogram of the flight serial number and the corresponding observation frequency (right) for the period of 00 UTC October 15, 2012.

FY2013 Plans:

First, all AirDat systems (NA and CONUS operational systems, CONUS and Alaska QC systems) will be upgraded from RAL RTFDDA 3.2.1 to RAL RTFDDA 3.3.1 and evaluated to ensure a successful transition to the new system. Second, the new WRF-RTFDDA based TAMDAR QC system will be implemented and evaluated for use in a European domain. Third, an ensemble RTFDDA (E-RTFDDA) system will be developed and implemented for the CONUS domain, with a 12-km grid size and 35 members. And finally, the effort to evaluate and optimize the operational forecasting systems' performance and to refine the QC and model-output post-processing components based on the analysis results will continue.

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RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

The RTFDDA-3DVAR Hybrid Radar Data Assimilation System

Background

Incorporating radar data assimilation (RDA) capability into the real-time operational framework of RTFDDA has been one of the major undertakings of the next–generation RTFDDA development. Traditionally the RTFDDA system uses an observational nudging scheme to assimilate a multitude of observations from common and specialized sources. To assimilate radar radial winds and reflectivity into the WRF-based RTFDDA system, a hybrid approach that couples RTFDDA and 3DVAR with a latent heat nudging (LHN) technique has been adopted (Fig. 1). In this approach, frequent (e.g. hourly) radar data analysis is first obtained using WRFDA 3DVAR and then a hydrometeor and latent heat adjustment that is based on radar reflectivity observations is applied. The radar analysis is then blended back to the model using the grid-nudging method. The goal of the hybrid radar data assimilation is to create dynamically and cloud/precipitation "spun-up" model initial conditions such that very short-term (0-12 h) forecasts can be improved.

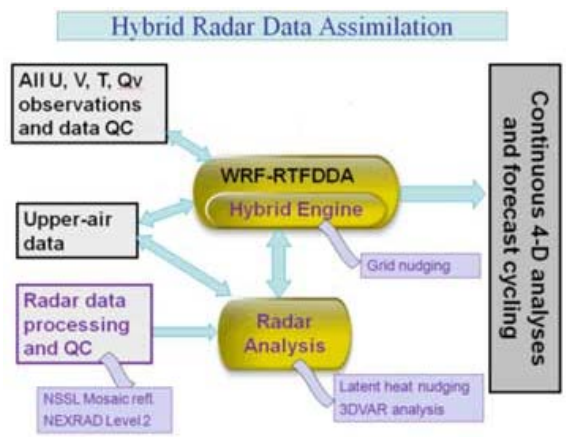

Figure 1. Schematics of the coupled system of radar data assimilation and RTFDDA

FY2012 Accomplishments:

Research was focused in three areas: (1) continued testing and improvement of 3DVAR and LHN techniques for radar data assimilation through retrospective case studies, over both the Colorado Front Range and the east coast of the U.S., (2) development of a prototype hybrid system that would run locally on a Linux cluster in real-time environment for a domain centered at the Army Aberdeen Test Command (ATC) range, and (3) implementation of software to integrate the radar data assimilation modules with the standard NCAR/ATEC RTFDDA build and release processes.

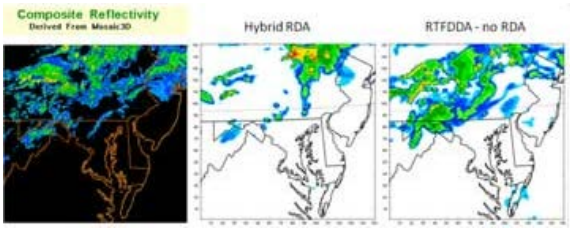

Figure 2. Radar observations (left) and 3-h model forecasts (center: hybrid system; right: RTFDDA alone) of composite reflectivity valid at 05 Z, August 28, 2012

Modifications to the WRFDA 3DVAR radar data assimilation code and adjustments to the rain control variables and precondition of the first guess fields with trace amounts of rain have been tested. An algorithm that integrates RTFDDA, 3DVAR and the latent-heat nudging approach together has been developed. Systematic real-time testing has been conducted for both the Colorado Front Range and the Army ATC. The impact of RDA on 0-12 h RTFDDA forecasts has been evaluated, and the value of adding radar data has been confirmed. Verification shows that the hybrid radar data assimilation technique improves 0-6 h forecasts of precipitation and surface temperature in both domains (Fig. 2). Several alternative configurations of 3DVAR and latent heating adjustment have been tested through the retrospective studies.

The RTFDDA-3DVAR hybrid radar data assimilation system has been implemented for real-time experimental operation for the Army Aberdeen Test

Command (ATC) range. This prototype system ingests NSSL 3D mosaic reflectivity data and Level II Nexrad observations from 16 radars (Fig. 3). It now runs continuously on the testing cluster, along with an RTFDDA run without RDA in the same domain. Monitoring and assessment are on-going. Through verification and parallel testing, this advanced radar data assimilation scheme continues to be refined.

To prepare for future operational implementation, the hybrid radar data assimilation modules have been integrated into the NCAR/ATEC RTFDDA build and release processes. Significant software engineering achievements have also been made: the radar data receiving, transfer and pre-processing procedures have been streamlined and integrated with other RTFDDA observation preprocessing modules. The 4DWX Model Manager code has been modified to include the RDA options. The forecast products from the prototype runs are displayed on a website that is accessible to ATC forecasters.

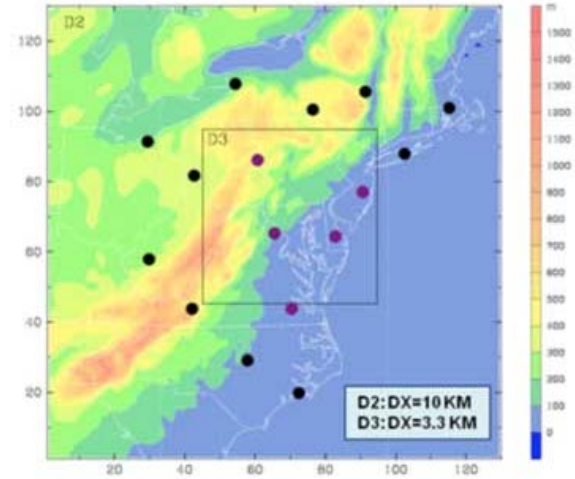

Figure 3. Domains of testing of the hybrid system at ATC

FY2013 Plans

We will continue to develop and test the RTFDDA–3DVAR hybrid radar data assimilation system in FY2013. The ATC prototype system will be continuously run and monitored by RAL scientists and ATC forecasters. Plans have been made to release the code to ATEC range users in early 2013. Prior to the release, we will be working on tuning and finalizing the code and configuration parameters for the ATC prototype system.

Retrospective case studies will be continued for various weather scenarios. The system will be tested for a Front Range domain for short-term forecasting of warm-season convection. Research work will be focused on developing and testing a newly derived radar reflectivity for rain, snow, and graupel mixing ratio relationships in the hybrid radar data assimilation system. We will also begin to investigate using lightning data in the hybrid radar data assimilation system.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Fine-Scale Precision Forecasting with WRF-RTFDDA-LES

Background

Demands for fine-scale precision weather forecasts from weather-sensitive businesses increase rapidly. To meet these needs, NCAR/RAL has taken advantage of its advanced real-time four-dimensional data assimilation (RTFDDA) weather forecasting system and increased computing power and is investigating the feasibility of bringing numerical weather prediction (NWP) capability to bear on sub-kilometer to Large Eddy Simulation (LES) scales. The newly developed system, the WRF-RTFDDA-LES model, can be directly nested into any domains from mesoscale to LES scales while boundary turbulence can be explicitly resolved at fine scales. Such a fine-scale precision forecasting system provides valuable fine-grid and detailed weather information that can be used to support weather-sensitive businesses to prepare for major disasters, to plan and manage energy and water resources, and to improve operational and logistic effectiveness. Research is being conducted to apply the WRF-RTFDDA-LES model to various fine-scale weather scenarios including tornado, storm and wind farm turbulence.

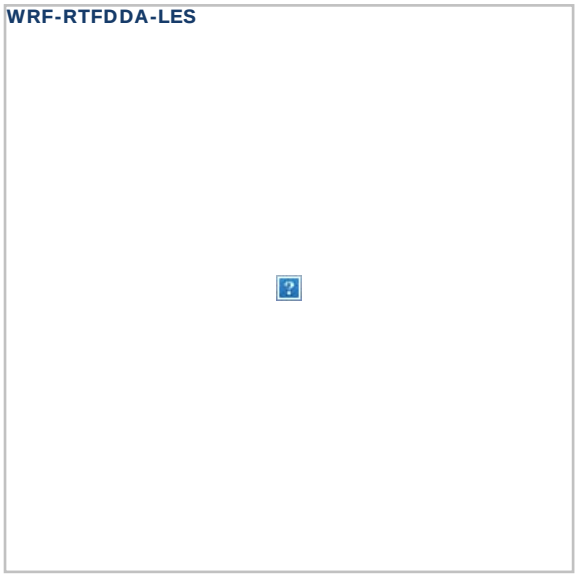
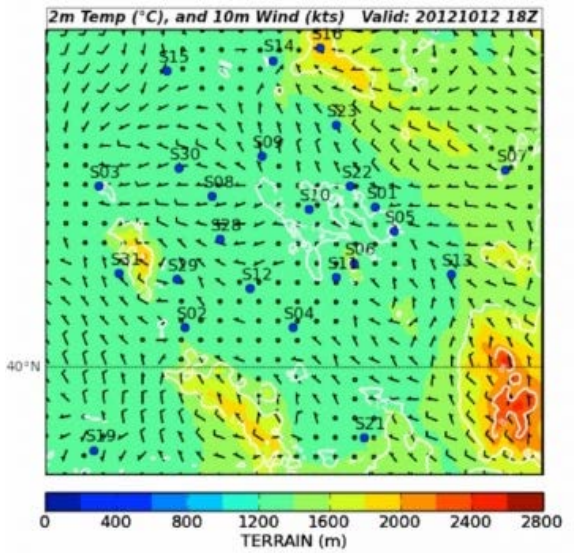


Figure 1. WRF-RTFDDA-LES simulation of severe tornado evolution during the April 27 2012 super tornado outbreaks in the Southeastern United States.

FY2012 Accomplishments

Fine-scale terrain and landuse datasets were updated using measurements from NASA SRTM, USGS NLCD 2006 and other resources for development of the WRF-RTFDDA-LES system. The updated static surface datasets cover the United States, East Asia and Middle East.

Scientific studies on severe weather events, such as tornado outbreak, have been conducted to better understand the dynamic mechanism, scale interaction, and physical processes in the fine-scale modeling system. Figure 1 illustrates the evolution of the simulated Enhanced Fujita scale 4 tornado (wind speed > 166 mph) during the 2011 April 27 Southwestern U.S tornado outbreaks. The wind starts accelerating and rotating rapidly from about 3000 m altitude downward at about 21:25 (30 minutes before the tornado touchdown), and the surface wind jumps to over 70 m/s from about 10 m/s in just a few minutes around 22:05 UTC accompanying 25 hPa surface pressure change. The model at 300m-grid spacing is able to capture key tornado-genesis elements: vigorous rotation, upward and downward drafts. This study demonstrates the modeling



system's utility in severe weather forecasting.

Mountain flows, which tend to have significant impacts on local weather and weather-sensitive operations, also require ultra-fine model resolution, but data assimilation at fine scales is challenging. To improve the forecast accuracy in mountain flows and fine-scale data assimilation, the WRF-RTFDDA-LES system was applied over several complex terrain and coastal areas. Figure 2 shows the simulated mountain flows at the Army Dugway Proving Ground, Utah, with 300m model grids along with observational stations. The test range has a local observation network with weather reports every five minutes at 31 special stations. 25 of the 31 stations are within the 300m-grid domain, which provides an excellent opportunity for studying fine-scale data simulation and verification. After numerous experimental tests and studies, the fine-scale precision forecasting system was implemented in the region for operation in a nested configuration from 8.1km to 300m. Figure 3 shows the station observations every five minutes and the hourly model analysis for one day. Clearly the ultra-fine resolution with proper configuration enables the modeling system to capture the observed fine mountainous flow reasonably well.

Figure 2. Near-surface mountainous flow forecast of the modeling system. Blue dots indicate the special surface observation meosnet.

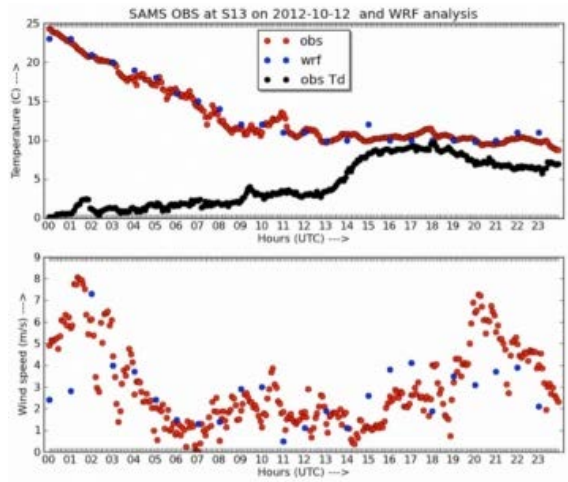


Figure 3. Observed five-minute surface air temperature, dew point temperature (black dots), wind speed at one of 31 special stations and the WRF-RTFDDA-LES model analysis (blue dots).

The fine-scale precision modeling system has also been used to study wind farm data assimilation and turbulent flows. It has been shown that the system is capable of capturing intra-farm wind variability, as well as forecasting the winds with the enhanced accuracy that is required for wind power predictions, planning and management. The analysis results show that the fine-scale model well reproduces the observed winds. The system has been implemented by Xcel Energy Co. for operational forecasting, and is in further development for use by the Korea Meteorological Agency.

FY2013 Plan

In FY2013, we will study and evaluate the modeling system with special attention paid to its fine-scale forecasting capability; investigate LES sub-grid filter schemes in the WRF model; and examine upscale impacts. LES-scale data assimilation and verification methodologies will be examined and refined along with fine-scale modeling dataset intelligent use and visualization.

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Log in

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RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

4D-REKF Ensemble Data Assimilation and Forecasting

The Four-Dimensional Relaxation Ensemble Kalman Filter (4D-REKF) ensemble data assimilation (EDA) and ensemble prediction system (EPS) has been under development at RAL/NCAR since 2010. The 4D-REKF system is built upon the WRF- and MM5-based RTFDDA (real-time four-dimensional data assimilation and forecasting system) for accurate mesoscale analysis and forecasting. It retains and leverages the advantages of both the Newtonian-relaxation and the Ensemble Kalman Filter (ENKF) data assimilation methods. On the one hand, the 4D-REKF system eliminates the ad-hoc specification of spatial weight function in the current station-nudging FDDA formulation, which extends the ability of the system to assimilate non-standard observations, such as Doppler radar radial winds and reflectivity. On the other hand, it extends the 3D-ENKF to a 4D data assimilation framework, and hence alleviates the spin-up problem of the ENKF for short-term weather forecasts.

The 4D-REKF system is intended to replace the NCAR RAL RTFDDA and ensemble RTFDDA technology as the next-generation mesoscale data assimilation and forecasting tool for supporting broad weather-critical applications.

FY2012 Accomplishments

Major tasks in FY2012 include testing, evaluating and optimizing the model code and algorithms. Computing and using the Kalman gain are both critical, but costly in terms of computing resources with the 4D-REKF data assimilation scheme. Therefore, several approaches to compute the Kalman gain with adequate accuracy and efficiency have been implemented and tested. The schemes tested include a 2D mathematical fitting function, a ray-tracing method and a "nearest-point" approach. It is found that the "nearest-point" method presents the best trade-off between accuracy and efficiency for the Kalman gain computation. In order to deal with diverse observation types, two kinds of the Kalman gain computation are designed. For fixed stations, the Kalman gains are calculated at the exact station locations. For time-space changing observations such as aircraft weather reports, the Kalman gains are computed at regular grid points and then interpolated to the observation locations.

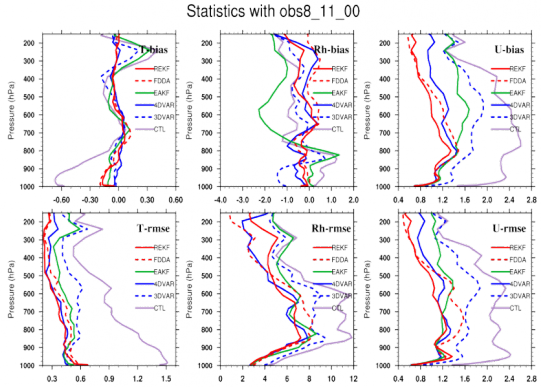

Figure 1. Verification statistics of the OSSE experiments of no-data assimilation (CTL), WRF 3DVAR, WRF 4DVAR, DART EAKF, RTFDDA (FDDA), and 4D-REKF(REKF) at the final analysis time of 00Z Feb 11, 2008.

To validate the 4D-REKF data assimilation system, OSSE experiments based on the "perfect-model-perfect-observations" approach have been conducted. For comparison, WRF 3DVAR, 4DVAR, and NCAR DART-EnKF developed at NCAR NESL have also been tested with the same OSSE framework and the data. The verification results of this OSSE study indicate that 4D-REKF outperforms other existing WRF data assimilation technologies. Figure 1 presents an example showing the bias and RMSE of various meteorological variables in 4D-REKF at the end of 6-hour data assimilation in comparison to those of WRF 3DVAR, 4DVAR, and NCAR DART-EnKF. Also shown in the figure are the bias and RMSE in the standard Station-Nudging FDDA.

FY2013 Plans

The research and development of 4D-REKF in FY2013 will focus on testing and evaluation using real weather cases and data. After further optimization and tune-up, the system will be implemented for real-time operational testing at an Army test range. Comparison studies of 4D-REKF with WRF DART-ENKF, the RTFDDA–3DVAR hybrid data assimilation,

and WRFDA-4DVAR data assimilation systems will be conducted for real weather cases. Development of a multi-variable analysis capability with 4D-REKF for assimilating radar radial winds and reflectivity is also planned for FY2013.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Real-time Ensemble-RTFDDA Wind Energy Forecast for China

Background

The wind power industry is one of the fastest developing energy industries with a total of 41 GW installed worldwide in 2011. More than half of this power is from China whose total installed wind power capacity has doubled for five consecutive years making it now the global leader in wind power capacity. This rapid development has, however, created great challenges with regard to safely and economically integrating wind power into the electric grid. Currently, many wind companies are facing "bottlenecks" in this integration process and have come to realize that accurate weather prediction and precise spatial analysis of mesoscale weather events are crucial to energy management.

In collaboration with scientists at CEPRI (China Electric Power Research Institute), NCAR RAL is developing a WRF- and MM5-based real-time four-dimensional data assimilation (FDDA) and forecasting system for supporting wind energy operations and power integration at the State Grid Corporation of China (SGCC). The long-term goal of the collaborative effort is to develop an optimal wind power forecasting system across China. During the first phase, we aim to implement two real-time ensemble FDDA wind modeling systems based on the existing real-time FDDA technologies developed at NCAR. The systems support two areas within the State Grid system with large wind power capacity: the western part of North China (including inner Mongolia, Gansu and Ninxia provinces) and Xinjiang, an autonomous region in the northwest of China. The NCAR ensemble forecast statistical post-processing technology for improving the real-time ensemble FDDA wind forecasts was also proposed for each wind farm in the two TSOs. These model output statistical post-processing technologies include an Analog-based Kalman filter for bias correction and a quantile-regression-based ensemble prediction calibration algorithm.

FY2012 Accomplishments

The project started in May 2012. The Initial Operating Capabilities of the first real-time ensemble FDDA system, which will provide service to about 70 wind farms located in western Inner Mongolia, Gansu province and Ninxia province, has been developed as of October 1, 2012. Major accomplishments of the project for FY2012 include: i) Designing the system, including assessment of hardware, software, and data availability at CEPRI, and specification of the modeling system configuration; ii) Setting up the first real-time ensemble FDDA and forecasting system for this area and conducting system optimization with case studies; and iii) Performing semi-operational forecast experiments to expose and solve outstanding modeling issues in association with the ensemble FDDA system model physics, data assimilation parameters, and ensemble perturbation approaches.

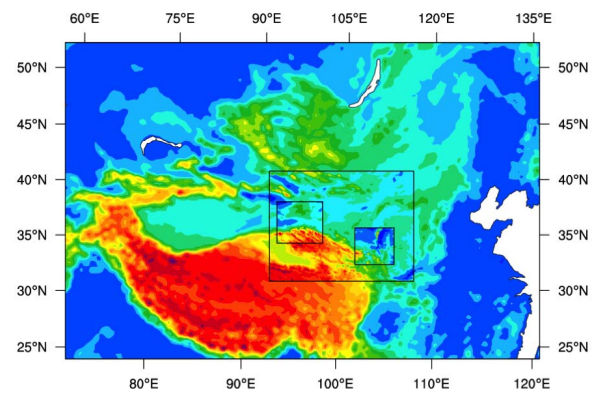

Figure1. Ensemble RTFDDA domain configuration (Δx = 24.3, 8.1, 2.7, 2.7 km) located in Gansu and Ninxia. The shadings represent the terrain height.

Figure 1 shows the domain configuration of the first CEPRI real-time ensemble FDDA and forecasting system. It contains four nested grid domains, with grid increments of 24.3km for the coarse grid, 8.1km for Domain 2, and 2.7km for both Domain 3 and Domain 4. The two parallel finest domains (D03 and D04) are designed for two major wind farm clusters. The real-time ensemble FDDA system runs four forecast cycles each day, producing real-time forecasts with 25 WRF members. A post-processing

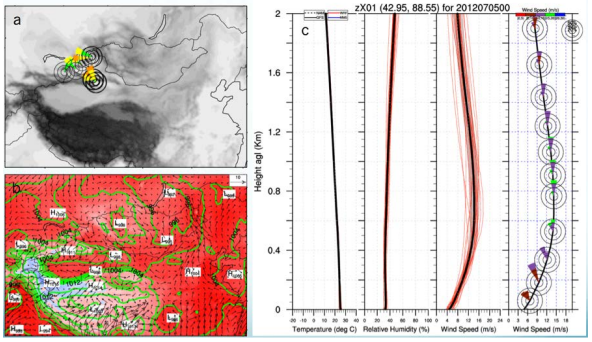

Figure2. (a) The wind rose plots and the color denote the wind speeds. The shade denotes the terrain height. (b) 10m mean winds are shown by the arrows, and the colorful shades denote the mean temperature. Thick green lines show the sea level pressure. (c) The temperature, moisture and wind profiles at a wind farm located at (42.95N, 88.55E).

package producing numerous graphics in real time and a web page displaying real time model products have been developed for evaluation of the forecasting system. The real-time products include meteorological fields and products for wind energy and solar energy for both the control run and the ensemble probabilistic prediction. Two-dimensional wind energy and solar energy distribution and time series of wind energy and meteograms are produced for individual wind farms. Also contained on the web page are observations and real-time model forecast verification information. Figure 2 presents an example of forecast products produced from the post-processing package.

Plans for FY2013

The RAL project team will continue to research the wind farm data that can be assimilated into the ensemble forecasting system through case studies. The second real time ensemble FDDA forecasting system for Xinjiang will be set up, tuned up and put into operation. RAL will also implement and demonstrate the value and advantage of NCAR ensemble forecast statistical post-processing technology, including advanced statistical bias correction and probability calibration algorithms. These algorithms will be implemented to improve the real-time ensemble FDDA wind forecasts for each wind farm in the two TSOs. One of such technologies is ANKF, with a Kalman Filter based model forecast bias correction scheme operated in analog space. The other one is quantile-regression (QR) based ensemble calibration algorithm, which will be used for error correction. The calibration especially focuses on wind farm wind prediction application. The ANKF and QR schemes will be integrated together for post-processing the two real-time ensemble FDDA and forecasting systems.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Modernization of Numerical Weather Prediction in Saudi Arabia

Background

In an effort to modernize its meteorological service, particularly with regard to numerical weather prediction capability, the Kingdom of Saudi Arabia is working with NOAA's International Office and NCAR to implement advances made by the Research Applications Laboratory in real-time operational data assimilation and forecasting. The aim of this collaborative project is to develop, deploy and customize a specialized operational WRF modeling system based on fundamental studies of the regional weather and climate in the Arab Peninsula and the Middle East. One of the challenges for accurate weather prediction in the region is the limitation of the observations that can be used for data assimilation and verification. Thus, one of the key components of the project is to study and develop an advanced modeling system that combines the NCAR mesoscale numerical weather prediction technologies including WRF-ARW (Weather Research and Forecasting – Advanced Research WRF core), RTFDDA (Real-Time Four-Dimensional Data Assimilation and forecasting system) and 3DVAR (Three-Dimensional Variational data assimilation). The hybrid data assimilation approach along with the advanced modeling system will be capable of significantly improving regional weather prediction and providing invaluable weather information for policy and decision makers.

FY2012 Accomplishments

As part of the collaborative project, RAL scientists have visited the Presidency of Meteorology and Environment (PME) regularly, and provided intensive trainings to PME staff on numerical weather prediction and WRF applications for the Middle East region in Jeddah, Saudi Arabia. Meanwhile, RAL scientists have also gained first-hand understanding of the needs and concerns of the Saudis with regard to weather and climate prediction. Of significant concern is urban area flooding caused by severe convective weather and dust storms which pose socioeconomic threats to the development of the country. Devastating damage, for example, resulted from recent flooding events (November 2009 and January 2011) in Jeddah and dust storms (February 2011) in Jeddah and Riyadh. RAL scientists and PME staff have jointly selected several weather and dust events for scientific investigation for better understanding of the regional characteristics and features of the weather and climate. A preliminary forecasting system based on WRF has been established at Jeddah, the PME's headquarters, using its limited computer capability. This system allows RAL scientists and engineers to further study and develop an advanced forecasting system, and serves PME staff as a valuable tool to advance their numerical modeling knowledge.

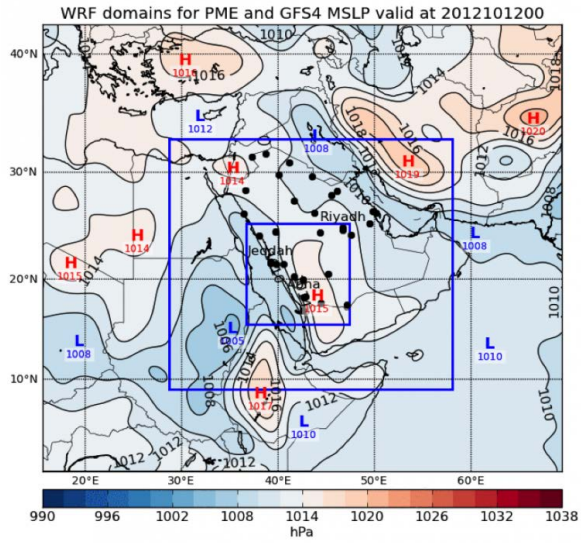

Figure 1. Proposed three-nested WRF domains (blue boxes) at 21.6, 7.2 and 2.4 km, and GFS4 mean seal level pressure projected on the coarse WRF domain. The black dots indicate the WMO stations in Saudi Arabia.

PME updated its computing facility with a more powerful 20-node Linux cluster in late summer 2012. The cluster currently sits at NCAR for RAL scientists and engineers for testing, research and development. Scientific and technical experiments have been performed on the new cluster, and a new set of WRF

domains was designed based on the experiments. The newly designed three nested domains are configured at 21.6, 7.2 and 2.4 km and 40 model levels, and are driven by NCEP half-degree GFS4 forecasts as shown in Figure 1.

NCAR scientists have also conducted preliminary studies, analyses and numerical experiments with the WRF-CHEM model on the predictability of the dust storms in Saudi Arabia and their meteorological causes. Figure 2 shows the simulated dust storm in the region that occurred in early February 2012.

The advanced modeling system will be implemented on the newly required 20-node Linux cluster for real-time operation at the PME in Jeddah after extensive testing and evaluation. Professional training in numerical weather prediction to PME staff will be provided by NCAR. Implementation of MET (Model Evaluation Toolkit) developed at NCAR is another key component in the project. In addition, this project will also explore the study of dust storms, frequent damaging events in Saudi Arabia, and the capability of the modeling system in predicting the events as mentioned before. This project may promote a long-term collaboration between NCAR and PME.

FY2013 Plan

In FY2013, further studies of regional weather and climate, especially on extreme events such as heavy rain flooding in an urban area (illustrated in Figure 3), will be performed to better understand regional weather regimes and to aid in model development and refinement. A hybrid approach to data assimilation will be explored and developed for the region, and a plan for verification using the Model Evaluation Toolkit will be developed. Further scientific research on dust storms and dust forecasting capability using WRF-CHEM will be another important focus area. The Linux cluster and operational modeling system, currently being tested at NCAR, will be delivered to the PME for on-site testing. Training for PME staff on the use of the modeling system--and numerical weather prediction in general—will also be provided.

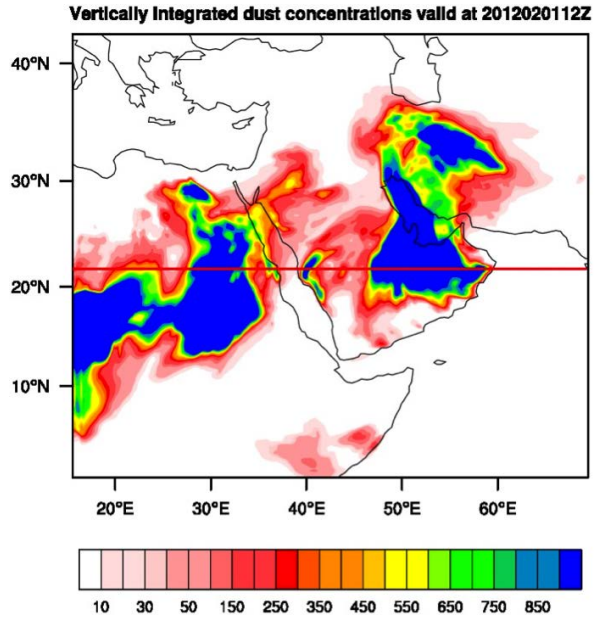

Figure 2. Simulated dust concentrations in the Middle East on February 1, 2012 with WRF-CHEM Model.

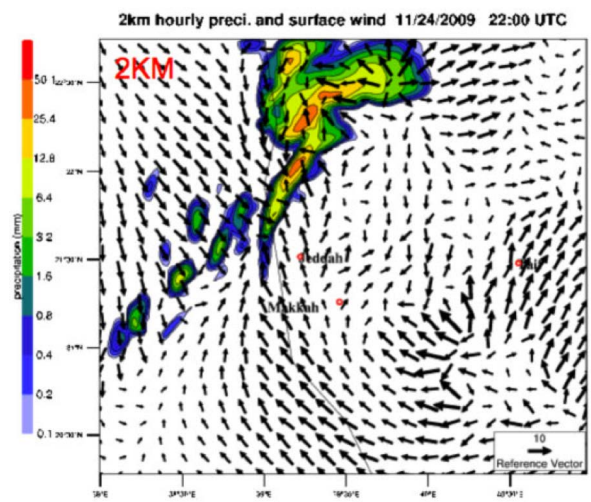

Figure 3. One heavy rain event in November 24-26 2011 simulated by the WRF modeling system. The event was caused by severe convection and resulted in 90 mm rainfall in three hours and flooding in Jeddah, Saudi Arabia.

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RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

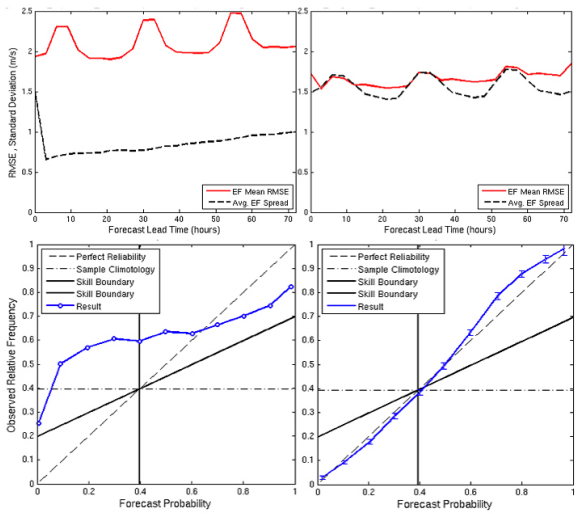
Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction

Background

The analog of a forecast for a given location and time is defined as the observation (or analysis grid point) that can be verified when a past prediction with matching selected features of the current forecast is valid. A novel ensemble design using analog forecasts has now been established. The analog ensemble (AnEn) approach takes the best analogs of a deterministic numerical weather prediction (NWP) model and combines them to form an ensemble which can then generate skillful and reliable probabilistic predictions. The analogs are generated from the operational National Centers for Environmental Prediction (NCEP) North American Mesoscale model (NAM) and 10-m wind speed observations from 592 METAR stations over the continental U.S. (CONUS).

FY2012 Accomplishments

The performance of this new probabilistic prediction ensemble has been compared to a state-of-the-science operational system, the Environment Canada Regional Ensemble Prediction System (REPS). We found that it outperforms REPS in several key areas, including reliability, resolution, sharpness, and spread-error consistency. As shown in the second panel from the top, the analog ensemble mean RMSE (red line) is much closer to its spread (dashed) than what it is observed for the REPS (top panel). This indicates that the spread of the analog ensemble provides a much more reliable estimate of the prediction uncertainty; also the analog ensemble is considerably more skillful as indicated by the lower RMSE of its mean (red line in second panel from the top) when compared to the mean of the REPS system (top panel). The two bottom panels confirm that the analog ensemble is more reliable than REPS. In the reliability diagrams shown, the forecast probability should match the observed relative frequency, and a perfectly reliable probabilistic prediction leads to a blue line overlapping with the one-to-one line (dashed). As shown, the analog ensemble (bottom panel) it is much closer to it than the REPS (second panel from the bottom).



Top panels: Root-mean-square-error (RSME) of ensemble mean (red) and ensemble spread (dashed) over the 0-72 forecast lead times (left: REPS, right: analog ensemble). Bottom panels: reliability diagrams for REPS (left) and the analog ensemble (right).

The analog ensemble has been applied also with success to the prediction of hub-height winds and power for wind energy applications. When compared to advanced power prediction systems, such as the one based on the European Centre for Medium-Range Weather Forecasts (ECMWF), the AnEn exhibited superior skill at a lower computational cost.

Finally, qualitative tests (which will be extended in FY2013, see below) have shown that the analog ensemble is a viable technology to improve dispersion predictions, and the reliability of their uncertainty estimates.

FY2013 Plans

In FY13 the potential of the analog ensemble technique will be further explored for several applications, including dispersion modeling, wind and solar energy, and aviation.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
    - Real-time Microscale FDDA Forecasting System for Korea
    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Mesoscale Ensemble Prediction

Background

Given the chaotic nature of the atmosphere and the imperfections of numerical weather prediction (NWP) models, the use of probabilistic information will likely produce more useful forecasts for a variety of weather-sensitive sponsors. To better provide this information, new mesoscale ensemble prediction systems are being developed, and real-time systems that incorporate ensemble models are moving into operational use. A challenging and exciting aspect of this effort is working with forecast users to help them better incorporate stochastic information into their decisions. Research in this area is currently being conducted through the sponsorship of the Army Test and Evaluation Command, Xcel Energy and China State Grid projects, whose broad objectives and progress are discussed elsewhere in this annual report.

FY2012 Accomplishments

The Ensemble RTFDDA (E-RTFDDA) analysis and forecasting system is one of the most important new capabilities recently added to the RAL Real–Time Four Dimensional Data Assimilation (RTFDDA) and forecasting system. Unlike most other mesoscale ensemble systems, E-RTFDDA is a multi–model, multi–scale, and cycling data assimilation and prediction system. The continuous cycling mechanism of E-RTFDDA allows the model to produce accurate nowcasts and short-term forecasts. In FY2012, two 30–member E-RTFDDA systems have been continuously operated, one at the US Army Dugway Proving Ground, supporting routine tests and decision–making for test planning, and the other at Xcel Energy, providing ensemble wind forecasts at the Xcel wind farms located in Colorado, Minnesota, Texas and New Mexico. In addition, a third 30-member E-RTFDDA system has been implemented to provide wind forecasting to support China State Grid Corporation's operation in wind integration, load balance planning and energy trading. The new advances in the E-RTFDDA core technologies accomplished in FY2012 are highlighted below.

E–RTFDDA research was focused in four areas:

1) adding and evaluating the WRF-NMM (non-hydrostatic mesoscale model) members to the system, 2) integrating and assessing the Canadian GEM (Global Environment Multiscale) model outputs to enhance E-RTFDDA boundary condition perturbations, 3) investigating perturbations with the stochastic kinetic energy backscattering approach, and 4) implementing and testing the NCAR DART ensemble Kalman filter (EnKF) tools with E-RTFDDA to enhance E-RTFDDA initial condition perturbations. WRF-NMM is the operational model used at NCEP and has a different dynamical core than that of WRF-ARW. With the addition of WRF-NMM, E–RTFDDA thus contains 3 model systems: WRF-ARW, WRF-NMM and MM5. The NCAR DART-EnKF (Data Assimilation Research Testbed-Ensemble Kalman Filter) system was integrated into E-RTFDDA to enhance the E-RTFDDA system in both member perturbations and data assimilation. The enhancement allows DART EnKF to take advantage of E-RTFDDA by means of deriving error covariance using the multiple perturbation E-RTFDDA forecasts; meanwhile, the updated EnKF means and a subset of the EnKF members are used to perturb the initial conditions of E-RTFDDA. Initial tests show that these additional perturbation schemes work properly and help mitigate the known underestimation of the E-4DWX spread, thus increasing forecast reliability (Fig. 1).

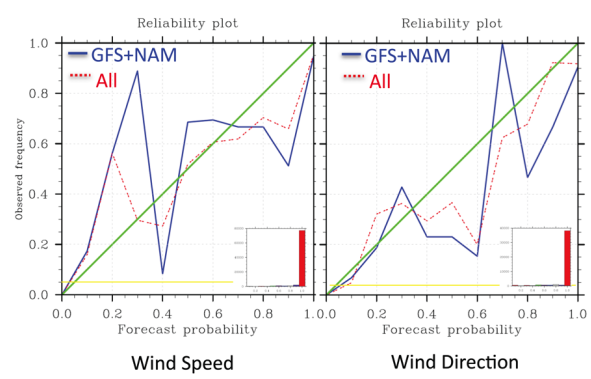

Figure 1. Reliability plot for wind speed (left) and wind direction (right) for GFS and NAM only (blue line) and all type perturbations included (red dashed line).

Finally, E-RTFDDA provides a scientific and technical cradle for development of an advanced next-generation 4DWX system with ensemble-based data assimilation (EDA) and the ensemble prediction system (EPS) paradigm. During FY2012, significant progress has been made in the development of this innovative NWP scheme. The new algorithm is referred to as 4D-REKF: Four-Dimensional Relaxation Ensemble Kalman Filter data assimilation and forecasting. The detailed description of 4D-REKF is reported elsewhere in the annual report. 4D-REKF was designed to advance the E-RTFDDA data assimilation technology by absorbing and leveraging the cutting-edge ensemble Kalman filter data assimilation methods, which introduces new measures to improve ensemble perturbations.

FY2013 Plans

Ensemble research and development at RAL will be focused in the following areas:

- Continued evaluation of the impact of WRF-NMM, GEM boundary conditions, SKEB and DART EnKF components on the E-RTFDDA simulations with semi-operational forecast experiments.
- Integration of more global models for better specification of the lateral boundary conditions perturbation for E-RTFDDA.
- Continued work to improve the ensemble forecast verification and calibration algorithms. The Quantile Regression calibration approach will be reformulated to train the correction according to different weather regimes. Improvement of the definition and determination of "Analogs" in the ANKF scheme will also be considered.
- Continued implementation and evaluation of the RAL next-generation, 4D-REKF, seamless EDA and EPS weather model system for probabilistic forecasts.
- Submission of proposals to U.S. and international agencies to implement E-RTFDDA for their specialized applications.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
    - Four-Dimensional Weather System
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    - MAGEN RTFDDA and 3DVAR Hybrid System
    - Xcel Energy NWP for Wind Power Forecasting
    - AirDat CONUS and North America RTFDDA Forecasting System
    - The RTFDDA-3DVAR Hybrid Radar Data Assimilation System
    - Fine-Scale Precision Forecasting with WRF-RTFDDA-LES
    - 4D-REKF Ensemble Data Assimilation and Forecasting
    - Real-time Ensemble-RTFDDA Wind Energy Forecast for China
    - Modernization of Numerical Weather Prediction in Saudi Arabia
    - Analog Ensemble Prediction and DART-based Data Assimilation for Wind Prediction
    - Mesoscale Ensemble Prediction
    - High Performance Computing for Operational Modeling
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

High Performance Computing for Operational Modeling

Background

RAL's research and development in advanced, small–footprint computing is focused on providing scalable solutions to high–resolution numerical modeling with demanding data storage requirements. By keeping abreast of the increasing speed and density of rack–mounted cluster computing, RAL delivers climate analyses and real–time weather predictions that fit into an ever-decreasing footprint. As hardware vendors continue to provide higher density computing, RAL is able to move toward more green computing, with lower power and cooling requirements.

An important feature of RAL/NSAP's computing design is its ability to provide solutions across scales. Given the need to deploy systems that range in size from 32 cores to 616 cores, and applications that range from global climatologies to large eddy simulations, the flexibility and extensibility of the computing architecture becomes a critical component for success.

Storage

RAL has achieved significant improvements in data storage management through the deployment of NAS (network attached storage) systems. The transition from RAID disks that were directly attached to a single computing cluster to NAS data repositories that are accessible across the local area network has been accompanied by greater reliability, increased data accessibility, and less time spent on storage maintenance by system administrators and users. In addition to the increased reliability, the NAS solution provides scalability for future growth that allows for incremental additions to data storage, while maintaining consistent, logical namespace. The end result is that data users no longer have to spend time juggling datasets across individual disks, leaving it to the NAS architecture to manage the mapping between logical and physical space.

Further enhancing the scalability of application to storage performance is the parallel IO method which each server uses to access file systems over a dedicated gigabit to 10Gigbit network. The parallel NFS standard minimizes hot-spot contention for data sets and provides a scalable topology where high demand IO requests are balanced over dozens of disk spindles and network ports to provide streaming of data in both write or read modes.

At the end of FY12 NSAP had approximately 206TB of this parallel, network attached storage deployed, with plans to expand by another 100TB in FY2013. In addition to available storage, as a result of commensurate networking upgrades, the data throughput will expand from 2.2 Gbps to 3.8 Gbps, providing a scalable solution for the increasing demands of higher and higher resolution weather and climate forecasting.

GPU Acceleration

One-time funding from NSF has supported investigation of the use of graphical processing unit (GPU) technology, taken from the gaming industry, for acceleration of scientific applications. Following initial investigations in FY2011, FY2012 activities in this project focused on the acceleration of the algorithm used for analog-based ensemble forecasts (AN-EN) as described in the paper, Delle Monache, et al. (2011) by porting it to GPUs.

During FY2012 the effort focused on porting Matlab-based code to C in an automated and repeatable method that would allow for continued research development in Matlab, developing a reference dataset for regression testing of the transformed code, and using the regression tests to explore algorithm optimizations.

In each of the accomplished tasks, significant insights were gained in the opportunities for accelerating the AN-EN algorithm through the use of multi-core CPUs, however the code that was analyzed and optimized during these steps remained in the C language. While GPUs present a promising multi-core platform for further acceleration, the labor cost in further porting to CUDA remains a high barrier to entry.

2012 marks the end of the one-time funding for GPU exploration. Further work in the area of GPU acceleration of the AN-EN algorithm will proceed as funds from other sources become available.

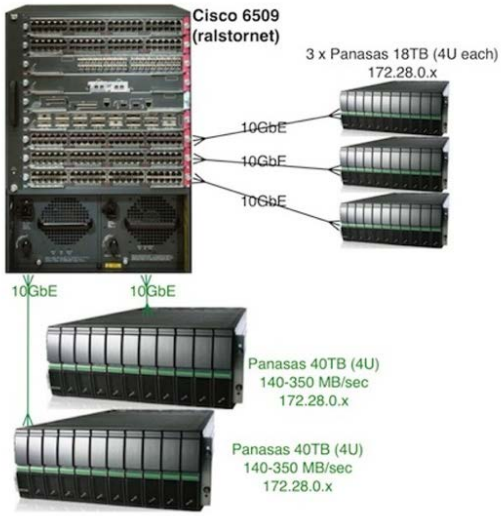

Figure 1: NSAP parallel IO network storage realm. This is a high-availability, network accessible storage realm providing simultaneous and parallel IO access to hundreds of compute nodes for WRF operational, research and development output. This architecture allows multiple, concurrent projects and clusters to access and manipulate large and small datasets for scientists and developers without requiring duplicate sets or labor intensive data management practices.

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Monitoring

In addition to continued expansion into smaller and more efficient use of computing and storage resources, FY2012 accomplishments include significant expansion in the use of network-enabled system monitoring and performance analysis tools. Through the deployment of these tools, technical staff receive email alerts and are able to evaluate a historical record of metrics graphically to help diagnose both system and application performance. The extensible community-supported, plug-in architecture allows developers to easily adapt existing monitoring examples to varied applications across different computing architecture without the need to write code from the ground up.

Plans for FY2013 include expansion in the area of real-time applications monitoring, in particular in applications associated with data management. These applications are responsible for providing observational and global model data to continuously running meso-scale forecasting systems and are critical to data assimilation within the forecasting systems.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Mesoscale Climate Downscaling

Computationally Efficient Climate Downscaling

"Climate downscaling" is a practice whereby coarse resolution climate data -- which comes from global atmospheric reanalyses (e.g., the "NCEP/NCAR Reanalysis") or global climate models (GCMs) -- is fed to physically-based or empirically-based techniques to simulate regional- or local-scale climate at much finer spatial and temporal resolution. The need for climate downscaling has grown tremendously in the past decade, as the scientific community endeavors to address an increasing number of weather and climate impacts issues related to agriculture, water resources, human health, etc. These issues are generally local or regional in scope, and therefore require fine-scale climate datasets. Climate downscaling can be either "statistical", "dynamical", or a combination of the two, as described below.

Statistical Downscaling

Statistical downscaling is a technique whereby empirical relationships are established between coarse-resolution atmospheric reanalysis or GCM output and some regionally representative, observationally-based dataset from the recent past (e.g., weather station and balloon measurements, radar reflectivity, satellite radiances, regional reanalyses). These statistical relationships, which implicitly account for biases in the GCM due to inadequate resolution of terrain or deficiencies in the treatment of fine scale physical processes, are then used to downscale both the present-day and future GCM data.

Statistical downscaling has the advantage that it is computationally inexpensive to implement, and therefore generally enables users to downscale many GCMs and obtain a probabilistic estimate of regional climate change outcomes. However, it has some important limitations. Firstly, statistical downscaling assumes stationarity, i.e., that the empirical relationships established for present-day will remain the same in the future. Therefore, the technique neglects the possibility that the empirical relationships could change in the future due to nonlinear climate feedback mechanisms (for example, that previously unobserved weather patterns could emerge in the future). Secondly, statistical downscaling -- although hypothetically applicable to a full suite of variables at multiple atmospheric levels –is generally only applied to a few key fields such as near-surface temperature or rainfall (e.g., Wood et al. 2004). In addition, a statistically downscaled set of atmospheric fields would lack physical consistency. This prohibits scientists from using statistically downscaled data to assess changes in physical process that might occur in response to climate change needed to elucidate the causality of regional climate change, because such studies require multivariate, multilevel, physically-consistent representation of the atmosphere in past and future states. Dynamical downscaling, described below, can overcome some of the problems of statistical downscaling but is expensive to implement.

Dynamical Downscaling

Dynamical climate downscaling is a technique whereby a regional climate model (RCM) --such as the Weather Research and Forecasting Model (WRF) -- is driven at its boundaries by coarse resolution climate data from a GCM, to simulate climate variability at finer spatial and temporal resolution over a region and scale of interest.

Dynamical downscaling with RCMs overcomes the limitations of statistical downscaling; however, it is typically too expensive to dynamically downscale ensembles of GCMs. Running a high-resolution RCM simulation for a 10-30 year period requires substantial computational, storage, and human resources. Therefore, with a few rare exceptions (i.e., NARCCAP), dynamical climate downscaling is generally only performed for one realization; for example, only one of the twenty-or-so available GCMs that support the Intergovernmental Panel on Climate Change(IPCC) assessments is usually downscaled over a specific region for a specific application. This inability to fully characterize the "envelope of uncertainty" in future climate projections severely limits the utility of dynamically-downscaled regional climate projections.

Hybrid Statistical/Dynamical Downscaling

Hybrid statistical/dynamical downscaling techniques developed at the Research Applications Laboratory (RAL) are aimed at overcoming the limitations of both downscaling techniques while exploiting the advantages of both. Hybrid statistical/dynamical downscaling techniques combine dynamical and statistical downscaling, with the objective of

producing high-resolution regional climate projections that are dynamically consistent, account for non-linear climate processes, properly characterize uncertainty, and (importantly) are economical to produce. Hybrid techniques must be elegant and simple to implement, to ensure they are pertinent for a wide variety users and stakeholder-relevant applications. Several hybrid techniques have been developed and/or applied within RAL. These include the Monte Carlo downscaling technique ("MC"; Rife et al. 2012) and the Analog-Ensemble technique ("AnEn"; Delle Monache et al. 2011). RAL scientists work on a variety of applications that employ dynamical, statistical, and hybrid downscaling techniques, some of which are described below.

Climate Downscaling Applications in RAL

Wind Resource Assessment

The demand for electricity generated from renewable sources is growing at a fast pace. From 2005 to 2009, the Department of Energy (DOE) states the annual growth in U.S. wind capacity averaged 40 percent. Since 2006, wind generators account for 36 percent of total electric power industry capacity additions To meet this growth, accurate placement of wind farms is crucial for developers and financiers. However, successful site selection often requires years of research and is often a key obstacle for developing this renewable energy source. To speed the site selection process, the RAL project team has developed a suite of hybrid statistical/dynamical downscaling techniques.

One method, the Monte Carlo ("MC") technique (Rife et al. 2012), employs the Monte Carlo statistical method to generate monthly-stratified samples of daily wind fields that closely match a full 10-30 year distribution of daily wind fields at a potential wind farm site. A small yet representative set of “case days” is thereby selected based on guidance from a large-scale reanalysis. When downscaled, the sample closely approximates the long-term local meteorological record at a location. This computationally efficient downscaling technique can reduce by up to 90% the number of days that must be dynamically downscaled, and decreases uncertainty compared to the standard downscaling technique currently used by industry (Fig. 1).

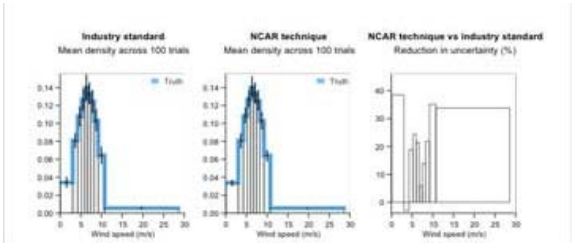

Figure 1. Data histograms for the (left panel) industry standard downscaling method, and (middle panel) those for the new Monte Carlo technique, for the hourly downscaled hub height winds, where the tower measurements at Cabauw, Netherlands serve as a proxy for the downscaling. A 365-day set of case days is used, selected from a full distribution of ~3,300 days. The sample data histograms represent the average outcome of running both algorithms 100 times. The 95% confidence intervals for each decile of the sample distributions are also displayed with thick vertical black lines. The differences between the widths of the confidence intervals for the two approaches (Monte Carlo minus industry standard) are shown in the rightmost panels.

While the MC technique allows one to select a subset of representative GCM days, the resulting dataset is necessarily discontinuous. Another recently developed technique, the analog ensemble (AnEn) technique described by Delle Monache et al. (2011, 2012), can be applied to efficiently extend a short, continuous dynamically downscaled dataset to a multi-decadal downscaled dataset. These increased efficiencies allow for utilization of increased resolution and/or more complex model physics in the dynamical downscaling. Alternatively, or, in addition, the increased efficiency allows for high resolution downscaling of multiple GCM or GCM scenarios to better estimate uncertainty due to model physics assumptions or unknown socio-economic responses.

Figure 2 shows the main steps of the AnEn algorithm. Given 20- and 2-year GCM and RCM estimates, respectively, the portion over which these sets overlap is the training period (which is contiguous in Fig. 3 only for illustration purposes only). The goal is to generate an ensemble of downscaled estimates of key fields for the 18-year GCM period not included in the training set. Given a GCM realization for a given point in space and time (blue square, panel 1), the best GCM matches in the training set are found (four green boxes, panel 2), where the degree of analogy is determined with the metric described in Eq. (6) of Delle Monache et al. 2011. Next (panel 3), the corresponding (in time and space) RCM estimates are selected (four black boxes). This group of four RCM estimates comprises a four-member analog ensemble (AnEn). The procedure is repeated independently for each variable of interest for each point in space and time.

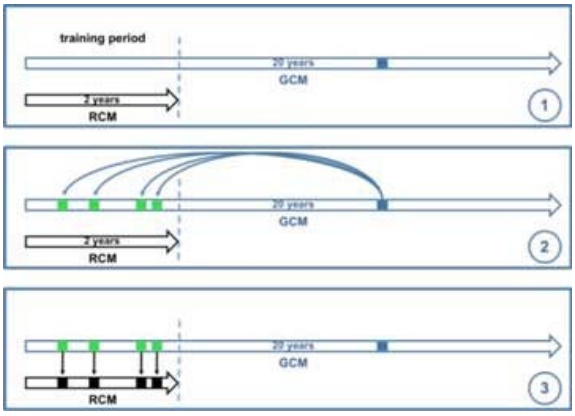

Figure 2. Main steps of the analog ensemble (AnEn) method.

Ensemble methods are widely known to yield more accurate and statistically reliable predictions than any single model realization. An ensemble approach additionally accounts for the uncertainties in the model solution, owing to the

unavoidably imperfect representation of the atmosphere within the model, incomplete specification of the initial and boundary conditions, assumptions included in the governing model physics.

In FY13 both the MC technique and the AnEn method will be throughout tested as part of two projects sponsored by the *National Aeronautics and Space Administration* (*NASA*) and the National Renewable Energy Laboratory (NREL). The results will be documented in technical reports and submitted for peer-reviewed publication.

The National Ground Intelligence Center (NGIC) Project

RAL scientists continue to support the DoD's National Ground Intelligence Center (NGIC) in its mission of assessing the consequences of the transport and dispersion of accidental and intentional releases of hazardous materials into the atmosphere. This is done by providing the agency with access to the RAL-developed GCAT (Global Climate Analysis Toolkit) system. GCAT is a fully automated dynamical downscaling system that allows NGIC scientists to remotely generate a high-resolution 30-year climatography for any region on the Earth. GCAT is based upon Climate Four-Dimensional Data Assimilation (CFDDA) technologies.

The fifth version of the NCAR/Penn State Mesoscale Model (MM5) has been replaced by the Weather Research and Forecasting (WRF) model as the main engine of GCAT. At the same time a fourth domain at 1.1km grid increment was added to the WRF C-FDDA, enabling NGIC to conduct transport and dispersion analyses at very fine scale. The capability to automatically classify WRF output fields into climatological regimes was extended to this fourth domain. The method is based on the Self Organizing Map (SOM) artificial neural network pattern recognition technique. Figure 3 shows the results of a SOM classification, in which 30 months (May 1981-2010) of WRF 1.1km hourly outputs have been used to estimate the main six regimes of the wind flow over the Energetic Materials Research and Testing Center in Socorro, NM. The six regimes that have been identified are given with their frequency of occurrence and their most representative days. Weather data valid for the representative days provides better forcing to NGIC's T&D climatological studies, as they didn't undergo averaging which can destroy important model physical properties (balance etc.) available with dynamical downscaling.

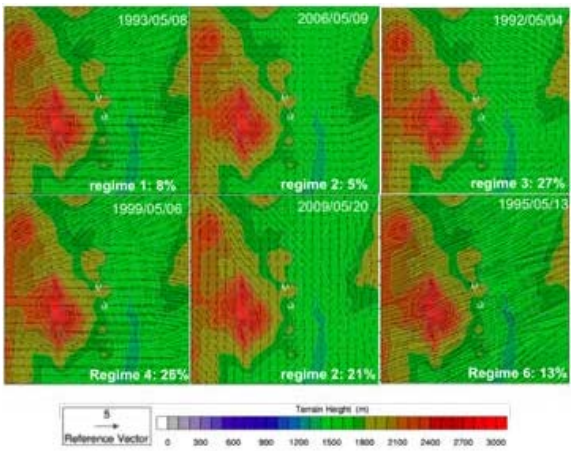

Figure 3. WRF 10-meter wind fine scale (1.1km) wind analysis at 00z for the most representative days of the 6 main regimes found by SOM classification over the Energetic Materials Research and Testing Center in Socorro, NM.

Plans for FY13 include integrating the SOM post-processing technique within the GCAT web interface to enable a user to configure and execute a SOM analysis on a climate reanalysis that suits their particular needs. We will also be extending the SOM analysis techniques to make use of medium range seasonal forecasts (0-9 months) from NOAA's CFS (Climate Forecast System) to account for current deviations from the long-term climate normal.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
  - Numerical Weather
  - Mesoscale Climate Downscaling
  - Atmospheric Transport and Dispersion of Hazardous Materials
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society

Atmospheric Transport and Dispersion of Hazardous Materials Research and Development

Background

Atmospheric releases of hazardous materials, either accidental or intentional, continue to pose a viable threat to both United States citizens and troops abroad and at home. To counter this threat, RAL is actively supporting the research and development of novel techniques and systems, which can be used to more accurately simulate the atmospheric evolution of the released material in both time and space, for planning, real-time response, and forensic purposes.

Atmospheric Transport and Dispersion Meteorological Data Services (Defense Threat Reduction Agency (DTRA) Sponsored)

Since late FY04, RAL has been sponsored by DTRA to develop tailored meteorological decision support applications for the military and domestic emergency–response communities. In particular, these applications are used to enhance the DoD's Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE) hazard prediction toolsets such as the Hazard Prediction and Assessment Capability (HPAC) and more recently the Joint Effects Model (JEM). The objectives of this particular effort are to:

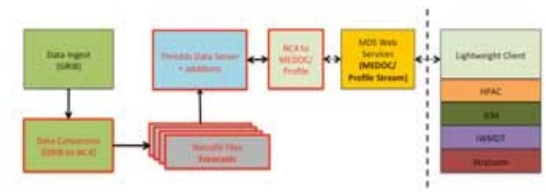


Figure 1: Conceptual *Open MDS* Architectural Schematic

1. Continue to develop and operationally deploy new features to the DTRA Next Generation Meteorological Data Server (NexGen MDS) systems
2. Continue providing weather software enhancements and fixes to DTRA's hazard prediction toolsets, including HPAC and JEM

The first official version (v1.0) of DTRA's NexGen MDS system, developed from the ground up by NCAR/RAL, became operational in late FY06. The purpose of this system is to provide one stop shopping for all meteorological products required by operational Transport and Dispersion (T&D) applications. Special care was taken developing the system interface so that an external software development group could easily integrate this interface into their larger toolset. The first official release of the MDS system Application Programming Interface (API) occurred concurrently with the NexGen MDS release in late FY06. Since that time, the API has successfully been integrated into the HPAC and JEM toolsets and continues to be adopted in other T&D applications.

FY2012 Accomplishments

The project focus for FY2012 was to develop a prototype of an Open MDS and light MDS client. The Open MDS system utilizes open standards for data formats and file communications between the server and client. Further, this system demonstrates equivalent performance and data content to the original MDS. A flow diagram illustrating the open MDS design is shown in figure 1.

A prototype for Open MDS was demonstrated to the government program managers on two occasions, one at NCAR in June and July 2012 at DTRA.

FY2013 Plans

- This program was completed in FY12 and at this time we have not been tasked by DTRA to continue this work via current contracts.

Hazardous Material Source Term Estimation (DTRA Sponsored)

In addition to requiring an accurate description of the atmospheric state (past, present, and future), AT&D modeling systems also require an accurate specification of the material release characteristics (e.g. location, time, quantity). For most real-time response scenarios, the specifics of the material release will be unknown, with only ancillary concentration sensor measurements available. Therefore, algorithms and techniques are being actively developed, within RAL, which can quickly reconstruct or estimate the material release source using these limited sensor observations. In particular, RAL has developed a tailored source term estimation (STE) and hazard refinement system labeled the Variational Iterative Refinement STE Algorithm (VIRSA), which is currently being integrated into the US Department of Defense (DoD) emergency response modeling systems (e.g. the Hazard Prediction and Assessment Capability (HPAC) and the Joint Effects Model (JEM) systems). The current STE system consists of a combination of models that include: the Second order Closure Integrated PUFF model (SCIPUFF), its corresponding STE model, a hybrid Lagrangian-Eulerian Plume Model (LEPM), its formal numerical adjoint, and the software infrastructure necessary to link them. SCIPUFF and its STE model are used to calculate a "first guess" source estimate based on the available chemical plume and meteorological observations. The LEPM and corresponding adjoint are then used to iteratively refine the SCIPUFF based STE and wind estimates using variational data assimilation techniques. Specific accomplishments since the last reporting period and plans for next fiscal year are summarized below.

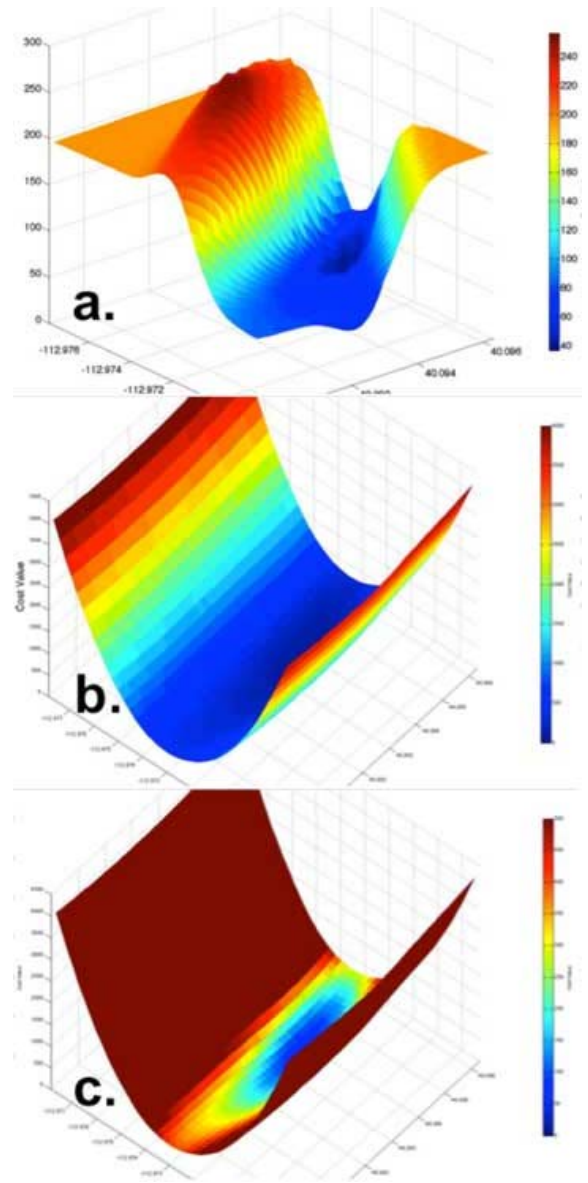


Figure 2: Physics-based method results: (a) is an unbounded cost function solution, (b) shows the bounded solution, and (c) shows the scaled solution.

FY2012 Accomplishments

- The VIRSA capability has been delivered to the Java based JEM system, managed by the Joint Programs Management Information Systems (JPM IS), in quarter 3 (Q3) of fiscal year 2012 (FY2012). The JEM system is very focused on encapsulating CBRN models and capabilities as independent modules that communicate to one another via a Common chemical/biological/radiological/nuclear (CBRN) Model Interface (CCMI). To facilitate the testing and development of these modules, the CCMI Application Test Tool (CATT) was designed with the ability to specify input and output wirings between dependent modules. The VIRSA model has been implemented into CATT using CCMI for input and output communication. To support the VIRSA implementation, several changes where made to the CCMI system to properly support source term estimation and CBRN hazard observations, both novel modules in JEM. Future versions of CATT will include the VIRSA capability module in addition to various NCAR implemented support modules created to feed data to the VIRSA.
- Developed a comprehensive and automated testing framework, which tests the system at multiple testing levels, against the various field trial datasets.
- The VIRSA system attempts to minimize a cost function to ascertain the AT&D source variables and meteorological variables of interest. This system provides the most computationally efficient solution, however, it may not provide the most accurate solution if the cost surface is complex. To combat this issue, uncertainty information was incorporated into the cost function via a regularization term. The addition of this term can transform a cost surface from one characterized by several peaks and valleys to one that is globally convex allowing VERSA to ascertain the appropriate solution. Physics based and ensemble based techniques were developed to incorporate this uncertainty information. Figure 2 illustrates how incorporating this uncertainty information can transform the cost surface using a physics based method.
- The VIRSA algorithm was briefed at the International Workshop on Methods for Estimating the Atmospheric Radiation Release from the Fukushima Dai-ichi Nuclear Power Plant. The National Science Foundation (NSF)

sponsored workshop that was led by NCAR brought together an international group of researchers to discuss how current state-of-the-science STE methods could be extended to address challenges of estimating the radiation release from the nuclear release incident.

FY2013 Plans

- Continue to investigate methodologies, which better characterize the adjoint cost function, when assimilating sensor data with thresholds
- Adapt STE algorithm to support longer range dispersion scenarios
- Continue to investigate uncertainty incorporation techniques to simplify the cost function surface
- Deliver ncremental advances in VIRSA to JEM

Virtual Atmospheric Dispersion Field Testing (DTRA Sponsored)

Originally developed to adequately test and evaluate the performance of these evolving STE systems, RAL developed the Virtual Threat Response Emulation and Analysis Testbed (VTHREAT), which enables simulation of physically realistic hazardous release scenarios, placement of material and meteorological sensors, and extraction of the resulting synthetic sensor readings. These synthetic observations can then be used to evaluate these STE systems' ability to accurately reconstruct the hazardous material release source specifications, under various atmospheric regimes and against various material release scenarios. VTHREAT is now applied to other CBRNE problems including the testing and evaluation of sensing technologies, as well as providing accurate representations of toxic load. The VTHREAT system uses high-fidelity atmospheric and transport and dispersion (T&D) models to generate physically realistic "single realization" CB material release data sets. The "single realization" data sets are then converted to observations through models that emulate the characteristics of the sensing platform. The sensor models typically include detailed information on sensor performance characteristics and can provide a mechanism to utilize information from development testing (DT) information during operational testing (OT). Sensor output is produced with the format and fidelity of the sensor, enabling the evaluation of sensor platforms and corresponding modeling and information systems relative to the virtual "truth" data set from which they were derived. VTHREAT has undergone a preliminary evaluation characterizing its ability to produce realistic virtual dispersion data sets, and has been used to support field programs and test future material sensor applications. Also, VTHREAT now includes other features developed to provide insight on other CBRNE problems. Specific accomplishments since the last reporting period and plans for next fiscal year are summarized below.

FY2012 Accomplishments

- Continued transition of data generation from EULAG (Eulerian/semi-Lagrangian fluid solver) to WRF (Weather Research and Forecasting) LES (Large Eddy Simulation
- Continued WRF LES validation against traditional atmospheric and dispersion field measurements
- Updated WRF to include an array of source release types such as continuous sources, instantaneous sources, mixed continuous and instantaneous sources, line sources, and moving sources. Also included is the ability to control the release duration
- Incorporated sensing technologies into the VTHREAT tool, which include:
  - Cup and Vane Anemometer
  - Fourier Transform Infrared Spectroscopy
  - Point Concentration Sensors
  - Path Integrated Concentration
  - Biological Agent Warning Sensor
  - Aerosol LIDAR
- Incorporated an indoor/outdoor concentration model for toxic load calculations
- Developed a prototype for the Next-Generation VTHREAT that adopts the OSGI architecture and will allow for modularity, easy 3rd party sensor/data plugins, custom deployments and easy updates

FY2013 Plans

- Continue WRF LES validation work
- Continue research into adding an aerosol background Interferrent capability.
- Incorporate boundary effects in WRF LES modeling using the Immersed Boundary Method
- Incorporate more sensing technologies into VTHREAT such as:

- The Doppler LIDAR
- Differential Mobility Spectrometry

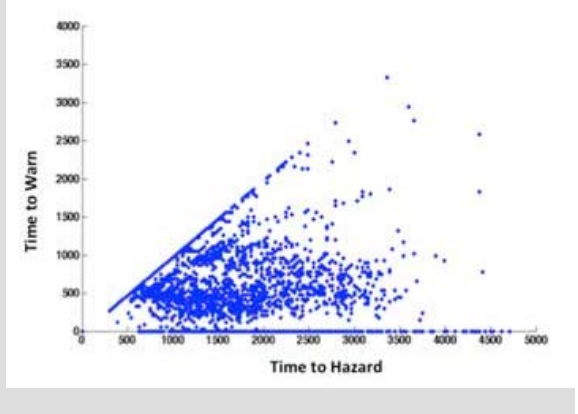
- Continue development of the Next-Generation VTHREAT software architecture
- Allow for offline dispersion calculations using a two-particle Lagrangian Particle Model

Sensor Requirements Analysis (DTRA Sponsored)

Beginning in FY2011 and coming to completion in FY2012, NCAR and The Massachusetts Institute of

Technology Lincoln Laboratory (MITLL) were funded to assess the technology trade-space for standoff chemical and biological sensors. The NCAR portion of this work utilized the VTHREAT tool described above to quantitatively determine the effectiveness of standoff technologies. Determining technology effectiveness required NCAR to model a set of environmental, operational and threat delivery scenarios that span the chemical and biological agent threat space. An ensemble of high-resolution transport and dispersion realizations based off of these scenarios were developed within the WRF LES framework. The transport and dispersion data is then passed through the sensing technology algorithms within VTHREAT, to determine the effectiveness of the sensing technology. The overall goal of this project is to investigate the trade space in existing standoff sensing technologies, and to provide direction on the sensor features that future standoff technologies should possess.

Figure 3:



FY2012 Accomplishments

- Developed a novel analysis methodology to determine the utility of standoff sensing technologies. This analysis methodology poses sensor performance as its ability to provide sufficient warning time to enact a certain response. Utilizing time as the independent variable allowed us to collapse results for all environmental scenarios into a single scatter plot, from which, one can ascertain the effectiveness of the standoff technology. Along with the specified warning time, the time to hazard (TTH i.e. the time elapsed from when the contaminant is released until it reaches the area of concern) and the time to warn (TTW i.e. the time elapsed from when the contaminant is first detected until it reaches the area of concern) are important for the analysis. An illustration of the scatter plot is shown in figure 3, which includes TTH on the abscissa and TTW on the ordinate.
- Incorporated more realism into a few of the sensing technologies used in VTHREAT
- Completed research

FY2013 Plans

- The remaining task for this project is to consolidate the research findings from both NCAR and MITLL into a unified report

Urban Transport and Dispersion

Beginning in FY2007, NCAR investigated the sensitivity of urban transport and dispersion to wind direction for colonial (Washington D.C) and modern (Denver CO) cities. The dispersion model used for this work is the Quick Urban Industrial Complex (QUIC), a computationally efficient, building-aware, dispersion modeling system developed at Los Alamos National Laboratory. It was shown that wind direction sensitivity varies with different building and road configurations and networks. The results of this effort were published in *Atmospheric Environment* in FY2012.

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Log in

Research Applications Laboratory | RAL
2012 ANNUAL REPORT

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
  - Mesoscale Modeling Systems
  - Advanced Verification Techniques and Tools
  - Data Assimilation
  - Tropical Cyclone
- Hydrometeorological Applications
- Climate, Weather and Society

Numerical Systems Testing and Evaluation

Maintain and expand a central collaborative function within NCAR and a distributive network of collaborators for developing, testing, and validating numerical forecast systems important to operational decision makers and the international research community.

- **Mesoscale Modeling Systems**
- **Advanced Verification Techniques and Tools**
- **Data Assimilation**
- **Tropical Cyclone**

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
  - Mesoscale Modeling Systems
  - Advanced Verification Techniques and Tools
  - Data Assimilation
  - Tropical Cyclone
- Hydrometeorological Applications
- Climate, Weather and Society

Mesoscale Modeling Systems

Background

The Developmental Testbed Center (DTC; **http://www.dtcenter.org/**) – a distributed facility with components in the Joint Numerical Testbed (JNT) (www.ral.ucar.edu/jnt/) at NCAR's Research Applications Laboratory (RAL) and the Global Systems Division (GSD) of NOAA's Earth System Research Laboratory (ESRL) – facilitates the transfer of research results into operations and provides the research community with an easily accessible state-of-the-art Numerical Weather Prediction (NWP) system for research. At this time, the DTC's main focus is on mesoscale forecasting systems, with a goal of accelerating the rate at which new mesoscale modeling technology is infused into operational weather forecasting. The DTC meets its goals by maintaining and supporting community codes that represent the latest NWP technology, performing extensive testing and evaluation of new NWP technology, maintaining a state-of-the-art verification package, and connecting the NWP research and operational communities through its visitor program.

FY2012 Accomplishments

Community Codes

Community code is a free and shared resource with distributed development and centralized support. The DTC's community code efforts are collaborative activities with developers at NCEP's Environmental Model Center (EMC), NCAR's Mesoscale and Microscale Meteorology (MMM) Division, NOAA/ESRL/GSD, NOAA's Geophysical Fluid Dynamics Laboratory and the University of Rhode Island (URI). During 2012, the DTC supported the following software packages to the community:

- Weather Research and Forecasting (WRF; http://wrf-model.org/index.php) – NWP model + pre- and post-processors
- Model Evaluation Tools (MET; http://www.dtcenter.org/met/users/) – Verification package including standard verification techniques, as well as more advanced techniques
- Gridpoint Statistical Interpolation (GSI; http://www.dtcenter.org/com-GSI/users/) – Data Assimilation System
- WRF for Hurricanes (http://www.dtcenter.org/HurrWRF/users/index.php) – Coupled model capabilities (atmosphere and ocean) in support of tropical cyclone forecasting

Periodic public releases of each package include the latest developments of new capabilities and techniques. Prior to each official release to the user community, the DTC ensures the integrity of all community code software components through a broad range of testing. The DTC also strives for system evolution, in particular through increased interoperability of existing system components, as well as adding new capabilities or techniques. In addition, the DTC provides user support for these packages in the form of Users' Guides, webpages, email helpdesks, and online and on–site tutorials.

Testing and Evaluation

The DTC provides a trusted facility that developers and the operational community can rely on for unbiased assessments of the operational prediction systems and potential new additions to those systems. Testing and evaluation undertaken by the developers of new NWP techniques from the research community are generally focused on case studies. Extensive testing and evaluation must be performed to ensure that these new techniques are indeed ready for operational consideration. Testing and evaluation by the DTC focuses on either extended retrospective time periods or real–time forecast

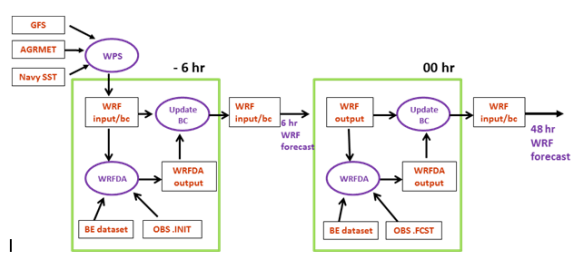

Figure 1: Schematic of workflow process for a functionally

similar environment to operations including warm start initialization with data assimilation. BC=Boundary Conditions; BE=Background Error.

experiments. These forecasts can either be generated by the DTC or provided by external modeling groups. The DTC's evaluations include use of standard verification techniques, as well as new verification techniques in some cases. All verification statistics include a statistical significance (SS) and practical significance (PS) assessment when appropriate.

The Weather Research and Forecasting (WRF) model is a mesoscale NWP system utilized in both research and operational forecasting applications. WRF can be viewed as a state-of-the-art model with many options; it is highly configurable and suitable for a broad range of weather applications. Due to the flexibility offered by the model, it is necessary to rigorously test select configurations and evaluate the performance for specific applications. During 2012, the DTC performed evaluations for a variety of testing activities including model inter-comparisons and stand-alone Reference Configurations. This year, a functionally similar environment to Air Force Weather Agency operations was also established at the DTC and is highlighted in Figure 1. Results associated with model inter-comparisons can be accessed on the DTC website at **http://www.dtcenter.org/eval/** and RC results can be found at **http://www.dtcenter.org/config**. Information distributed on each website includes a description of the configuration and the extensive testing that was performed. An executive summary of the results is provided, along with the full set of verification plots, which include additional spatial and temporal breakdowns.

Testing Protocol and Mesoscale Model Evaluation Testbed

A wide range of NWP science innovations are under development in the research community. With this extensive number of new techniques, a testing protocol detailing the procedures necessary to advance new innovations through the research to operations (R2O) process is imperative. Ultimately, the effort should be streamlined to make it not only efficient, but also effective, providing a path to potential operational use. A testing protocol document detailing a three stage process of testing conducted by the research community, DTC and, ultimately, operational centers was established during 2012.

Associated with this testing process, the DTC also established the Mesoscale Model Evaluation Testbed (MMET; **http://www.dtcenter.org/eval/mmet**). MMET provides the opportunity for each user to conduct their own T&E of a new technique; consistent use of the data provided by MMET allows for direct comparison between researchers' results. To-date, nine cases have been populated and are being distributed to the community-at-large via RAMADDA, a **R**epository for **A**rchiving, **M**anaging and **A**ccessing **D**iverse **DA**ta, developed and supported by Unidata (**http://www.unidata.ucar.edu/software/ramadda**). RAMADDA provides a web interface to access the MMET data sets, which include a variety of initialization and observation data sets that have been gathered and packaged for distribution. Baselines for select operational configurations established by the DTC utilizing the MMET data sets are also available through RAMADDA. These baselines will assist the research community in demonstrating improved forecast performance with new innovations.

Hydrometeorological Testbed

From December 2011 to April 2012, JNT staff contributed to a DTC evaluation of an ensemble modeling system produced by NOAA/ESRL/GSD as part of the HydroMeteorology Testbed HMT-West. For comparison, several operational baseline models from NOAA/Environmental Modeling Center (EMC) including the Global Forecast System (GFS), the North American Mesoscale Model (NAM), the Short Range Ensemble Forecast System (SREF), and the Air Force Weather Agency (AFWA) Mesoscale Ensemble Prediction System (MEPS). This is the third year the DTC has been involved in this evaluation, with a focus on Quantitative Precipitation Forecasts (QPF) during extreme rainfall episodes in northern California. To better understand the dependence of performance on aspects of ensemble configuration, especially the impact of microphysics parameterization, additional critical fields were also evaluated to assess the models' ability to capture the synoptic and mesoscale forcing of these cool season events. Variables evaluated include: temperature, pressure, height, specific humidity, winds, and precipitable water. Analysis of results continues for this evaluation.

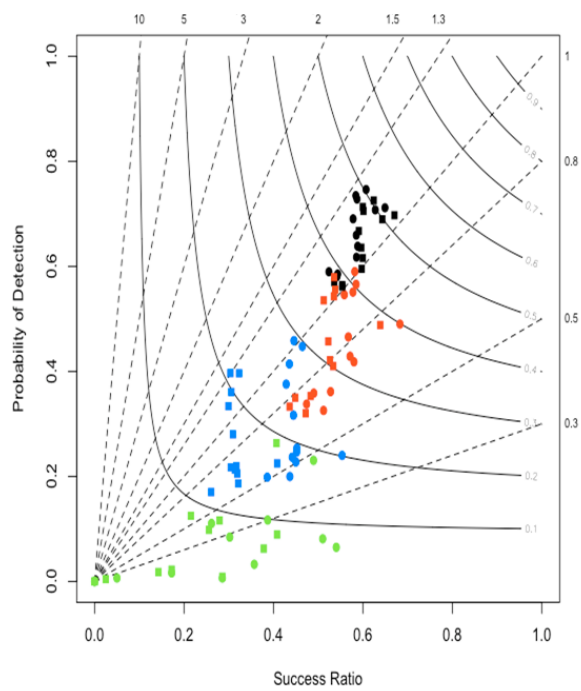

Figure 2: Performance diagram showing performance as a function of observation type, where Stage IV results are shown as dots and results for the CCPA precipitation estimates are shown as rectangles. Different colors represent various

An assessment was also conducted to assess the impacts of observation dataset choices on evaluation metrics for the HMT evaluation. Evaluation of model predictions using the relatively new NCEP/EMC-based Climatology-Calibrated Precipitation Analysis (CCPA)

precipitation thresholds, with Black = 0.1", Red = 0.5", Blue = 1", and Green = 2". Curved lines represent constant values of Critical Success Index, dashed lines represent frequency bias. Differences in performance are clearly seen as a function of the observations used, especially for larger threshold values. (Note: Success Ratio = 1 – False Alarm Ratio).

and the commonly used Stage IV Quantitative Precipitation Estimates (QPE) was undertaken to determine whether changing to the CCPA QPE would result in similar statistics and hence not lead to inconsistent results. Statistics related to model performance were aggregated over the 2010-2011 HMT-West season. The results of the analysis indicated enough difference between the two models to warrant continuing to use the Stage IV dataset as in previous years. Figure 2 shows an example of a comparison of verification statistics based on these two QPE systems, which illustrates the impacts of the choice of QPE system on the forecast verification results.

The DTC also provided comparisons among the participating cloud-permitting ensemble systems, such as the GSD HMT-West Ensemble (2 domains at 9km and 3km), and the AFWA MEPS system (4km), and the operational mesoscale ensemble, SREF (32-35 km). For extreme precipitation events, the cloud permitting ensembles appeared to have greater skill in both QPF and the probability of QPF exceeding thresholds of 0.5, 1.0, and 2.0 inches over 6 hours. Additional comparisons between the HMT-West ensemble, initialized using different members of the GFS Ensemble, and AFWA MEPS, initialized using four different global models, indicate that there may not be any significant benefit to using perturbations of multiple models for the initial boundary conditions. Journal articles summarizing the research findings are in progress.

FY2013 Plans

In the coming year, the DTC will continue to support various community codes, including the WRF model and post–processor, coupled model capabilities, MET, and GSI. Collaborations with the NOAA Hydrometeorological testbed will continue. The DTC will also help organize and support tutorials on the community codes that it supports, related to mesoscale models, data assimilation, hurricanes, and forecast verification.

While the DTC will continue WRF-based T&E activities for the foreseeable future in context of RCs, WRF for hurricanes, and various ensemble configurations, it has become necessary to broaden the scope of internal T&E activities to include new software frameworks (e.g., the NOAA Environmental Modeling System, NEMS) utilized by the relevant operational centers (e.g., NOAA). This effort is vital for the DTC to continue to serve as a bridge between research and operations and work is on-going on this front.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
  - Mesoscale Modeling Systems
  - Advanced Verification Techniques and Tools
  - Data Assimilation
  - Tropical Cyclone
- Hydrometeorological Applications
- Climate, Weather and Society

Advanced Verification Techniques and Tools

Background

Forecast verification and evaluation activities typically are based on relatively simple metrics that measure the meteorological performance of forecasts and forecasting systems. Metrics such as the Probability of Detection, Root Mean Squared Error, and Equitable Threat Score provide information that is useful for monitoring changes in performance of single aspects of forecast performance with time. However, they generally do not provide information that can be used to improve forecasts, or that can be helpful for making decisions. Moreover, it is possible for high quality forecasts– such as high-resolution forecasts – to have very poor scores when evaluated using these standard metrics, while poorer quality forecasts may score higher. In response to these limitations, the RAL Verification Group develops improved verification approaches and tools that provide more meaningful and relevant information about forecast performance. The focus of this effort is on diagnostic, statistically valid approaches, including feature–based evaluation of precipitation and convective forecasts, distribution–based approaches that can provide more meaningful information (for forecast developers as well as forecast users) about forecast performance. In addition, the RAL Verification Group develops forecast evaluation tools that are available for use by members of the operational, model development, and research communities. Development and dissemination of new forecast verification approaches requires research and application in several areas, including statistical methods, exploratory data analysis, statistical inference, pattern recognition, and evaluation of user needs.

FY2012 Accomplishments

Spatial verification methods and the spatial method inter–comparison project

The initial forecast verification methods intercomparison project focused on comparing the capabilities of newly developed spatial forecast verification methods.; The project was completed in 2011 and resulted in a special collection of articles in the journal Weather and Forecasting (see WEB SITE).; A second intercomparison project is being developed in partnership with international collaborators; ICP2 will focus on wind and precipitation forecasts in complex terrain. Initial ICP2 planning took place at the WMO forecast verification workshop in December 2012. The ICP2 will be implemented during 2013.

To simplify use of many of the spatial verification methods for the ICP2 and other efforts, the RAL verification group has developed a spatial verification methods package in the R programming language (SpatialVx; **www.r-project.org**). The package is still under development and currently includes features-based verification, neighborhood methods, kernel smoothers, and many other statistical and image-based verification approaches. Figure 1 shows diagnostic graphics from the spatial prediction comparison test for simulated data. This test determines whether two spatial predictions differ on average across the entire field, accounting for the spatial correlation of the fields.

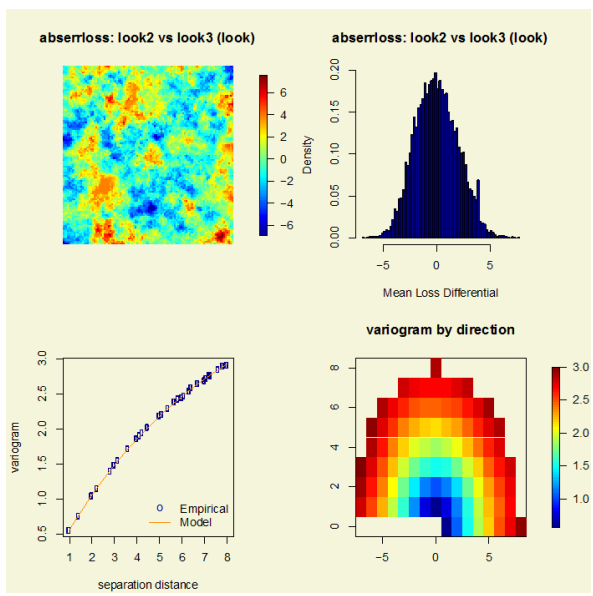

Figure 1: Diagnostic plots used for doing the spatial prediction comparison test. The upper left plot is a graph of abs(y_1 - x) - abs(y_2 - x), the difference in the prediction errors between two competing forecasts. The upper right plot is the histogram for the graph in the upper left. ;The lower left panel is the empirical variogram (circles ignoring direction, dots including direction) along with an exponential fitted variogram (line) and

The extension of object–based and other spatial

the lower right panel plot is a variogram by direction. These examples used randomly generated data from a normal distribution.

verification approaches is in progress and will continue into the next fiscal year. Fields other than precipitation have been examined with promising results. Atmospheric rivers, radar reflectivity and echo top, and ensembles were evaluated with MODE during 2012 collaborations with NOAA testbeds, and each seems to lend itself well to evaluation with spatial methods. For atmospheric rivers, the domain was varied to examine different qualities of the forecast. ;For example, a small coastal domain makes it possible to examine the timing of the landfall of the atmospheric river, while a much larger domain facilitates analysis of size, intensity, and location.

The Method for Object-based Diagnostic Evaluation (MODE) tool has been extended to include the time dimension and this extended version of MODE will be implemented in a future release of the Model Evaluation Tools (MET).;; Another spatial verification method – image warping – is also being extended by E. Gilleland and others to include the time dimension; an initial method has been developed and has been documented in an NCAR Technical Report (available at http://opensky.library.ucar.edu/collections/TECH-NOTE-000-000-000-850).

Model Evaluation Tools (MET)

The Model Evaluation Tools (MET) (http://www.dtcenter.org/met/users/) is a freely available software package for forecast evaluation that was developed and is supported by RAL/JNT staff.; MET Version 4.0 was released to the community in June 2012 and Version 4.1 is expected to be released during winter 2013. Currently MET has more than 1800 registered users, with about half of them from the university community.; In preparation for the next release, development has focused on new data formats and additional methods for ensemble forecasts, new data formats, and cloud verification approaches. The METViewer system, a capability for storing MET verification statistics in a database and analyzing and displaying the results, has been expanded to include additional tools for ensemble spread-skill analyses, reliability diagrams, and receiver operating characteristic curves. METViewer plots are highly configurable, based on MET or other verification results contained in a database.; METViewer is used by the DTC for testing and evaluation activities, and has also been installed at the National Centers for Environmental Prediction.

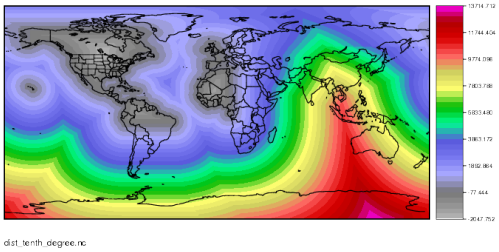

Figure 2: Distance to (nearest) land from all points on the globe. This information is used to stratify tropical cyclone locations during verification.

A major effort this year has focused on development and implementation of new tropical cyclone (TC) forecast evaluation tools. The MET TC package, to be released with MET4.1 in 2013, has been developed, and testing is underway. This package replicates current verification capabilities of the National Hurricane Center, but in an easily extensible, widely available, and supported package. ;Basic track and intensity verification statistics are produced.; In addition, the package is designed to give the user an extensive variety of filtering options. For example, Figure 2 shows the distance to land from all locations across the globe. This information can be used to stratify cyclone tracks since researchers often wish to analyze landfalling TCs separately from those over water. In the future, more advanced verification methods for tropical cyclones will be included in this package.;

Use of A-train satellites for verification

This investigation makes use of unique NASA observations of cloud properties from "A-Train" instruments to improve numerical weather prediction (NWP) products, with the goal of enhancing decision making for aviation applications. The key observations being used include products from the CloudSat Cloud Profiling Radar (CPR), along with CALIPSO's active lidar and Aqua's MODIS imaging spectroradiometer.; The project supports activities that will lead to the development of new tools to incorporate satellite products into MET.; The addition of satellite observed clouds will provide enhanced testing and evaluation capabilities for NWP forecasts of clouds and cloud attributes (cloud areas, cloud top height, cloud icing regions, etc).

This research is in collaboration with scientists and engineers at the Cooperative Institute for Research in

the Atmosphere (CIRA) at Colorado State University. The research team is developing and adapting statistical techniques to make full use of the satellite observations for evaluations of forecast cloud products and features that will help identify why particular algorithms or numerical parameterizations of clouds are sometimes deficient. At the end of the four-year project, the satellite enhanced MET package will include satellite-based evaluation tools that will enhance NWP development and aviation-specific predictions.

During FY12, the project focused on developing and testing methodologies for comparison of model forecasts and satellite observations. The A-Train satellite observations (with a focus on CloudSat products) provide very useful information for examining the vertical structure of clouds, and for comparing forecast and observed cloud structures.; Figure 3 shows a comparison of MODE objects created to compare satellite-based reflectivity measurements to reflectivity forecasts from the Rapid Update Cycle (RUC) model.; Identification of objects in this way allows comparison of particular features associated with the forecasts and observations, such as location, timing, and intensity. ;A similar approach is being used to compare the structure of hurricane forecasts to structures observed by the CloudSat radar.; An example of a CloudSat evaluation with the Advanced Hurricane WRF (AHW) is shown in Figure 4.;

The satellite evaluation tools are being enhanced to include the evaluation of aviation relevant cloud properties. ;In FY 2013, these tools will be evaluated during winter- and summer time demonstration experiments at NOAA's Aviation Weather Center (AWC).

FY2013 Plans

The MET releases in 2013 will include the new TC verification tool package, new data formats, and enhanced cloud and ensemble verification methods. An initial capability to evaluate land surface model output will also implemented in MET. The capability to handle additional satellite observations will also be included in a future MET release. Further research on appropriate methods for evaluating forecasts through time will be conducted, and included in a later MET software release if appropriate.; Further, the object time tracking extension to MODE will be made operational and included in the next release of MET.

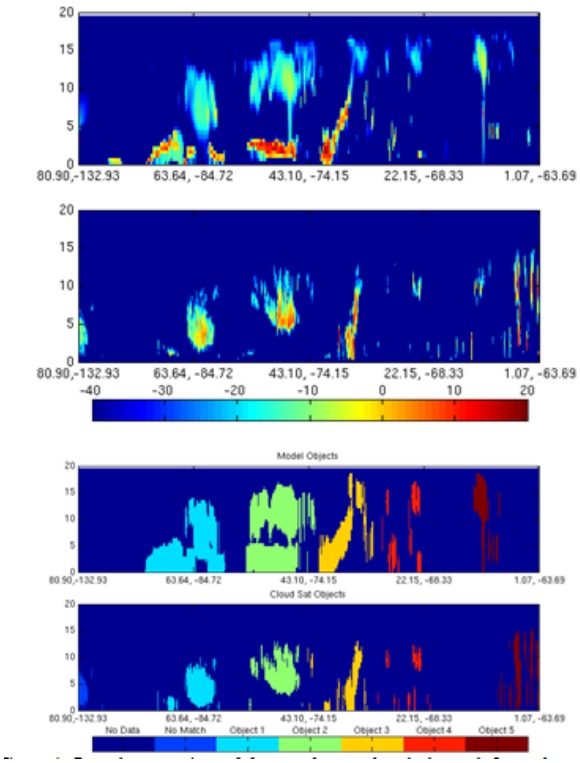

Figure 3: Example comparison of forecast (top row) and observed (bottom) reflectivity fields using the Method for Object-based Diagnostic Evaluation (MODE).

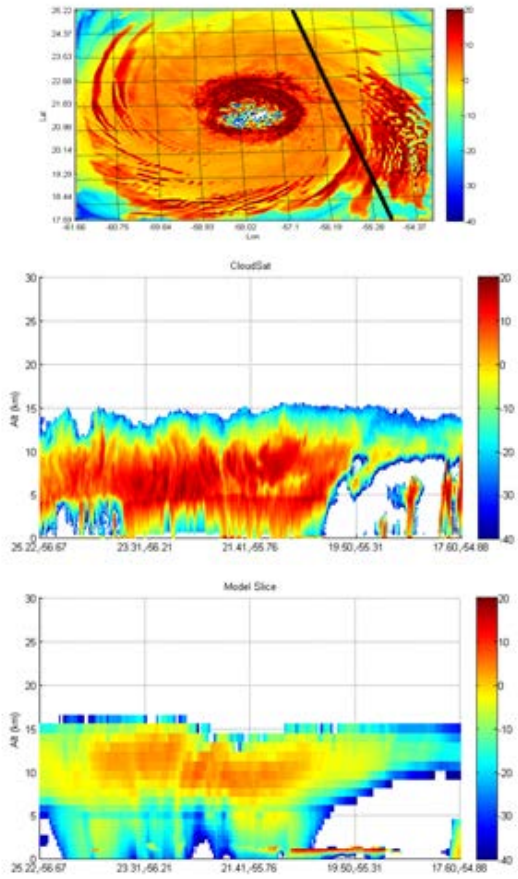

Figure 4: Example of a hurricane overpass (top panel) with vertical observation of radar reflectivity from CloudSat (middle panel) and corresponding model forecast of reflectivity along

the CloudSat track (bottom panel).

Experimental use of MODE on fields other than precipitation will continue. The METViewer software will undergo a GUI redesign, to increase usability and user friendliness.

Implementation of ICP2 will be a focus for the next year, in collaboration with international members of the verification community. Specific cases will be selected, related to wind and precipitation forecasts in complex terrain.; Participants will be asked to apply their methods to the identified test cases as well as some newly-defined artificial and perturbed cases.; The image warping and MODE tools will be included in this project.

The satellite work for 2013 will continue to focus on diagnostic forecast evaluation algorithms, techniques, and methodologies that will utilize the NASA observations, which will be integrated into the MET framework. An interactive tool, designed to help identify appropriate MODE parameter settings for the cloud comparisons, will be demonstrated and evaluated at the AWC during a winter experiment. In addition, aviation applications will be identified through interactions with the operational aviation weather forecasting community, and a scientific publication will be prepared. Focused tests will be conducted to optimize the new methods to provide meaningful results for forecast evaluation processes and decision support applications.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
  - Mesoscale Modeling Systems
  - Advanced Verification Techniques and Tools
  - Data Assimilation
  - Tropical Cyclone
- Hydrometeorological Applications
- Climate, Weather and Society

Data Assimilation

Background

The goals of the Data Assimilation Team (DAT) are to provide (a) a pathway between data assimilation research and operational capabilities; (b) a framework for distributed development of new capabilities and advances in data assimilation; (c) an environment for the objective testing and evaluation of state-of-the-art data assimilation techniques; (d) a rational basis for enhancement of data assimilation techniques and systems; and, (e) eventually, numerical weather forecast systems for operational centers and the research community. Much of this works is done under the auspices of the **Developmental Testbed Center** (DTC).

FY2012 Accomplishments

Community Support

The DAT currently maintains and supports a version of the Gridpoint Statistical Interpolation (GSI) data assimilation (DA) system with community features (http://www.dtcenter.org/com-GSI/users/index.php). The GSI system is the operational data assimilation system for various forecasting and analysis systems and applications, including the North American Mesoscale (NAM) Forecast System, the Global Forecast System (GFS), the Real-time Mesoscale Analysis (RTMA) System, and the Hurricane Weather Research and Forecasting Model (HWRF) at NOAA/NCEP, the Goddard GMAO Global Forecast System at NASA, and the RApid Refresh (RAP) System at NOAA. The DAT is working with these operational and research centers to coordinate the distributed development via a GSI Review Committee hosted by the DTC. The GSI Review Committee is the core of the GSI collaborative effort responsible for coordinating and code review of the GSI code.

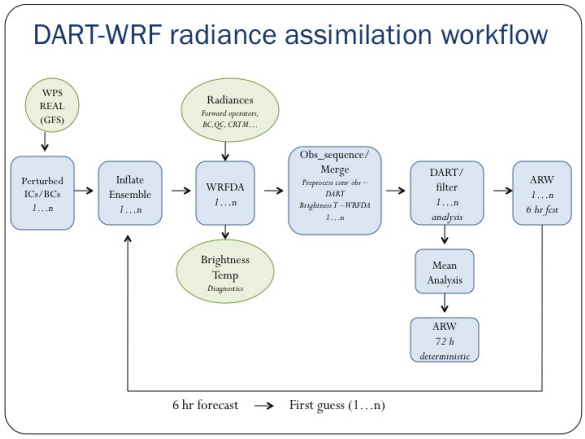

Figure 1: DART-WRF radiance assimilation workflow diagram.

The DAT maintains and updates the Boulder community GSI repository, synced with the NCEP GSI developmental code, performs multiple platform tests, improves the code portability and develops utilities and tools for GSI applications and diagnostics. Working with the GSI developers, the DTC has provided user support to the research community since 2009, including annual public code and documentation releases, annual community GSI tutorials, online tutorials and documentation, and answering users' questions via the GSI helpesk (gsi_help@ucar.edu). Currently, the testing and support of this GSI system by the DAT focuses on limited area numerical weather prediction (NWP) applications coupled with the Weather Research and Forecasting (WRF) Model. More than 600 GSI users have registered through the GSI website (http://www.dtcenter.org/com-GSI/users/). The DTC released version 3.1 of the GSI code in July 2012 and hosted the Third Community GSI Tutorial in August 2012.

Testing and Evaluation

Data assimilation testing and evaluation this year focused on exploring new data assimilation techniques/systems, including the NCAR Ensemble Kalman Filter DA system developed by the NCAR/Data Assimilation Research Testbed (DART) and the NCEP GSI based hybrid ensemble-variational

DA system primarily developed by the NOAA and NCEP.

The goal for the DART ensemble DA system test was to determine if there is any added benefit from assimilating Microwave Humidity Sounder (MHS) radiance data in addition to the Advanced Microwave Sounding Unit-A (AMSU-A) radiance and conventional observation data. The DTC added the capability to the DART system using the Community Radiative Transfer Model (CRTM) built into the WRF Data Assimilation (WRFDA) system as the radiance forward operator for computing radiance prior ensembles. The vertical weighting function for the MHS channels defined as , where Tr is transmittance, was calculated in WRFDA using layer optical depth output from the CRTM. The DART/WRFDA workflow is shown in figure 1.

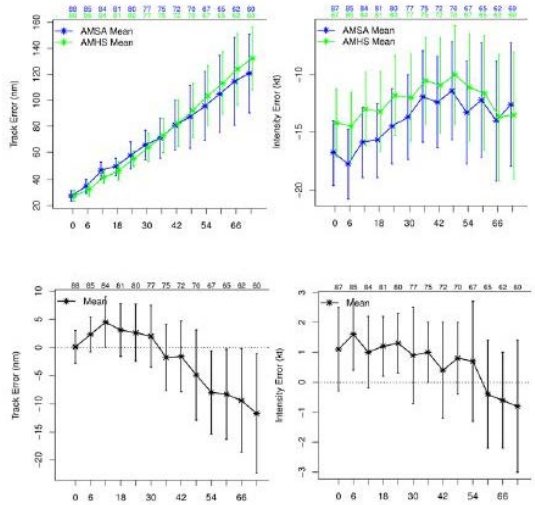

Figure 2: Absolute tropical cyclone track (left) and Intensity (right) error for AMSA (blue) and AMHS (green).

Grid-based verification aggregated over the full testing month was performed against the ERA-interim re-analysis as well as sounding observations. Basic parameters such as temperature, u and v wind components, and humidity were studied at various levels and forecast times. Two experiments highlighted in this report are outlined in Table 1. The results indicated statistically significant (SS) differences (at the 95% confidence level) favoring the AMSA run for temperature and wind fields, but SS differences favoring AMHS for moisture fields. Further investigation of the AMHS and AMSA differences in the analysis for the full month indicated that the AMHS run produced drier air relative to the AMSA run in the South Atlantic region. This drier air was closer to the conditions in the ERA-interim re-analysis than in the AMSA. Aggregations over the five tropical storms in the domain show SS differences favoring AMHS for intensity out to one day. Conclusions based on these results indicate that addition of the MHS data does not improve all parameters across the board, but it may have benefit for applications where moisture is particularly important.

Table 3.1a: Description of assimilated data in experiments

Experiment Name	
AMSA	Conventional observations + AMSU-A (NOAA-18/METOP-2) channels 5-7
AMHS	Conventional observations + AMSU-A (NOAA-18/METOP-2) channels 5-7 + MHS (NOAA 18/METOP -2) channels 3-4

Testing and evaluation of the GSI-hybrid system, which are still in progress, focuses on testing the NCEP regional GSI-hybrid system for tropical storm predictions, using the NCEP Global Forecast System ensembles to generate the initial ensemble perturbations. The background error covariances for the hybrid system are described by the static error variances from the traditional three dimensional variational GSI system plus the flow-depended error covariances computed using the ensembles. The impact of using the hybrid error covariances in weather forecasting systems, especially for forecasts for tropical storms, is being investigated. This system is intended to be the next generation DA system as part of the NCEP Hurricane WRF (HWRF) System, if the forecast impact is proved to be positive.

FY2013 Plans

The DAT will continue to work with other partners in providing community support for the GSI data assimilation systems and techniques. The DAT will also continue to conduct T&E activities to assess the latest development of the data assimilation systems and techniques and evaluate observation impacts on short-range weather forecasts.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
  - Mesoscale Modeling Systems
  - Advanced Verification Techniques and Tools
  - Data Assimilation
  - Tropical Cyclone
- Hydrometeorological Applications
- Climate, Weather and Society

Tropical Cyclone

Background

The focus of the JNT's Tropical Cyclone Modeling Team (TCMT) is the evaluation of experimental models for tropical cyclone forecasting (**http://www.ral.ucar.edu/jnt/tcmt/**). The primary sponsor of this work is NOAA's Hurricane Forecast Improvement Project (HFIP; **http://www.hfip.org/**) which has a number of goals, including improving the accuracy and reliability of hurricane forecasts; extending the lead time for hurricane forecasts with increased certainty; and increasing confidence in hurricane forecasts. Achieving these goals requires major investments in enhanced observational strategies, improved data assimilation and numerical weather prediction (NWP) systems, and expanded forecast applications based on the high resolution and ensemble-based NWP systems. HFIP's modeling efforts are organized into three development paths. Stream 1 refers to the yearly upgrades made to operational NWP capabilities, Stream 2 refers to efforts that will require multiple years to enhance operations, and Stream 1.5 refers to improved models and/or techniques that the National Hurricane Center (NHC), based on prior assessments, wants to access in real-time during a particular hurricane season but that cannot be made available by the operational modeling centers in a conventional production mode. During each hurricane season, HFIP conducts an experiment, referred to as the Demonstration (Demo) Evaluation, which attempts to demonstrate model capabilities that go well beyond the current capability of the operational global and regional models. In addition, a Retrospective Evaluation is conducted during the pre-hurricane season for modeling systems that wish to be considered for inclusion in the Stream 1.5 evaluation during the Demonstration Evaluation in the hurricane season.

FY 2012 Accomplishments

During FY2012 the TCMT focused on several activities related to HFIP. In particular, the TCMT led the planning and evaluation of the 2012 Stream 1.5 retrospective model evaluation. TCMT also enhanced the real-time multi-model ensemble forecast and display system

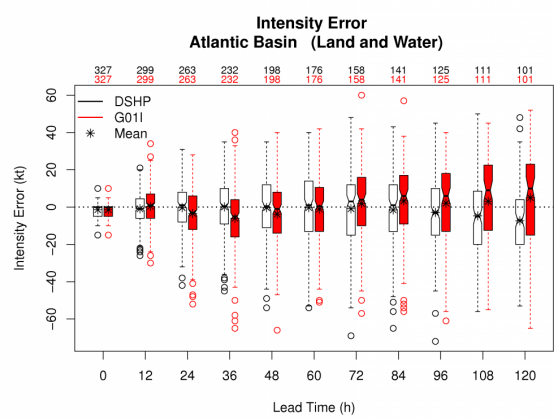

Figure 1: Example of comparisons of hurricane intensity error distributions from the 2012 HFIP Retrospective Evaluation.

(**http://www.ral.ucar.edu/projects/hfip/d2012/forecasts/**) and provided participants access to track and intensity products for the 2012 HFIP Forecast Demonstration (**http://www.ral.ucar.edu/projects/hfip/d2012/data_output/**). In addition, TCMT staff supported the development of the HFIP Real-time Display System (**http://www.hfip.org/products**). TCMT implemented the HFIP Data Service (**https://verif.rap.ucar.edu/ramadda/**), and supported the development of a community tropical cyclone (TC) verification toolkit.

A specific testing and evaluation methodology was developed for the evaluation of the 2012 Stream 1.5 candidate models, which included evaluation of the uncertainty in verification measures through confidence intervals and paired

statistical tests to compute the distributions of errors of model-based tropical cyclone track and intensity forecasts (Figure 1). This methodology provided a consistent set of results that allowed the forecasts from the various models to be comparably and fairly evaluated. Each Stream 1.5 candidate was evaluated based on three basic criteria: 1) performance relative to an operational baseline or baselines, 2) impact on the performance of the model consensus guidance, either by adding the Stream 1.5 candidate to the consensus members or replacing the comparable member, and 3) performance relative to the top-flight operational models. A detailed report was written for each candidate model, which summarized results of the evaluation. These reports were provided to NHC and the HFIP project office and were used to make decisions regarding which models would be included as Stream 1.5 models and demonstrated to NHC forecasters during the 2012 hurricane season.

The Stream 1.5 evaluation included TC cases from the past three (2009-2011) hurricane demonstration periods (August 1 – October 31). The TCMT 2012 Retrospective Testing website

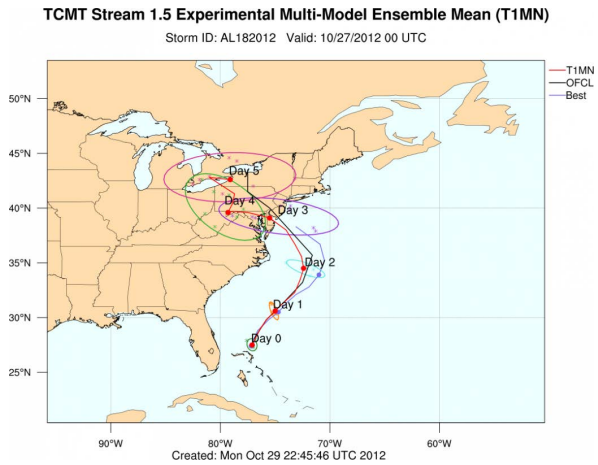

Figure 2: Example ensemble forecast ellipse display for Hurricane Sandy tracks during the 2012 HFIP Demonstration.

(**http://www.ral.ucar.edu/projects/hfip/h2012/**) has more information on the methodology and cases. Eight different research model configurations were included in the evaluation. Both global and mesoscale numerical weather prediction (NWP) systems were included, as well as ensemble and statistical forecast systems for predicting hurricane intensity.

With support from the Developmental Testbed Center (DTC), the TCMT developed a multi-model ensemble forecast product for the 2012 HFIP Demonstration. Three different ensemble forecasts were computed: (1) Stream 1.5 forecasts only; (2) Stream 2 forecasts; and (3) all available forecasts (Stream 1.5, Stream 2, operational models). A real-time display system was enhanced for the 2012 Demo, which displayed plots of track, intensity, and ellipse of forecast tracks for the three sets of forecasts, along with best track, and official NHC forecasts. An example of the ellipse track product is shown in Figure 2.

TCMT also supported infrastructure development for the HFIP product website. This effort was coordinated with staff at NOAA/GSD. The TCMT effort focused on developing the tracker display, developing the data transfer protocol, and database structure to support the display system. TCMT is also hosting and maintaining the HFIP product website on a JNT webserver.

The TCMT developed a HFIP data service that supplies real-time files from the demonstration model forecasts as well as past retrospective data to the HFIP community. Unidata's RAMADDA is being used to serve the data to the community. Data can be assessed by the HFIP community through a password protected interface, including real-time tier 1 (stream 1.5 and 2) and diagnostic files. Previous retrospective and demo data, as well as current tier 2 files are also becoming available as the data service continues to be updated. While the current set-up adequately supplies stream 1.5 and 2 data to the full HFIP community, current progress is being made to take advantage of many advanced features available within RAMADDA (e.g., integrated IDV graphics for files containing model fields) and to the general RAMADDA interface in order to increase ease of use.

FY2013 Plans

In FY2013, tropical cyclone track and intensity forecasts collected during the HFIP 2012 Demo will be evaluated using consistent tools and approaches for all models. Retrospective model testing and evaluation will be undertaken once again, in collaboration with NHC and a variety of research and operational modeling groups. Statistical approaches will be developed and implemented for the evaluation of other relevant attributes of tropical cyclone forecasts, and an initial version of the hurricane verification tools will developed and made be available to the community. A real-time monitoring system will continued to be enhanced with additional display graphics and evaluation products. The tropical cyclone database will continue to be enhanced with additional datasets of track and intensity, diagnostic products, and gridded fields.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
  - Short-Term Explicit Prediction Program
  - Coupled Surface Hydrometeorological Processes and Regional Climate
  - Aerosols and Precipitation
  - Winter Weather
  - Western Water
  - Water, Energy and Food Security
- Climate, Weather and Society

Hydrometeorological Applications

Provide relevant information to water resource decision makers through directed and basic research and development in hydrometeorology, aerosol-precipitation interactions, precipitation nowcasting, microphysical modeling, and winter weather.

Short-Term Explicit Prediction Program
Coupled Surface Hydrometeorological Processes and Regional Climate
Aerosols and Precipitation
Winter Weather
Western Water
Water, Energy and Food Security

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Log in

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- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
  - Short-Term Explicit Prediction Program
  - Coupled Surface Hydrometeorological Processes and Regional Climate
  - Aerosols and Precipitation
  - Winter Weather
  - Western Water
  - Water, Energy and Food Security
- Climate, Weather and Society

Short-Term Explicit Prediction (STEP) Program

Background

The Short-Term Explicit Prediction (STEP) Program is a cross-laboratory activity at NCAR aimed at improving the short-term (0-36 hours) forecasting of high-impact weather events such as severe thunderstorms (heavy rain, tornados, downburst, flash flood, lightning and hail), winter storms (snow, freezing rain and drizzle), and hurricanes. The STEP program emphasizes several research areas that are crucial for advancing the science and application of the short-term prediction of high-impact weather, including basic understanding of high-impact weather systems, development of data assimilation and forecast techniques at the convection-permitting scale, real-time demonstration of high-resolution forecast systems, advanced nowcasting techniques that make use of NWP models and observations, object-based verification, and optimal use of new observations. This collaborative effort incorporates national and international scientists, engineers, and operational personnel from universities, government institutions and the private sector. The forecasting/nowcasting systems and analysis tools developed under STEP are available to the communities for the support of research and real-time operations.

In FY12, RAL was awarded six projects out of the total of 11 funded proposals. These RAL projects were primarily focused on the study of terrain-induced precipitation using data over the Rocky Mountain Front Range and over Taiwan. The RAL effort includes observation analysis, nowcasting development, data assimilation, modeling, and verification. The major accomplishments from these RAL projects are summarized below.

Assessing the value of polarimetric radar products for flash flood modeling applications in the Rocky Mountain Front Range

Traditionally, there exists significant uncertainty in quantitative precipitation estimates (QPEs) from single polarization radars. This is because of the non-uniqueness in returned radar echo strength that exists for a variety of different precipitation conditions. For example, a collection of several small raindrops with a few very small ice particles may exhibit a similar echo return as would a collection of a few very large rain drops. However, the hydrological responses (i.e. streamflow production) from two such precipitation events would be dramatically different. Over the past year we have collected radar surface gauge and streamflow data from additional case studies in the Rocky Mountain Front Range region to further understanding of rainfall-runoff processes in this region. Specifically, in collaboration with radar meteorologists at the Colorado State University (CSU) and NOAA Earth System Research Laboratory (NOAA/ESRL) we have focused on evaluating a selection of intense rainfall events in which dual-polarization radar data was collected. Comparison of dual-polarimetric, hydrometeor identification-based QPE products against surface raingauge and disdrometer data has revealed several interesting findings. First, a calibrated single-reflectivity QPE product can have a similar bias or root mean square error value as does a dual-polarization radar QPE product, the dual-pol QPE product tends to exhibit better discrimination of

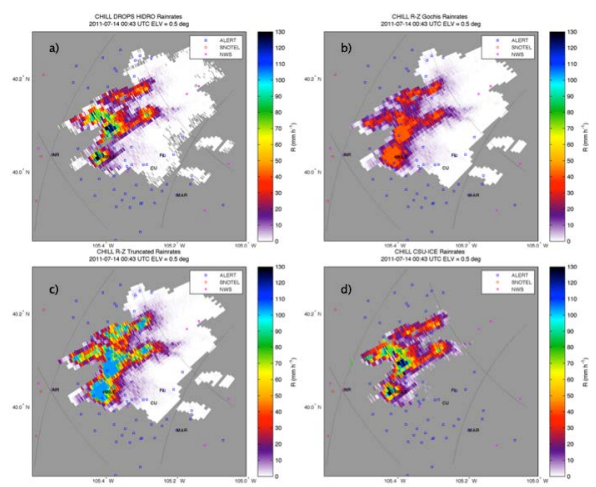


Figure 1. QPE products from the CSU-CHILL radar during the 2011 Fourmile Canyon flood event. Panels are the polarimetric 'HIDRO' retrieval (a), a regionally tuned single polarization Z-R (b), a single polarization Z-R with the standard NWS Z-R coefficients (c) and an older polarimetric retrieval named 'ICE'.

the locations in which it is raining. This property relates to lower 'false-alarms' or higher 'probabilities of detection' than do single reflectivity QPE products. To evaluate the impacts of these error characteristics on modeled streamflows we have fed these QPE products into the physics-based, fully-distributed WRF-Hydro modeling system and evaluated the simulated streamflows. Spatial maps of the radar QPE products are shown in Figure 1. While each QPE product captures the basic timing and form of the heavy precipitation event, several differences arise that relate to the magnitude of heavy rainfall and its spatial pattern. The four products shown are derived from the CSU-CHILL radar. The two polarimetric based estimates (panels a and d) show much greater localization of heavy rainfall. Statistical verification of the polarimetric QPE products tend to show that they have better spatial discriminating capabilities than the other two traditional Z-R based QPE products (b and c). These precipitation estimates form the basis of an 'ensemble' of QPE's which, in turn, can be fed into a hydrological model to produce an ensemble streamflow prediction. Figure 2 shows a map of the location of a flood event that occurred in July of 2014 over a recently burned landscape in Fourmile Canyon, near Boulder, Colorado. The topographic map is overlain with spatially-distributed values of streamflow from the WRF-Hydro model and show a snapshot of the flood wave caused by the heavy rainfall moving down the channel network towards Boulder. The inset graph shows the ensemble of streamflow simulations produced by feeding each of the QPE products from the CSU-CHILL radar and the NOAA radar into the hydrological model. The uncalibrated ensemble spread nicely bounds the observed flows, shown as diamonds, in both timing and peak flow value. This example illustrates an emerging capability in producing ensemble streamflow predictions from multiple radar-based QPE products.

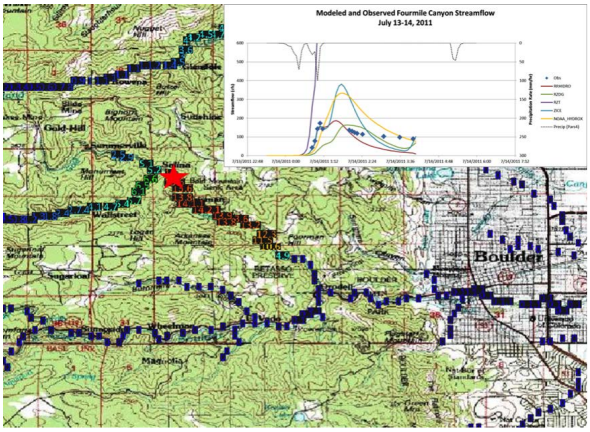


Figure 2. Map shows spatial pattern of modeled streamflow values (m^3/s, blue=low flow, red=high flow) in response to heavy rainfall from radar QPE products. Inset hydrographs illustrate ensemble hindcasts of streamflow generated from different radar QPE products. Blue diamonds are observed streamflow at location of red star.

Nowcasting Convective Precipitation over the Complex Terrain of Taiwan

Taiwan is extremely vulnerable to flash floods resulting from heavy rain produced by local thunderstorms and by a spectrum of large-scale synoptically forced weather. Taiwan Central Weather Bureau (CWB) forecasters are being tasked in the coming years to issue frequently updated, short-term forecasts of heavy precipitation. The Terrain-influenced Monsoon Rainfall Experiment (TiMREX) conducted in 2008 during Taiwan's warm season gathered high resolution dual-polarization radar, surface, sounding and special vertical profiling measurements prior to and during heavy rainfall events. These high resolution observations are being used by Jim Wilson, Rita Roberts and Jenny Sun to examine storm formation and evolution, identify critical nowcast predictor fields, and develop real-time applications for nowcasting heavy rainfall over complex terrain. Until the NWP models can provide specific, highly reliable, accurate forecasts of precipitation occurrence on 1-5 km scale and on the 0-2 hr nowcast timescale, the approach taken here is to use a heuristic nowcast system that employs fuzzy logic to combine all available observations with selected numerical model output fields and high resolution wind and thermodynamic fields from the 4D-Variational Doppler Radar Analysis System (VDRAS) to provide location-specific forecasts of heavy rain.

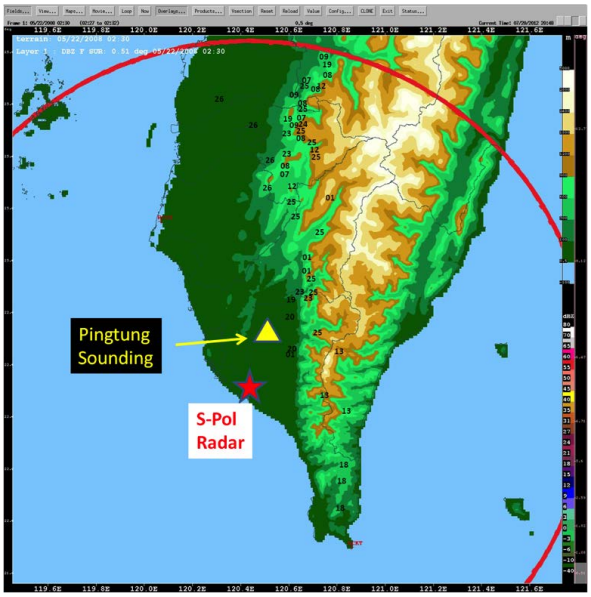


Figure 3. Location of radar, sounding and heavy rain during TiMREX for weakly forced synoptic days with afternoon thunderstorms. The numbers refer to the day of the month during May and June 2007 were heavy rain events occurred. Multiple heavy rain events often occurred on the same day.

A study utilizing 2008 TiMREX data was conducted to identify parameters from a mid-day radiosonde that might be useful for nowcasting heavy rainfall from afternoon thunderstorms under weakly forced synoptic situations. During TiMREX a 1100 LT

sounding was available almost daily from Pingtung which was about 25 km north of the NCAR S-POL radar. The S-Pol radar was used to estimate the occurrence of heavy rainfall which was defined as 50 mm in 3 hours. During TiMREX 20 days were classified as weakly forced synoptic days. Figure 3 shows the location of S-Pol, Pingtung sounding site and the location of heavy rainfall events. Fifteen of the days had radar estimated heavy rainfall occurrences, the locations are marked in Fig. 3 with the day of occurrence. For each day the amount of area receiving heavy rain was related to parameters obtained from the Pingtung sounding, there were three days (indicated in red in Fig. 4) when the 1400LT sounding was utilized. Figure 4 compares the amount of area receiving heavy rain for each day with four sounding parameters that indicated a relationship to the occurrence of heavy rain. These parameters were a) CAPE, b) Cin, c) mean relative humidity in the layer between 850 and 500 mb, and d) the height of the level of free convection. Heavy rainfall became highly likely when the following conditions were met:

1) Cape > 1000 j/kg

2) Cin < 50 j/kg

3) 850-500 mb layer mean relative humidity > 50 %

4) Level of free convection > 780 mb

Because of the positive relationship between the above sounding parameters and the occurrence of heavy rain it is recommended that a test be conducted in the Taipei area where a noon day sounding is released from June through August at the Banchiao site to determine if a similar relationship can be obtained for the Taipei region.

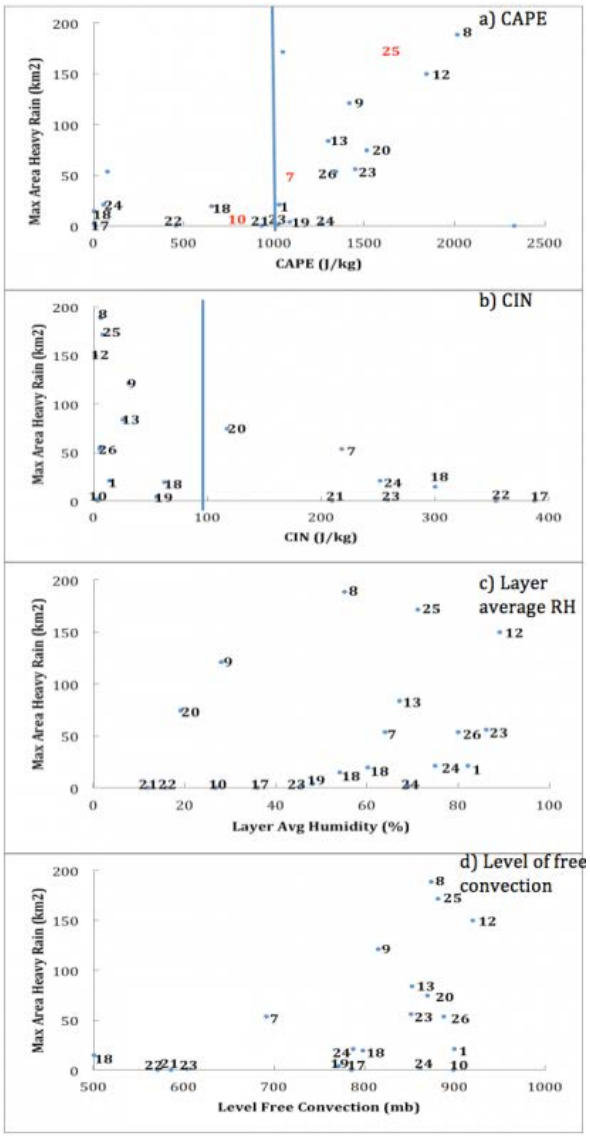
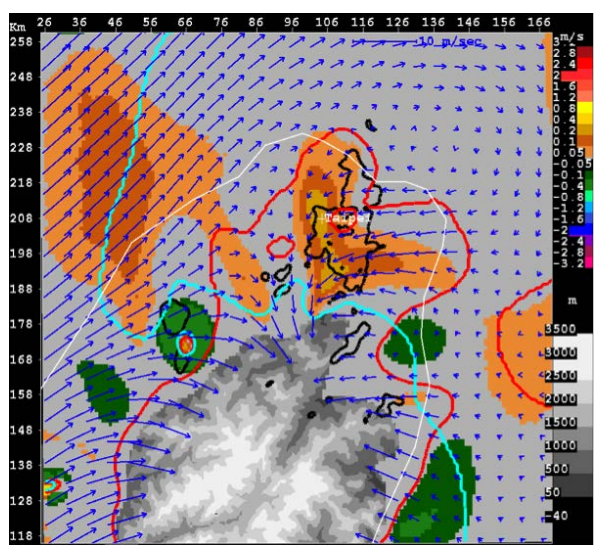


Figure. 4. Scatter diagrams of the daily area of rainfall covered by heavy rain compared to sounding parameters from the Pintung midday sounding. The rainfall is estimated from S-Pol. The numbers refer to the day of the month the heavy rain occurred between 18 May and 25 June. a) CAPE, b) CIN, c) layer average humidity and d) level of free convection.

Studies of storm initiation over complex terrain using VDRAS

VDRAS is a 4D-Var (4-dimensional variational) based data assimilation system that aims at high-resolution analysis using Doppler radar observations. VDRAS was applied to convective cases in Taiwan that had significant influence of the complex terrain of high mountains and coast to study convective initiation in the Taipei area. The goal was to investigate whether the high-resolution analysis produced by VDRAS with radar data assimilation can provide mesoscale predictors that is typically lacking from NWP model and observational networks. Figure 5 is an illustration of overlaid VDRAS fields for the identification of favorable locations for convective initiation. It shows that the convective storms (indicated by 35 dBZ echoes, black contour) occurred at a location with high CAPE (over 900 J/kg, red contour), high relative humidity (over 85%, Cyan contour), and high vertical velocity (color). The vertical velocity is a result of a mesoscale easterly jet in east of Taipei. Further studies both with Taiwan cases and cases collected in the Front Range region of Rocky Mountains will be examined to investigate the mechanism of terrain induced convective initiation and the implications to nowcasting.



To improve the performance of VDRAS over mountainous regions, an effort has begun to add terrain into the cloud model and its adjoint in VDRAS using the Immersed Boundary Method (IBM). IBM does not require the change of the existing model coordinate. Rather, it assumes the earth surface is immersed in the constant height coordinate. Preliminary results using an idealized mountain indicate that VDRAS with terrain yields reasonable simulations of lee vortices, similar to classic results from previous model simulation studies. Figure 6 shows the lee vortices obtained from the VDRAS cloud model with the terrain effect added through the IBM method.

Improving WRF physics for improved prediction of high impact weather

Physics parameterizations have been shown to have a strong impact on the short-term forecasting of convective storms, in particular the parameterization for raindrop breakup was shown to have a strong influence on the evolution of organized convection via its impact on the cold pool. For this study, idealized simulations of a squall line observed on 20 June 2007 in central Oklahoma were compared with dual-polarization radar and raindrop disdrometer observations. The baseline model configuration, using the Morrison microphysics scheme, qualitatively reproduced key storm features, but under-predicted precipitation rates and generally over-predicted median volume raindrop diameter. Storm characteristics exhibited considerable sensitivity to the parameterization of breakup, especially for moderate (0.0048 s^{-1}) shear. Simulations with more efficient breakup tended to have *higher* domain-mean precipitation rates under both moderate and higher (0.0064 s^{-1}) shear, despite the smaller mean drop size and hence lower mass-weighted fallspeed and higher evaporation rate for a given rainwater content. In these simulations, higher evaporation lead to stronger cold pools, faster propagation, larger storm size, greater updraft mass flux (but weaker convective updrafts at mid- and upper-levels), and greater total condensation that compensates for the increased evaporation to give more surface precipitation. The impact of drop breakup on mass-weighted fallspeed was also important and lead to a non-monotonic response of storm characteristics (surface precipitation, cold pool strength, etc.) to changes in breakup efficiency under moderate wind shear. In contrast, the response was generally monotonic at higher wind shear. Figure 7 help illustrate the findings from this study.

This study also noted that other aspects of the treatment of raindrop size distributions (DSDs) may also be important to the development of the cold pool. For example, the parameterization of DSD shape or width (i.e., m for the gamma DSD) impacts processes such as rain evaporation and sedimentation, and this is the subject of current investigation in which disdrometer observations of m are being used to help constrain the parameterization. This case was featured as a multi-model comparison case for the 8th WMO International

Figure. 5. VDRAS analyses of vertical velocity (color shading) at z=1km and wind vectors at z=0.2 km valid at 0400 UTC 16 July 2012. The red, and cyan contours are 85% relative humidity (RH) and 850 J/kg CAPE at z=1km respectively. The storm (35 dBZ reflectivity shown by black contour) at 0500 UTC is initiated in an area of CAPE>850 J/kg and RH>85% and over the region with high vertical velocity. The gray shading shows terrain height.

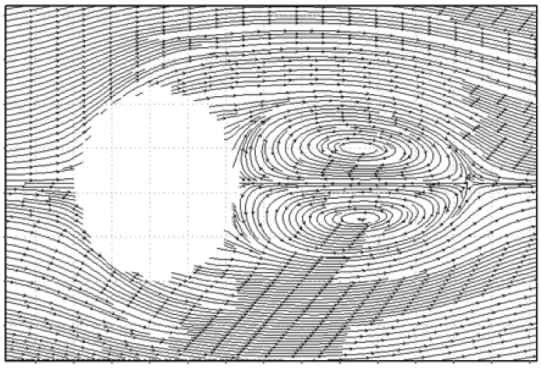


Figure. 6. Lee vortices simulated by VDRAS cloud model with an idealized mountain.

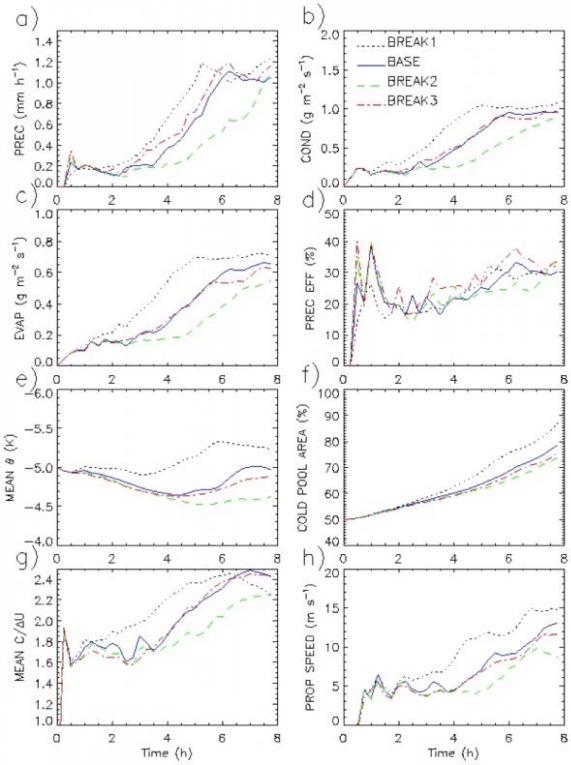


Figure. 7. Time series of a) domain-mean surface precipitation rate, b) total condensation rate, c) total evaporation rate, d) domain-mean precipitation efficiency, e) mean lowest-level θ' within the cold pool, f) cold pool area, g) ratio cold pool intensity and difference in 2.5 and 0 km wind, C/ΔU, and h) propagation speed, for the BREAK1, BASE, BREAK2, and BREAK3 simulations (listed in order of highest to lowest breakup efficiency, given the drop size threshold for breakup is smallest in BREAK1 and largest in BREAK3).

Cloud Modeling Workshop, which has resulted in refinements to the case initialization and set up. This work has also resulted in one published journal article with a second article in preparation.

Spatial verification

The object-based verification algorithm MODE (Method for Object-based Diagnistic Evaluation) developed by a team led by Barb Brown was extended to include the temporal dimension. Inclusion of the time dimension (TD) allows, among other things, tracking of spatial objects (e.g., storm cells) over time – a capability desired by many STEP researchers. Most of the object attributes assessed by the MODE tool can be easily generalized to the TD case. In particular, the same underlying fuzzy logic scheme used in MODE object matching and merging will work for MODE-TD. Storm cells may be merged into composite or "cluster" objects, as for MODE. Object attribute statistics can be stratified by these matches (or misses and false alarms). Statistics on storm lifetimes can also be produced, including measures of when during a storm's life cycle the most intense precipitation is produced. Some of the MODE object attributes acquire new meanings when generalized to the TD case. For example, the object axis measured by MODE provides information on object orientation. In the TD case, the tilt of the axis from the vertical gives information on the object's average velocity. Similarly, in MODE, the centroid separation between forecast and observed objects carries purely spatial information.

In the TD case, the centroid separation has a temporal component that gives information on forecast timing errors. MODE-TD was applied to the STEP IHOP cases and an initial analysis of the object attributes was completed. Some of the variables evaluated include an overall measure of performance called the MMI, storm speed, and storm longevity. MODE-TD was applied to a variety of cases from the Hazardous Weather Testbed spring experiment. The results are being included in a paper describing the methodology as well as the results of the application. In addition, through a visitor project through the JNT, Dr. Marion Mittermaier (UK Meteorological Office) collaborated with R. Bullock of RAL on an application of MODE-TD to the occurrence of cloud-free areas over the United Kingdom. This application demonstrates the versatility of the MODE and MODE-TD approaches to evaluation of meteorological phenomena. Results of this study are included in a journal article that has been submitted. R. Bullock also worked with Adam Clark, a visitor to the Developmental Testbed Center (DTC) on an application of MODE-TD to several fields from high-resolution forecasts of severe weather.

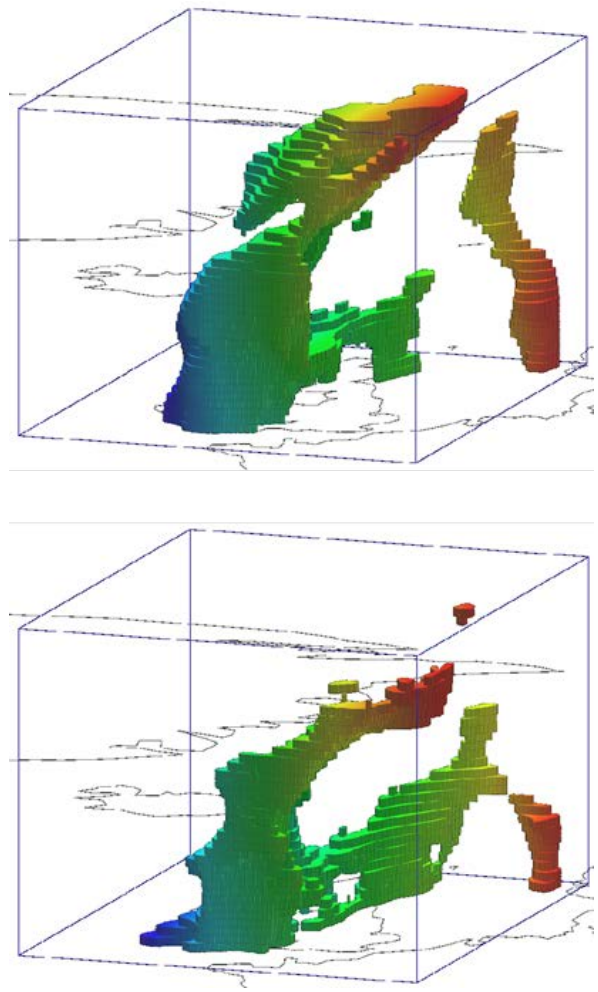


Figure 8. Example of MODE-TD applied to a case representing cloud-free areas over the United Kingdom. Time is the vertical axis. Upper diagram is forecast, lower is analysis. Multiple 3-D objects are identified in the forecast and observed grids (colors do not indicated matches).

FY2013 Plans

One of the major activities for FY13 will be the development and demonstration of an integrated end-to-end forecasting system that includes NWP models, radar data assimilation, qualitative precipitation estimation (QPE), qualitative precipitation nowcasting/forecasting (QPF), and stream flow forecasting. We plan to demonstrate this system first using multiple cases and then in a real-time experiment in the Front Range region covering the FRONT (Front Range Observational Network

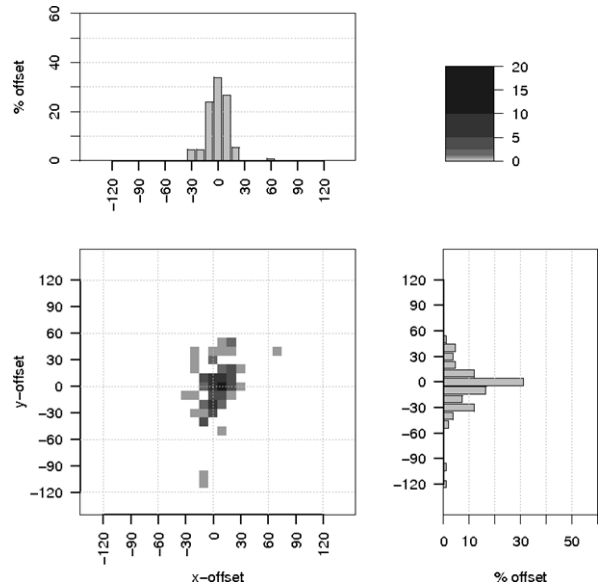


Figure 9: Example results from application of MODE-TD applied to a case representing cloud-free areas over the United Kingdom, showing offsets in centroid locations between forecasts and observed objects. Histograms show frequencies along each dimension.

Testbed) area. Some specific activities are detailed below:

- Develop a real-time integrated QPE product that utilizes rain gauges, single and dual-polarization radar data
- Modify the ANC to produce precipitation rate nowcasts for the 10-60 min period in 10 min intervals and feed this product to steam flow forecasting model
- Run radar data assimilation and 0-12 forecast experiments using WRF 3DVar and RTFDDA over same Front Range cases and compare their performances.
- Continue the study on storm initiation over complex terrain with VDRAS using the same dataset as ANC, RTFDDA, and WRF 3DVar
- Provide skillful, probabilistic hydrological forecasts at lead times from a few minutes out to a few days by employing several different prediction tools to generate forecasts
- Work with collaborators both within NCAR and the university community to incorporate more advanced nowcasting techniques as well as numerical weather prediction models which utilize four-dimensional data assimilation
- Refine the microphysical basis for calculating cloud optical depth as part of the radiation schemes to improve forecasts of long-lived convection
- Enhance the treatment of high-density ice by creating a 3-moment graupel/hail hybrid category to improve forecasts of storm evolution and precipitation
- Expand and refine the methods for nudging microphysical quantities in the hybrid radar data assimilation system to improve convective storm initiation forecasts
- Develop real-time verification and bias correction algorithms for QPE and QPF
- Complete the MODE-TD article and submit for publication
    - Develop a new verification capability using the MODE technique as well as other traditional and spatial verification methods as part of a coordinated hydrometeorological nowcasting and forecasting system for STEP. Initially, a variety of methods will be tested using several existing cases, and the results demonstrated to the nowcast and forecast developers.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
  - Short-Term Explicit Prediction Program
  - Coupled Surface Hydrometeorological Processes and Regional Climate
  - Aerosols and Precipitation
  - Winter Weather
  - Western Water
  - Water, Energy and Food Security
- Climate, Weather and Society

Coupled Surface Hydrometeorological Processes and Regional Climate

Advances in Land Surface Modeling: Development of the community Noah-MP land surface model

Multi-physics Land Surface Modeling (Noah-MP)

A community effort is underway to develop the next-generation land surface model to address shortcomings in the current Noah LSM, which is widely used in operational weather and climate models. The new Noah-MP (Multi-Physics) LSM provides the capability to conduct ensemble simulations by including options to treat or enhance the following physical processes:

- Canopy radiative transfer with shading geometry
- Dynamic vegetation using a carbon allocation model
- Ball-Berry photosynthesis-based canopy resistance
- Multi-layer snowpack with liquid water retention
- Frozen ground physics
- Ground water with a dynamic water table and vadose zone interactions

The new Noah-MP model has been evaluated in both offline and coupled mode for warm and cold season simulations, and was released in the community WRF V3.4 in April 2012.

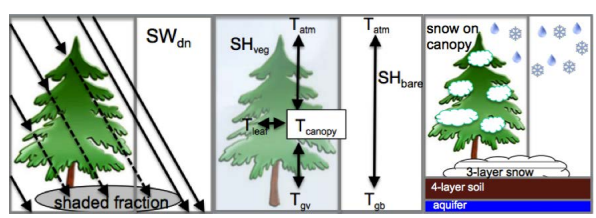
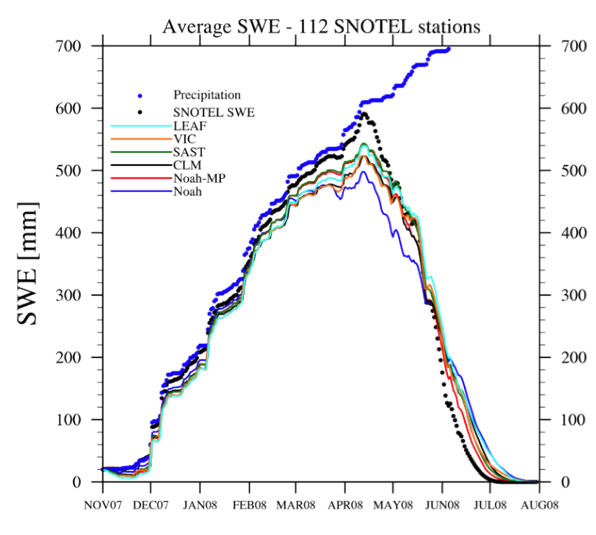


Figure 1: A schematic of enhanced physical processes in the Noah-MP land surface model. (From left-to-right; canopy influences on radiative transfer, canopy heat exchange and snow-aquifer enhancements)

Inter-comparison of land surface models' ability to represent snowpack evolution in complex terrain and the forested central Rocky Mountains

The timing and amount of spring snowmelt runoff in mountainous regions are critical for water resources management. A community effort is underway to utilize data from 112 SNOTEL sites in the Colorado Headwaters region and two Ameriflux sites to evaluate the ability of six widely-used land-surface/snow models (Noah, Noah-MP, VIC, CLM, SAST, and LEAF-2) in simulating the seasonal evolution of snowpack in the central Rockies. All models reasonably captured the seasonality of SWE evolution fairly well (Figure 2), although they underestimated both early-spring (March-April) snow accumulation and late spring ablation. Underestimating snowmelt from mid-May to mid-June allowed models to compensate for lower SWE in spring, and consequently resulted in a prolonged snow season. No single model performed the best (or the worst) in reproducoing three important features of snow evolution: maximum SWE depth, the timing of maximum SWE and the timing of spring snow disappearance. However, models exhibited large disparities in simulating the surface energy partitioning, which is equally important for correctly representing snow-atmospheric interactions in weather and climate models. Some models underestimated the solar energy absorbed at the



forest-soil-snow interface from December to March. That resulted in too little outgoing long-wave radiation and sensible heating returned to the atmosphere, which could be a crucial deficiency for coupled weather and climate models. Those model differences and deficiencies can be further traced down by examining the treatment (or lack of it) of turbulence and radiation processes within and under the vegetation canopy. Excessive shortwave and long-wave radiation transfer from canopy to ground/snow often led to larger sensible heating from canopy to ground/snow surface, and resulted in larger, undesired weekly SWE change in both accumulation and ablation phases

Figure 2: Observed and modeled Snow Water Equivalent (SWE) by six land surface models, averaged over 112 SNOTEL sites.

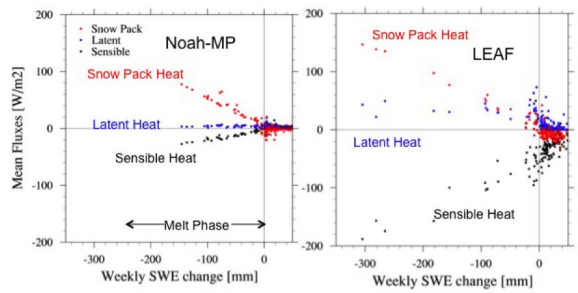


Figure 3: Weekly SWE change (mm) and weekly averaged surface fluxes simulated by Noah-MP (left) and LEAF (right) models.

Fully-coupled Hydrometeorological Modeling with WRF-Hydro

Accounting for fully-coupled, two-way interactions between the land surface and the atmosphere is a core challenge in the emerging Earth System modeling discipline. The chaotic and non-linear response of the atmosphere to land surface perturbations implies that relatively small heterogeneities in land surface states and fluxes have the potential to drive upscale responses in the atmosphere. Improper representation of land surface processes such as the spatial patterns of soil moisture and snowpack may significantly limit prediction skill for many meteorological events. Similarly, there are increasing needs for development of spatially-distributed, physics-based, conservative modeling approaches for a variety of applications such as regional hydroclimate impacts of climate change and flood forecasting from minutes to seasonal timescales.

The community WRF-Hydro modeling framework is addressing these needs by providing a flexible and extensible model structure for representing distributed hydrologic processes in a fully-coupled environmental prediction system such as the Weather Research and Forecasting (WRF) model or the Community Earth System Model (CESM). Core model development efforts over the past several years have focused on the creation of a modeling architecture that accommodates a variety of hydrological model structures as opposed to a single model structure. The initial WRF-Hydro development follows the WRF modeling paradigm of relatively simple extensibility of model physics within the existing WRF modeling framework.

The WRF-Hydro modeling system is now being used in more than seven countries around the world by research groups and operational prediction agencies. With a growing domestic and international network of model developers users and increasing record of improved model skill, it is becoming clear that WRF-Hydro is poised to become an essential community resource for hydrometeorological and hydroclimatological prediction. Current activities include the modeling of seasonal water supply from the Colorado Headwaters region, evaluating the impact of new radar technologies on streamflow forecasting, fully-coupled hydrometeorological prediction from extreme Mediterranean storm events in Italy, Turkey and Israel, land-atmosphere coupling controls in the North American Monsoon region, and regional climate change impacts on water supply in India.

In Figure 4 we highlight the capabilities of the WRF-Hydro system in simulating a flash flood event in an urban area as part of a NASA-funded Flash Flood Decision Support System development project with collaborators at NASA and the NOAA Office of Hydrological Development. Under this project the WRF-Hydro system has been coupled with the NASA Land Information System (LIS) architecture and therefore adds an improved operational capability for hydrologic prediction. The event in Figure 4 shows a modeled flood wave propagating through the Denver, Colorado urban corridor. This flood was particularly damaging because it originated downstream of a major flood control reservoir in the urban area (southern part of the map). When driven by high-quality precipitation observations from surface gauge networks, radars or satellites, this new capability should be able to add valuable minutes of skillful lead-time prediction to flash flood warnings.

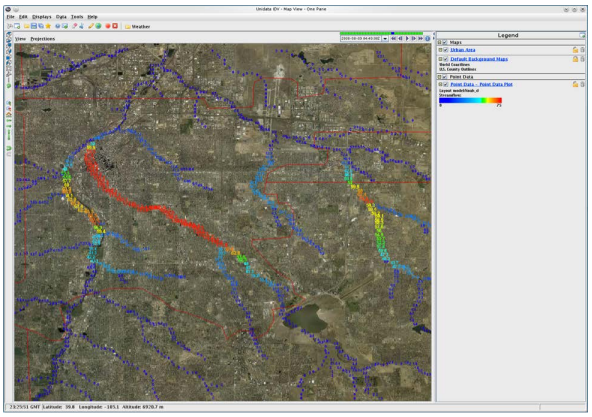


Figure 4: WRF-Hydro simulated flash flood wave moving through south Denver on 8-9 Aug. 2008. The flood wave was well-captured in both timing and magnitude when the model was driven by polarimetric radar data from the Colo. State CHILL radar. The underlying image is a satellite view of the southern part of Denver. Red lines indicate county borders. Pixel values of streamflow range from 0 (blue) to 75 cubic meters per second (red).

FY2013 Plans

The WRF-Hydro team is on track to release version 1 of the model to the community as an official

extension package of the WRF model. We are also engaging in several other community-based efforts to expand the functionality and utility of the WRF-Hydro system through projects like the NSF EarthCube initiative and a joint NSF-EU program to improve cyberinfrastructure for hydrometeorological predictions for U.S. and European researchers.

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- National Security Applications
- Numerical Systems Testing and Evaluation
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  - Short-Term Explicit Prediction Program
  - Coupled Surface Hydrometeorological Processes and Regional Climate
  - Aerosols and Precipitation
  - Winter Weather
  - Western Water
  - Water, Energy and Food Security
- Climate, Weather and Society

Aerosols and Precipitation

Background

RAL's Aerosol and Precipitation group has been engaged in scientific research to evaluate precipitation enhancement techniques for several decades. Work has focused on analyzing existing data and collecting specialized data for assessing current weather modification projects, as well as for developing feasibility plans for new cloud seeding activities in the USA, United Arab Emirates, Australia, West Africa, India, Saudi Arabia, Oman, Indonesia, Thailand, Turkey, Mexico and Italy. Work accomplished in the last twenty years with hygroscopic seeding techniques has shown promising results in statistical field tests in South Africa, Mexico, and Australia. Associated cloud measurements and cloud model calculations have provided a physical basis to support the hypothesis that seeding with small hygroscopic particles at cloud base can, under some conditions, enhance rainfall.

India CAIPEEX Program

The Indian Institute of Tropical Meteorology (IITM) initiated a multi-year national research program, the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX), in 2008. In 2011, Phase II of CAIPEEX was executed, and an intensive observation period (IOP) from August to November was conducted. RAL provided overall scientific guidance to this effort, working closely with scientists from IITM and the University of the Witwatersrand, South Africa. Local logistical support was contracted with Krishi Consultants.

CAIPEEX Phase II-2011 continued with studies that focused on the interaction of aerosols with cloud microphysics and precipitation. The measurements focused on a region between Hyderabad, Anantapur and Sholapur. Mahabubnagar which lies at the center of the experiment area was chosen as a base for a ground based observational campaign where several state of the art instruments were deployed. The research aircraft flew routinely over the ground site to make aerosol and cloud measurements. Also new for Phase II-2011 was a randomized seeding experiment. This randomized experiment was conducted within the range of an EEC WSR-74C C-Band (5 cm wavelength) weather radar installed at Mahabubnagar.

FY 2012 Accomplishments

RAL continued to deploy a large instrumentation payload on the CAIPEEX research aircraft; the South African Weather Service (SAWS) Aero Commander 690A, during the 2011 field effort. RAL field scientists, trained and experienced in the operation of these specialized instruments, ensured the collection of high quality data for the three-month duration of the campaign. Other RAL scientists supported the field effort from the NCAR - Boulder facilities.

CAIPEEX has collected a large data set that describes the contrasting aerosol and cloud microphysical properties over India. These data were collected during the pre-monsoon, monsoon and the transition period between the two. Aerosols over the Indo-Gangetic Plains,as well as over the elevated slopes of the Himalayas, have received growing attention in recent years due to their potential effects on the seasonal evolution and long-term variability of the summer monsoon. A subset of the CAIPEEX research flights were conducted in and around convective clouds over the foothills of the Himalayas during the spring and summer of 2009. Figure 1 shows

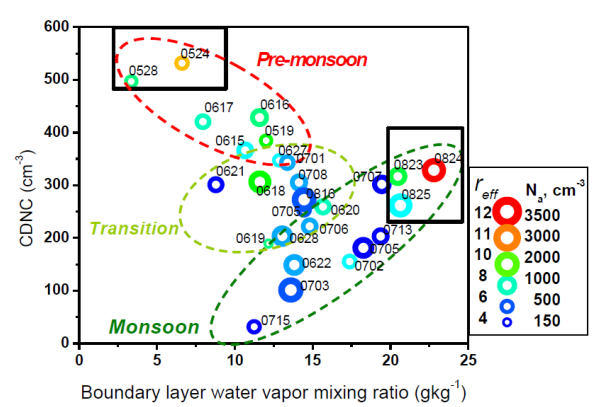

Figure 1. Variation of CDNC with boundary layer water vapor for cloud observations during CAIPEEX Phase I. Labels are marked with date of observation (mmdd; month and date) and grouped (shown with ellipses) to pre-monsoon, transition and monsoon period . Rectangular boxes show observations with two extreme conditions of water vapor and high pollution. The aerosol number concentration (Na) is shown with color and cloud averaged effective radius (reff) with size of the symbols

as described in the legend.

averaged cloud droplet number concentration (CDNC), plotted against boundary layer water vapor mixing ratio, cloud averaged effective radius (r_{eff}) and aerosol number concentration (N_a). Each point in the figure corresponds to a CAIPEEX cloud observation. Three regimes based on the available water vapor in the boundary layer and progression of monsoon is identified (shown with ellipses in Figure 1). This analysis shows a very dry regime in the pre-monsoon, a moderately wet transition and a wet regime during the monsoon. Within the monsoon regime, the CDNC increases with increase in water vapor mixing ratio. Observations in the monsoon and pre-monsoon regime show relatively high droplet number concentrations. These observations were conducted in the Ganges valley during the pre-monsoon (May 24: 0524 and May 28: 0528) and active monsoon (Aug 23: 0823, Aug24: 0824, Aug25: 0825) periods. The high CDNC monsoon cases are associated with very moist and polluted conditions. During the pre-monsoon, cloud microphysics may be characterized as "super-continental", meaning that the cloud droplets are very small and delay the formation of warm rain.

Journal papers resulting from the RAL-IITM collaboration during CAIPEEX include:

Prabha, T. V., S. Patade, G. Pandithurai, A. Khain, **D. Axisa**, P. Pradeepkumar, R. S. Maheshkumar, J. R. Kulkarni and B. N. Goswami, 2012: Spectral width of premonsoon and monsoon clouds over Indo-Gangetic valley, J. Geophys. Res., 117, DXXXXX, doi:10.1029/2011JD016837.

Prabha, T. V., A. Karipot, **D. Axisa**, B. P. Kumari, R. S. Maheskumar, M. Konwar, J. R. Kulkarni, and B. N. Goswami, 2012: Scale interactions near the foothills of Himalayas during CAIPEEX, J. Geophys. Res., 117, D10203, doi:10.1029/2011JD016754.

Freud, E., D. Rosenfeld, **D. Axisa**, and J. R. Kulkarni, 2011: Resolving both entrainment-mixing and number of activated CCN in deep convective clouds, Atmos. Chem. Phys. Discuss., 11, 9673-9703, doi:10.5194/acpd-11-9673-2011.

FY 2013 Plans

Collaborative analysis between RAL and IITM is leading to advances in the understanding of monsoon clouds over the Indian subcontinent. Increasing air pollution over this region could modify the radiative balance through direct, indirect, and semi-indirect effects associated with aerosols. CAIPEEX aircraft observations and continued collaborative analysis continue to describe the aerosol-cloud sensitivities in the region. During FY 2013 RAL will collaborate with IITM on various data analysis topics including (1) the identification of ice hydrometeors in optical array probes, (2) the conversion of supercooled cloud and rain drops into ice hydrometeors, as a function of temperature and aerosol concentration, (3) cloud droplet preferential concentrations due to turbulent mixing, and (4) the effects of aerosol with different microphysics and chemistry on the development and evolution of the drop size distribution at cloud base.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
  - Short-Term Explicit Prediction Program
  - Coupled Surface Hydrometeorological Processes and Regional Climate
  - Aerosols and Precipitation
  - Winter Weather
  - Western Water
  - Water, Energy and Food Security
- Climate, Weather and Society

Winter Weather

Wyoming Weather Modification Pilot Program

Background

The Wyoming Weather Modification Pilot Program (WWMPP), funded by the State of Wyoming through the Wyoming Water Development Commission (WWDC), is an orographic cloud seeding research program covering three target areas (the Medicine Bow Range, Sierra Madre Range and Wind River Range). It is unique among state-sponsored programs in that it includes a substantial independent evaluation component to determine the feasibility of cloud seeding and to quantify its effectiveness. The logistics, infrastructure, and operations of the program are covered under a contract with Weather Modification Inc. (WMI), while the evaluation activities fall under a separate contract with the Research Applications Laboratory (RAL) of the National Center for Atmospheric Research (NCAR).

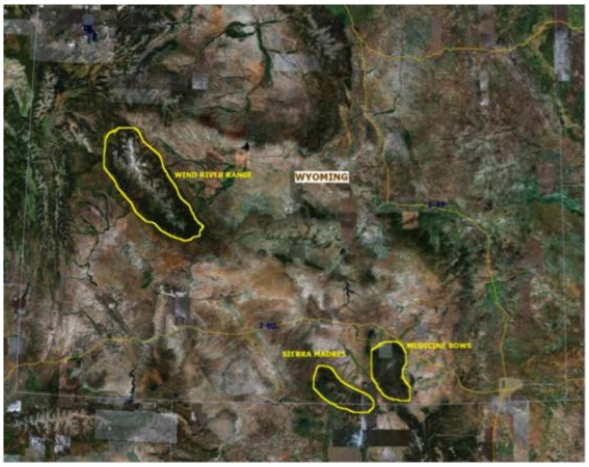


Figure 1. Composite satellite view of Wyoming. Yellow areas denote the three mountain ranges in the winter orographic cloud seeding program: Medicine Bow, Sierra Madre, and Wind River. The randomized seeding experiment involves only the two southern ranges, the Medicine Bows and Sierra Madres.

Natural precipitation in winter storms occurs when clouds: a) contain supercooled liquid water (SLW); b) exist in a temperature range where small particles, ice nuclei, will cause some of the SLW to freeze, forming ice particles; and c) persist long enough for the ice particles to grow and fall to the ground. Many clouds are naturally inefficient in producing snow because there are few ice nuclei active at the temperatures in the cloud where significant SLW is found. Such clouds may be induced to precipitate by supplying artificial ice nuclei in the regions of SLW. This is the essence of cloud seeding.

Figure 2. Orographic clouds over the Medicine Bow range.

Both short-term research projects and long-term operational programs to increase snowpack by seeding clouds have been carried out for well over fifty years. Average increases of 10 to 15% have been reported in some research experiments, but the topic remains controversial and many operational programs and scientific experiments have ended without conclusive results. Because of the large natural variability of precipitation, and the relatively small seeding effect expected, multiple layers of evidence, both statistical and physical, are required to provide a consistent picture of the effect of cloud seeding.

The evaluation of the WWMPP is based on this two-prong approach: a) a statistical experiment to collect a randomized set of seeded and unseeded cases, and b) exploratory observations to investigate the different physical processes in cloud seeding to show that the seeding hypothesis is physically-based. Collaborations with other scientists, particularly those at the University of Wyoming, have led to "piggy-back" studies applicable to the assessment of seeding impacts

on precipitation formation and eventually on streamflows.

The Randomized Experiment

At the end of 2007, after initial measurements and required permits were obtained, the Medicine Bows and Sierra Madres were established as targets for a randomized winter time cloud seeding experiment, using ground-based seeding generators, with an annual seeding period from 15 November through 15 April. High-resolution precipitation gauges were deployed for snowfall measurements, along with auxiliary instruments to assist in determining seeding conditions and seeding impacts.

The randomized seeding experiment (RSE) design includes the following: 1) target areas near the crests of the Medicine Bows and Sierra Madres; 2) a cross-over design in which one range is randomly seeded and the other acts as the control, resulting in paired cases; 3) a seeding period of four hours with a "buffer" period of four hours to clear the areas of seeding material; 4) high-resolution precipitation gauge measurements within each target area; 5) two control gauge sites (unaffected by seeding) in each range to help describe the natural variability in precipitation between target areas and between snowfall events; 6) seeding conditions occurring in each range simultaneously (i.e., cold enough temperatures for the seeding material to work, wind flow of the right direction for the seeding generators to affect snowfall in the target areas, and the presence of SLW); and 7) enough cases to provide quantifiable results with statistical significance (i.e., high level of confidence in the results).

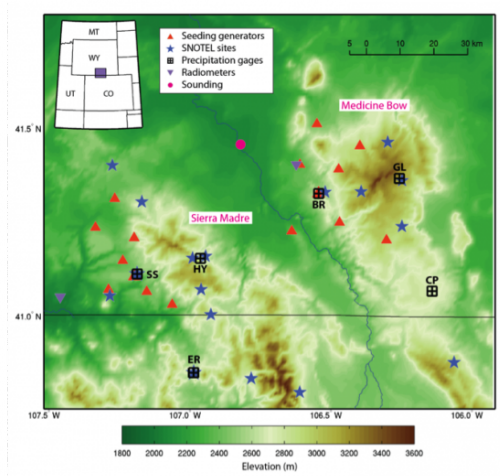


Figure 3. Layout of facilities for the randomized seeding experiment in the Medicine Bow and the Sierra Madre Ranges.

Resources used for carrying out the experimental design include 16 ground-based seeding generators (8 in each range), 20-23 precipitation gauges at 8 sites (with redundancy at each site and some experimental gauges), 12 weather stations (at each gauge site and four at generator sites), two microwave radiometers for detecting SLW, a radiosonde unit (balloon-borne instrument for measuring temperature and winds at cloud heights), and a numerical forecast model, cycling every three hours with updated observations. The seeding generators, radiosonde unit, and one radiometer are operated by WMI. The precipitation gauge network, one radiometer, and forecast model are operated by RAL/NCAR.

FY2012 Accomplishments

Non-randomized seeding was conducted in the Wind River Range as part of the WWMPP, with evaluations based on SNOTEL data, occasional auxiliary data sources, and numerical modeling. The main tool used in the evaluation in this range is the Weather Research and Forecasting (WRF) model, which is used to provide storm simulations using nested grids (to <1-km resolution) and detailed microphysics for both the design and evaluation portions of the WWMPP. WRF is also used with the Real-Time Four-Dimensional Data Assimilation system (RTFDDA) at a more computationally manageable grid resolution (2-km) to provide daily forecast guidance during operations. A wide variety of publicly-available data as well as experimental data sources (e.g., NASA and NOAA for specific satellite products) are utilized for model initiation though the FDDA technique and for model validation.

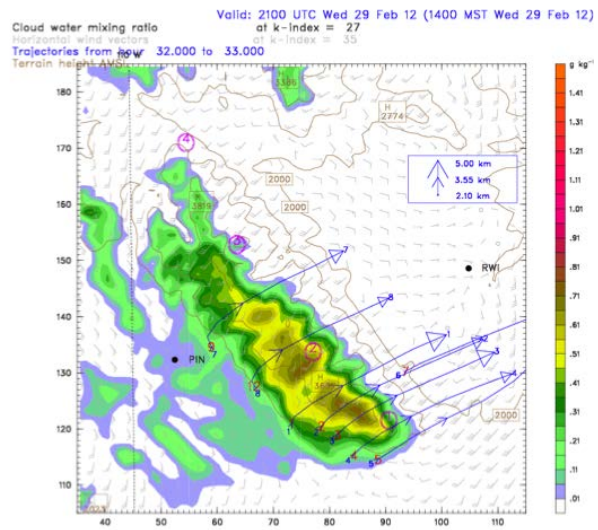


Figure 4. Example of WRF forecast model output of cloud water (color contours) and trajectories from seeding generators.

In 2012, aircraft measurements taken in previous field seasons were analyzed to: 1) investigate spatial and temporal variations of cloud liquid water and ice particles through cloud mapping flights; and 2) characterize background aerosols, both in general

and over specific sites if warranted, through low-level mapping flights. Comparisons of these measurements were also made with the WRF forecast model.

Radiometer data has been collected in the Winds (viewed from the Boulder area on the west side) over the past several seasons. A comparison of the radiometer output (at one time slice) with the WRF forecast model shows good agreement with the existence and quantity of super-cooled liquid water. Systematic analysis of the radiometer data should provide a consistent evaluation of seeding conditions and the capability of the WRF model to capture such conditions.

Development of a seeding module that provides realistic seeding parameters and output has enabled the WRF model to simulate seeding effects. Verification of the veracity of the seeding module as applied to the WRF model needs to continue, but this approach provides the greatest promise of evaluating seeding in the Winds.

The design of the RSE included estimates of the number of cases required to achieve a statistically significant conclusion on the effect of seeding, based on several assumptions regarding precipitation characteristics (from SNOTEL data) and a range of possible seeding effects. As the experiment has progressed, estimates of the required sample size are able to be refined, based on the measured precipitation characteristics. These characteristics include the quality of the precipitation data, the correlation in target areas between the ranges, and the variability of precipitation amounts during the 4-hr periods of the cases. These new estimates and the cases sampled thus far can then be used to address the two main questions regarding the progress of the program: How many cases are needed, and what are the seeding effects to date?

Updated sample size estimates were recalculated, and indicate that roughly 60 more cases are needed to reach a statistically significant conclusion, assuming a seeding effect of 10% or more. This implies that two more seasons are needed, at the current rate of ~30 cases per season, to complete the experiment. Funding for the final two seasons was recently approved in an extension of the WWMPP by the 2012 Wyoming State Legislature.

Analyzing the cases collected thus far, the results of a seeding effect are not yet statistically significant, and thus no conclusions should be drawn regarding any effect. Preliminary analysis of the data, however, shows that the significance of the results has increased with each successful year of the program, and that the results are consistent with a positive seeding effect. While this is a promising trend, the number of cases is still too small to reach a credible conclusion concerning the effect of seeding. To achieve that result requires the additional 60 or so cases indicated above, or two more operational seasons. At that point the WWMPP would be uniquely successful in completing such a randomized statistical experiment testing the efficacy of winter-time cloud seeding from ground-based generators.

FY2013 Plans

In the southern ranges, the 2011-2012 winter was

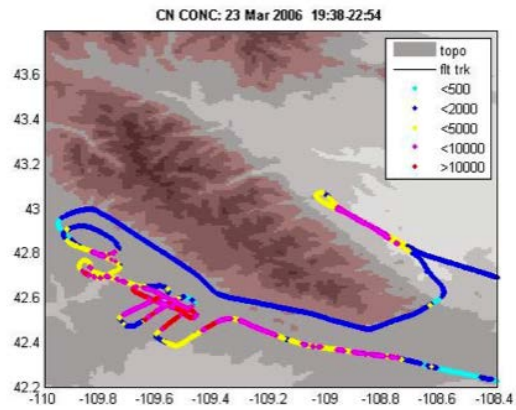


Figure 5. Variations in aerosol concentrations at low levels around the Winds (color differences along aircraft track indicate changing aerosol conditions).

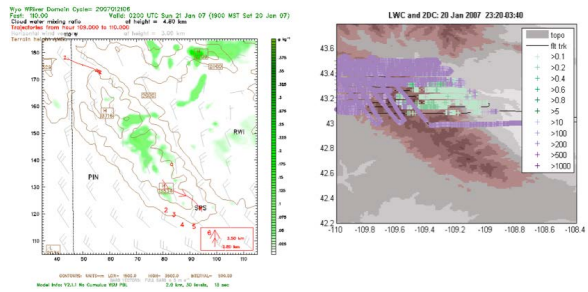


Figure 6. Comparison of cloud conditions between the WRF forecast model on the left and aircraft measurements on the right (different map projections). Cloud water is shaded green in both plots. Cloud ice (not in the WRF plot) is shaded purple. Wind is from the NNW.

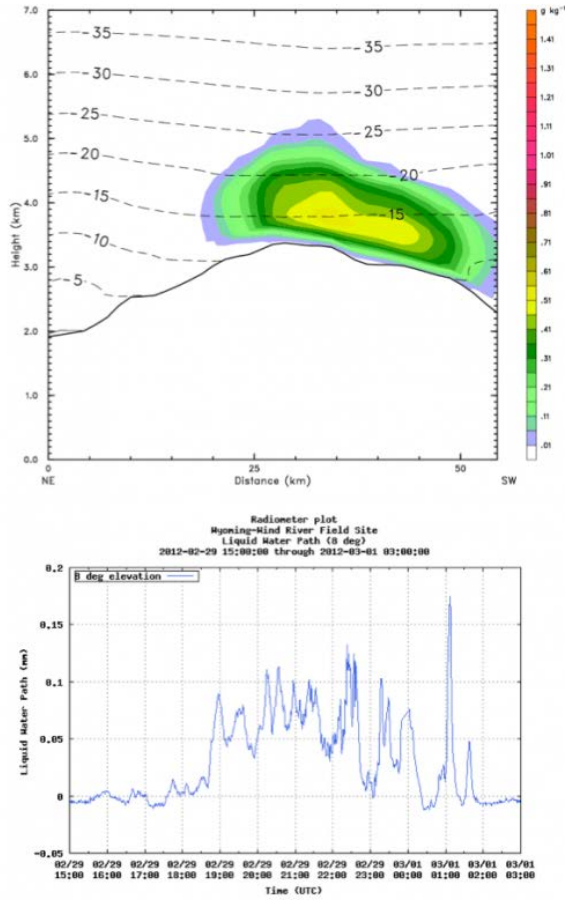


Figure 7. Cross-section of WRF model output over the central Winds showing cloud water (colored contours). Below is a time-series of radiometer-measured liquid water path, close to the WRF cross-section, showing the development of cloud water during the storm on 29 Feb 2012. The red arrow is at the time of the WRF cross-section.

the fourth full season of operations under the final design of the randomized seeding experiment (RSE). It was successful in terms of case calling and data collection but unusual in its far below normal snowfall. Only 15 cases were called.The continuation of the RSE to collect sufficient numbers of cases is the highest priority for the next two seasons.

Along with the precipitation measurements required to assess the WWMPP, additional instruments are being deployed, in collaboration with researchers from the University of Wyoming and the University of Colorado, to better understand and document the physical chain of events hypothesized to be affected by cloud seeding.These include surface-based instruments at the GLEES site, such as a hotplate sensor (for high-precision snow rates), a disdrometer (for measuring particle-size spectra), a radiometer, and a vertically-pointing K-band radar.A second K-band radar will be deployed at the western base of the Medicine Bows to compare changes in reflectivity and particle fall-speeds between the two sites. Additional funds granted by agencies in the lower Colorado River basin will allow us to deploy a ceilometer upwind of the Sierra Madres, similar to past years, for documenting cloud base development and height/temperature in that range. Analysis of the data collected from these additional, complementary instruments will continue over the next two seasons. The goal is to document any changes due to seeding and to optimize and extend potential seeding opportunities.

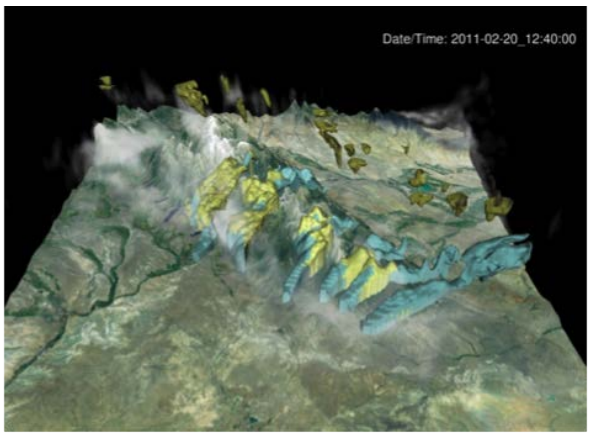


Figure 8. "Snapshot" of WRF simulation of clouds and seeding plume on 20 Feb 2011 at 12:40 UTC. White shading indicates cloud liquid water, brown patches show cloud ice. Blue shading shows seeding plume where yellow indicates the seeding plume in cloud and snow. Resolution is 667 m; view is from the south.

Idaho Power Project

Background

Idaho Power conducts a winter cloud seeding program to augment snowfall along the Snake River Basin and its tributaries for hydro-generation purposes. The program is presently focused in two areas; the Payette River watershed and the upper Snake River system in eastern Idaho. Plans are being developed for potential expansion into the Salt and Wyoming rivers in Western Wyoming. For the past two years RAL has conducted a numerical modeling cloud seeding

study in support of Idaho Power.

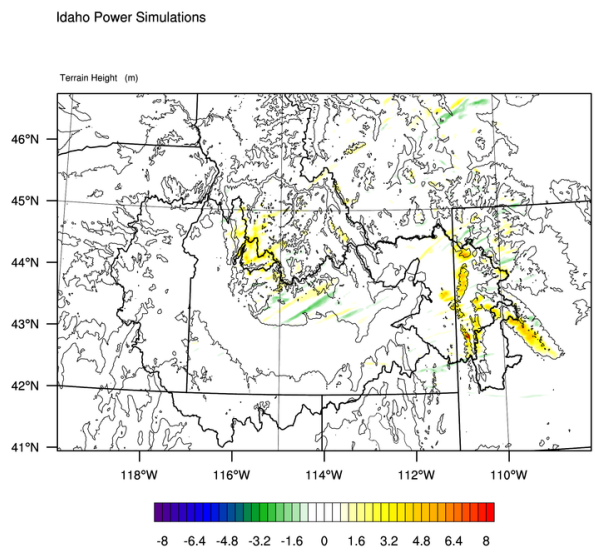
FY2012 Accomplishments

A "Phase Two" study was undertaken to investigate the sensitivities of the seeding effect in the Weather Research and Forecasting (WRF) cloud seeding module and compare the WRF model output with available observations. The sensitivity studies are essential for improving the model, determining how to best interpret the simulated results, and ultimately leading to the development of a targeted real-time model for cloud seeding guidance.

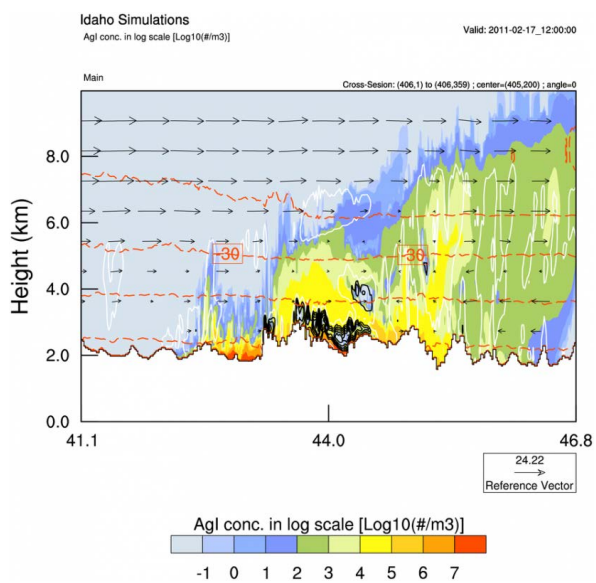
The sensitivity tests showed that the simulated seeding effect is most impacted by the seeding rate and whether the seeding occurred via airborne seeding or ground based. Airborne seeding was shown to be more effective than ground-based seeding in all cases due to the improved targeting of the silver iodide (AgI) to the optimal cloud regions for snow crystal growth and fallout. The results also showed that small changes in the background meteorological conditions (such as wind speed and relative humidity) could induce precipitation changes similar in magnitude to the seeding effect.

The optimal configuration for cloud seeding simulations needs to effectively simulate precipitation, cloud water, and the dispersion of AgI. The model configuration tests indicated that the initialization data and the choice of domain and resolution are highly sensitive factors impacting the simulated precipitation field, while the boundary layer scheme has less of an impact. However, our analysis with the Wyoming ice nuclei measurements concluded that the boundary layer schemes do not adequately simulate the vertical diffusion of AgI from ground seeding. Rather, a large eddy system (LES) framework coupled with high horizontal and vertical model resolution seems to capture the transport of AgI much more accurately.

The description of the cloud seeding module and results of the sensitivity studies have been submitted for publication in two journal papers. A "Phase Three" effort has begun, which includes the development of an algorithm that evaluates real-time model forecast conditions and calls the seeding module in near real time to serve as a cloud seeding guidance system.



Simulated precipitation difference (mm) between the control run and the simulation with cloud seeding for a case on 16-17 February 2011.



Vertical cross section of simulated silver iodide concentration (color contours), with contours of cloud water content (black; contours starting at 0.1 g/kg every 0.1 g/kg) and supersaturation with respect to ice (white; contour at 1.04). Isotherms (orange) and wind vectors (black) are also overlaid.

FY2013 Plans

- Implement the cloud seeding module and real-time seeding algorithm into a real-time modeling forecast system
- Investigate the use of high resolution modeling simulations of seeding combined with observations to statistically evaluate cloud seeding effects
- Determine optimal seeding locations for ground generators and aircraft tracks
- Investigate the impact of cloud seeding on hydropower generation

Support for the Solid Precipitation InterComparison Experiment (SPICE)

Marshall Field Site Testbed

For the past four years, NCAR/RAL has made its Marshall facility available to NOAA's Climate Reference Network (CRN), supporting its efforts to

provide future long-term homogeneous observations of temperature and precipitation that can be coupled to long-term historical observations for the detection and attribution of present and future climate change. Data from the CRN are being used in operational climate monitoring activities and for placing current climate anomalies into an historical perspective. Since 2009, the Marshall field site has functioned as the Western U.S. testbed for evaluating a variety of weather sensors before they are deployed to CRN stations.

FY2012 Accomplishments

NCAR/RAL provided support for CRN's participation in the World Meteorological Organization's (WMO) Solid Precipitation InterComparison Experiment (SPICE). This program, scheduled to run from November 2012 through May 2015, is an international effort to establish a standard automated gauge/shield combination for measuring solid precipitation. Countries from around the world will be contributing to this study with each participant supplying a testbed in their country for evaluating various sensors, gauges and wind shields. At the recommendation of the CRN, the WMO has selected the Marshall facility as the U.S. test site for SPICE. NCAR has also been designated as the main data repository for all participating sites and will archive the data and make it available to the international community through the Marshall web page.

During the summer of 2012, necessary electrical upgrades to the Marshall test facility were made to accommodate the arrival of new instrumentation. RAL staff also developed plans for the deployment, calibration and testing of the instruments in preparation for their deployment in November. A new website was created to display data collected during SPICE.

RAL also hosted a workshop in the summer of 2012 which representatives from Canada, Finland, Switzerland, Australia, Norway, Italy and the U.S. attended. This workshop established the priorities of SPICE and outlined the research priorities of each participating country. Data archival and quality control protocols were also established, with NCAR designated as the lead for archiving all of the SPICE data from all the participating countries.

FY2013 Plans

Approximately 25-30 new precipitation gauges/shields and other snow measurement devices will arrive at Marshall in the fall of 2012. The instruments will be deployed, calibrated and tested in preparation for the start of the program in November. Data will then be collected and made available on a new SPICE web site. Manual measurements of snow will also be taken at the site every 12 hours to support comparison of the new automated measurements with the original manual measurements.

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- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
  - Short-Term Explicit Prediction Program
  - Coupled Surface Hydrometeorological Processes and Regional Climate
  - Aerosols and Precipitation
  - Winter Weather
  - Western Water
  - Water, Energy and Food Security
- Climate, Weather and Society

Western Water

Background

NSF base funding supports the NCAR Water System research program. Within that larger program, RAL conducts a Colorado Headwaters project that examines the impact of climate change on water resources in this critical region. In FY2012 researchers have continued their analysis of different scenarios of mid-21st century future hydroclimate with continuous, 8-year, very high resolution (4km) regional climate model simulations using the Weather Research and Forecasting (WRF) model. New analyses of these continuous 8-year climate downscaling runs are generating new insights into how the partitioning of the hydrologic cycle will change under a warmer climate.

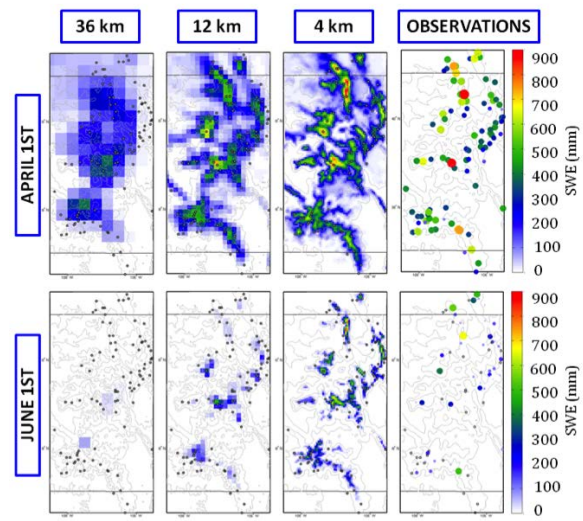

Figure 1. WRF simulations of snow water equivalent for April 1st (top row) and June 1st (bottom row), at multiple resolutions over the Colorado Headwaters, compared to observations from the SNOTEL network.

FY2012 Accomplishments

During 2012, several additional model experiments were conducted to highlight the uncertainties in water budget analyses that are introduced when models of insufficient resolution are employed in downscaling studies. As with global models, coarse resolution regional climate models (e.g. those using grid spacings > 10km) tend to produce too much summertime precipitation and have very significant errors in the timing of snowmelt and availability of soil moisture. Figure 1 illustrates this situation; showing that the 4-km simulations have substantially higher snow water equivalent (SWE) on April 1st, which persists longer into the summer (as evident in the June 1st simulations). These results highlight the elevational control on precipitation, snow fall, and snow melt, which has subsequent impacts on soil moisture and evapotranspiration during the growing season, and on land-atmosphere fluxes.

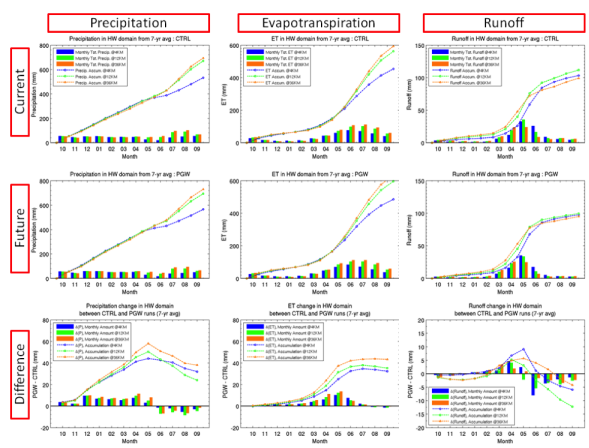

Figure 2. Seasonality of water budget components for current climate and a future climate scenario, for the WRF simulations at 4-km, 12-km, and 36-km.

The downscaled climate change experiments illustrate interesting compensatory effects for different water budget components – Figure 2 illustrates that the increases in precipitation in winter are offset by increases in evapotranspiration, resulting in a net decrease in runoff. The dependence on spatial resolution is strikingly apparent during summer, where summertime precipitation is much higher in the coarser 12-km and 36-km simulations, resulting in higher levels in soil moisture during the growing season, and larger increases in evapotranspiration Moreover, consistent with the snow water equivalent (SWE) simulations in Figure 1, runoff occurs much earlier in the coarser-resolution simulations

because of the poor representation of the terrain. Such large differences in the portrayal of the ecological and hydrological impacts of climate change associated with model resolution have bearing on the design of future climate change experiments, especially on determining tradeoffs between the number of scenarios examined and the horizontal resolution of the models.

FY2013 Plans

These analyses are motivating a series of new studies to investigate not only the impacts of the changing hydroclimate patterns, such as on water management, but also into the physical reasons behind the changes found. Additional work focusing on the reasons behind the decrease in summer precipitation is currently underway. New runs using a modeling domain which covers most of the coterminous U.S. are also planned so that we can begin to compare and contrast the change signals from the Colorado Headwaters regions to other regions such as the Pacific Northwest, the U.S. Great Plains, and the Mississippi River basin.

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  - Coupled Surface Hydrometeorological Processes and Regional Climate
  - Aerosols and Precipitation
  - Winter Weather
  - Western Water
  - Water, Energy and Food Security
- Climate, Weather and Society

Water, Energy and Food Security

Background

Policy and management decisions regarding water and energy figure prominently in efforts to adapt to and mitigate anthropogenic climate change. To be effective, these decisions need to consider the interconnections between energy, water and food production and use–the *water–energy-food nexus*--and to assess the implications of a changing climate for the reliability of energy and water supplies. A number of important, quite complex research efforts are currently underway addressing each side of the nexus. Assessments of water use in generating hydroelectric power, are for example, studying freshwater use and consumption as a function of the generation type (combustion turbine, combined cycle, etc), fuel used (coal, natural gas, nuclear, etc.) and the cooling system technology (once–through, recirculating, dry, etc.). Analyses focusing on the consumption of energy by the water sector are also underway, examining energy use extraction, transport, delivery, pre– and post–use treatment, and user applications. Both sides of the *energy–water-food nexus* are being examined, but typically as loosely connected puzzle pieces rather than as integrated components of a coupled resource management system.

While the *water-energy–-food nexus* information–base has been growing, there remains a dearth of modeling tools to evaluate long–term interactions and feedbacks between these sectors in the context of a changing climate. In particular, a spatially-explicit coupled modeling system is needed to facilitate a more complete and accurate evaluation of the workability and consequences of alternative climate mitigation and adaptation strategies.

To address these needs, RAL in collaboration with the Stockholm Environment Institute US-Center (SEI) and the Union of Concerned Scientists, has made exploration of the water-energy-food nexus in the Western United States a research frontier in its Strategic Plan. Initial efforts in FY2012 have been conducted with support from a NOAA SARP grant, the NSF, and a Norwegian firm, Der Norske Veritas.

FY2012 Accomplishments

The physical sciences in support of Integrated Water Resources Management (IWRM) is extremely useful, yet conventional approaches to natural resource management, based on physical sciences alone often fail to fully address the continual need to negotiate tradeoffs between conflicting resource use and changing interests. A coupling is needed between the natural, social, and the ecological systems with interactions across spatial and temporal scales. Along with the Stockholm Environment Institute-US Center, we have successfully linked two planning-purposed models with a long legacy of successful use in decision support in their respective disciplines; the Water Evaluation and Planning (WEAP) and the Long-range Energy Alternatives Planning (LEAP) modeling systems. WEAP and LEAP have been recently coupled to better explore the *water-energy-food nexus.*

As part of this work, Yates and Miller (2013) have explored the implications of energy alternatives on water in the southwestern U.S.; their paper, "Integrated Decision Support for Energy/Water Planning in California and the Southwest", has been accepted for publication in the *International Journal of Climate Change: Impacts and Responses.*

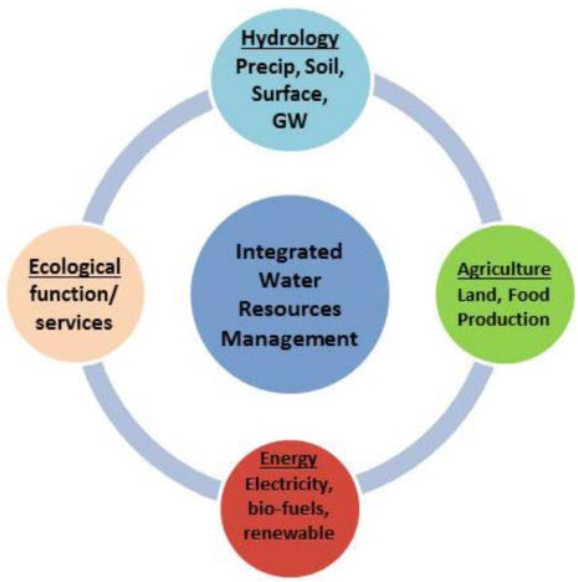

Figure 1. A simplified representation of the . Groundwater (GW)

FY2013 Plans

Research is needed to better understand the interactions, and possible collisions, between water-management and energy-management decision making. National-scale guidance is needed on energy policy and decision making that leads to reduced greenhouse gas emission, and avoids unintended consequences related to water management in the context of energy generation. Different energy management strategies will have different water management implications that extend from the local, to the regional, and ultimately to the national scale. Further, it is recognized that the local importance of these impacts will be defined by the characteristics of individual water systems within which energy management strategies are implemented.

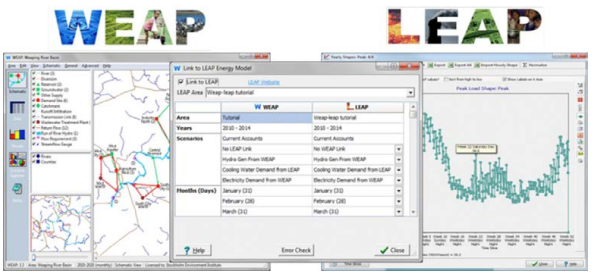

Figure 2. The Integrated WEAP and LEAP tools, showing the linking window (center), where common modeling areas, scenarios, periods of analysis, and timesteps are matched.

Proposed areas of focus include:

- In collaboration with the Headwaters Program, explore how improved scientific understanding of seasonal changes in precipitation, sublimation, snow water equivalent, snowmelt, soil moisture, and transpiration in the western USA impact the water-energy-food systems of the region. Explore the particular emphasis to changes associated with a shift to earlier snowmelt and the potential shift from energy-limited to water-limited systems.
- Using improved scientific understanding of the magnitude of the expected drought through the use of high-resolution climate models (in association with the Colorado Headwaters Project), explore water-energy-food relationships in the region.
- Work closely with the social science community, both at RAL and externally, to explore the impacts of climate change on the *water-energy nexus* from a societal perspective.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society
  - Use and Value of Weather Information
  - Governance and Adaptation
  - Resilient and Sustainable Cities
  - Weather, Climate and Health
  - Geographic Information System (GIS) Program

Climate, Weather and Society

Promote societal welfare by conducting interdisciplinary research on the interactions between society and weather and climate in order to increase societal resilience to the associated risks and to support decision making.

- Use and Value of Weather Information
- Governance and Adaptation: Socio-ecological Systems in a Changing Climate
- Resilient and Sustainable Cities
- Weather, Climate and Health
- Geographic Information System (GIS) Program

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society
  - Use and Value of Weather Information
  - Governance and Adaptation
  - Resilient and Sustainable Cities
  - Weather, Climate and Health
  - Geographic Information System (GIS) Program

Use and Value of Weather Information

Background

Weather and climate affect all economic sectors, regions, individuals and communities. Improved weather forecasts – and better use of current forecasts – could save lives and millions of dollars annually. To realize the potential benefits associated with improved weather forecasts and stakeholder decision making, in 2004 NCAR established the Collaborative Program on the Societal Impacts and Economic Benefits of Weather Information (aka Societal Impacts Program or SIP) to create a dedicated focal point for assembling, coordinating, developing, and synthesizing research and information on the societal impacts and economic benefits of weather information. The SIP is a collaborative effort with researchers from the Mesoscale and Microscale Meteorology Division of NCAR's Earth System Laboratory and supported in part by the Integrated Science Program.

The SIP aims to improve the societal gains from weather information by infusing social science research, methods, and applications throughout the weather enterprise and to be the premiere focal point for integrating social science and societal impacts understanding into the weather enterprise through cutting-edge research and capacity building. The SIP endeavors to:

- Advance knowledge on the socio-economic impacts of weather and the communication, use, and value of current and improved weather information.
- Build a multi-disciplinary, multi-stakeholder community of researchers and practitioners engaged in developing and applying knowledge on societal aspects of weather information.
- Enhance social science aspects of policy-making, development, and use of related weather information

FY2012 Accomplishments

National Household Survey on Use of Weather Forecast Information

Analysis was completed of data collected from a national survey of 1465 adults living in the United States designed to perform a confirmatory factor analysis on the Weather Salience Questionnaire (WxSQ). WxSQ is a 29-item instrument designed to measure the ways in which weather is psychologically significant for people. The original measurement model of the WxSQ was confirmed in the present sample and additional work also was performed to create a WxSQ short form consisting of seven items. We also examined the relationship of weather salience with the respondents' climate zones of residence and several other weather-related attitudes and behaviors that were assessed in the national sample. The results imply that the general public is quite varied in the significance that they attach to weather. Peoples' level of weather salience, at least in part, affects their uses of weather information and affects their confidence in it.

Assessment of Hurricane and Flash Flood Warnings

Work continued on two closely related NSF funded research effort examining decision processes employed by institutions, organizations, and individuals in analyzing, disseminating, and interpreting warnings of two important weather hazards: hurricanes and flash floods. These projects represent a critical effort by balanced research teams representing the fields of meteorology, sociology, economics, public policy analysis, and decision sciences to evaluate warning processes and systems holistically. One effort included in-depth interviews and observational sessions with NWS forecasters, emergency managers, and the media from the Greater Miami area were analyzed to examine their roles, goals, and interactions, and to identify strengths and challenges in how they communicate with each other and with the public. Together, these groups succeed in partnering with each other to make information about approaching hurricane threats widely available (*Figure Y - Conceptual representation of the primary geographic and subject matter specialties of the groups in the hurricane warning system. Areas of overlap represent overlap in specialties, not necessarily interactions among the groups.*). Results indicate that NWS forecasters sometimes find that the information they provide is not used as they intended; media personnel want streamlined information from NWS and emergency managers that emphasizes the timing of hazards and the recommended response and protective actions; and emergency managers need forecast uncertainty information that can help them plan for different scenarios. Another effort explored risk communication with several groups that may be at particular risk of hurricane impacts: older adults,

newer residents, and persons with disabilities. Focus groups conducted in Miami, Florida examined how members of these groups express their own vulnerability or agency in terms of receiving, interpreting, and responding to hurricane risk information. Findings indicate that people's interactions with risk information are deeply contextual and are facilitated by their individual agency to cope with their vulnerabilities.

Improving the NWS Public Forecasts through Integration of Social Science

A primary channel through which the National Weather Service (NWS) directly disseminates everyday and hazardous weather forecast products is its website, *www.weather.gov*. Among the more heavily accessed NWS webpages is the point-and-click (PnC) forecast webpage which has everyday and hazardous weather forecast information in graphical and textual formats over all land areas in the United States. This NWS-funded research project assessed the primary strengths and weaknesses of the weather forecast and observation information on the PnC webpage and identified ways to more effectively communicate this information. We conducted two, large-sample, nationwide surveys of PnC webpage users in which we employed an experimental design to evaluate PnC webpage forecasts with new attributes created to better convey threat existence and timing (*Figure X - example experimental forecasts with the box, start-time text, and end-time text*). We found that adding coupled start-time and end-time text information was adequate for helping individuals identify the existence of a threat and understand when the threat goes into effect and expires. We also examined the use of a red box coupled with text placed around the forecast-at-a-glance icon to better identify the threat. The addition of the box to the PnC webpage was perceived as visually enhancing hazardous weather threats, most respondents prefer having it to not, and most want the box for warnings, watches, and advisories.

Assessing Current Storm Surge Information

Using focus groups, in-depth interviews, literature reviews, and telephone and web-based surveys, work continued to explore emergency managers' and the public's awareness and understanding, or lack thereof, concerning storm surge and currently available storm surge information. This research aims to assess whether new storm surge informational approaches should be developed to improve the communication and decision-making with respect to extratropical and tropical cyclone storm surge risk.

FY2013 Plans

Work will continue on several projects on communication, understanding and use of warning information particularly with respect to NWS provided web-based weather information, flash flood warnings, hurricane warnings, and storm surge information.

Analysis of primary survey data and in-depth interviews will continue on two NSF and NOAA funded projects. The first project is developing an integrated understanding of warning systems and processes with a focus on hurricanes in Miami, Florida, and flash floods in Boulder, Colorado by:

- Addressing the role of uncertainty throughout the warning process, including information dissemination and decision making
- Identifying more completely the suite of factors influencing organizational and public decision making and action during extreme weather events
- Characterizing public preferences for different attributes of forecast and warning information

The second project focuses on the communication of hurricane forecast advisories and warnings by examining:

- The communication channels used by various actors in this process
- The impact of different communication efforts on members of the public's stated intentions to evacuate during a hurricane threat
- Assessing the public response to a range of advisory and warning products varied in their content and format

Work will continue on the Assessing Current Storm Surge Information project, including analysis of focused research assessing broadcast meteorologists' perspectives, uses, and needs for storm surge information in all coastal US surge-vulnerable areas.

The ongoing project improving the NWS public forecasts will analyze and compare results from two surveys on understanding, preferences, and uses of the PnC webpages – one survey of members of the general public and a parallel survey of self-identified PnC webpage users.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society
  - Use and Value of Weather Information
  - Governance and Adaptation
  - Resilient and Sustainable Cities
  - Weather, Climate and Health
  - Geographic Information System (GIS) Program

Governance and Adaptation: Socio-ecological Systems in a Changing Climate

Background

Natural resource management typically entails decision-making in both public forums and by private entities. A variety of natural resource governance arrangements have evolved in different socio-ecological settings to define use rights, decision-making procedures, enforcement mechanisms and methods for resolving disputes. These arrangements often involve complex hierarchies of public agencies and private entities having authority over different types of decisions. In addition, policy development may involve a contentious process of balancing competing interests and values, in which uncertainty about natural and social processes can play a significant role. The extent to which governance arrangements facilitate coordination across multiple layers of decision making will determine the quality of resource management outcomes and the ability of these socio-ecological systems to adapt readily and effectively to climate variability and change.

The science community can contribute to more effective and adaptive natural resource governance in two ways: 1) by improving the ability to forecast the behavior of the managed natural system and the implications of specific management decisions; and 2) by improving understanding of the functioning of the decision environment itself. In particular, research can help to clarify options for building more resilient natural resource governance regimes. Our research goals in this area include exploring and documenting the complexity of natural resource management decision environments, and the effects of alternative sets of governance arrangements on the capacity to respond effectively to climate-related impacts. In addition, we seek to understand how and why governance arrangements change over time, and how conscious policy choices could improve the adaptive capacity of natural resource governance regimes.

In FY 2012 CSAP research focused on analysis of governance and adaptive capacity for water resources and marine fisheries. Each of these systems is characterized by large numbers of independent resource users, whose activities are regulated either well or poorly by a variety of public authorities. In addition, the need to cooperate across national boundaries is often a central part of the management problem.

FY2012 Accomplishments: Water Resources

In FY 2012, work focused on investigating the role of political institutions in shaping the outcomes of urban climate policy and planning. Drs. Romero-Lankao and Hughes worked on identifying the determinants of institutional capacity in Santiago and Mexico City; the role of institutionalization in the use of climate science and information in Delhi and Mexico City; the effects of introducing a regional collaborative institution in southern California; and the determinants of justice in urban climate change planning. Three papers were submitted for publication, and a fourth is in preparation as a result of this work:

Related Papers:

Hughes, Sara and Stephanie Pincetl. “Evaluating Collaborative Institutions in Context: The case of regional water management in southern California,” *Environment and Planning C: Government and Policy*. (Accepted)

Romero Lankao, Patricia, Sara Hughes, Angelica Rosas Huerta, Roxana Burquez, and Melissa Haeffner. “Institutional Capacity for Climate Change Responses: An examination of construction and pathways in Mexico City and Santiago,” (Accepted with revisions at *Environment and Planning C: Government and Policy*).

Hughes, Sara.“A Research Agenda for Understanding the Mechanisms of Injustice in Urban Climate Change Planning,” (Under Review at *Ecology and Society* as part of a special issue on Governing Adaptation)

Hughes, Saraand Patricia Romero Lankao. “Institutional Drivers, Science Politics, and Urban Climate Change Planning in Mega-Cities”(In preparation; presented at APSA 2012)

Other CSAP work related to water resource governance included Miller’s continued mentorship of Shannon McNeeley’s work on water planning processes in the Yampa/White River Basin of Colorado, and Miller and Wilhelmi’s contributions to a NOAA-funded project in collaboration with the University of Colorado on “Interactions of Drought and Climate Adaptation for Urban Water.”

FY2012 Accomplishments: Marine Fisheries

It is notoriously difficult to maintain environmentally responsible and economically efficient management of commercially-exploited marine fisheries. The common-pool nature of fishery resources makes them vulnerable to competitive harvesting that can result in a race to "the tragedy of the commons." To be effective, marine resource governance arrangements must not only control that tendency, but also must be able to maintain ecologically sustainable harvesting levels for targeted species despite often complex, highly variable and difficult-to-observe biophysical processes driving the dynamics of those populations and their supporting ecosystems. In FY 2012 CSAP's Dr. Miller led an international team in writing a paper on the governance of marine fisheries in a changing climate. The paper reviews the current state of marine fishery stocks and current impediments to their effective governance. In addition, it reviews the scientific literature on the possible impacts of climate change on major marine fisheries and discusses the problem of international coordination in the context of inherent uncertainties regarding both current and future variations in the size and productive potential of internationally shared fish stocks. The theory of strategic optimization is brought to bear in discussing both successful and dysfunctional multinational efforts to manage shared fisheries that have been significantly affected by climate-related perturbations.

Dr. Miller also worked with an international team of social, biological and physical scientists on a paper initially submitted to *Science*, then revised and resubmitted to *Nature,* where it is currently in review. She also gave a lecture on the sustainability of marine fisheries in a changing climate at Iowa State University and she was a co-organizer of a half-day side meeting and a session on Oceanic Ecosystem Governance at the "*Planet Under Pressure"* conference in London, March 2012, at which she presented a paper on game theoretic insights on cooperation and conflict in oceanic ecosystem governance.

Related Papers:

Miller, K.A., G.R. Munro, U.R. Sumaila and W. W.L. Cheung. Governing Marine Fisheries in a Changing Climate: A Game Theoretic Perspective. Submitted to *Canadian Journal of Agricultural Economics*, Special Issue 2013: "Applied Economic Analysis of Marine Resource Management Issues in the 21st Century." (In Revision).

Maury, O., K. Miller, L. Campling, H. Arrizabalaga, O. Aumont, Ö. Bodin, P. Guillotreau, A.J. Hobday, F. Marsac, Z. Suzuki and R. Murtuggude. A global science-policy partnership for progress towards sustainability of oceanic ecosystems and fisheries. Submitted to *Nature*. (In Review).

FY2013 Plans

In FY2013, Dr. Miller, Dr. Wilhelmi and Kevin Sampson will collaborate on an analysis of the legal, economic and geographic aspects of transbasin water diversions from the Colorado River Basin to Colorado's Front Range, as part of the NSF-WSC project: "Snowpack-ecosystem feedbacks and the sustainability of transbasin diversions under a changing climate." At present, transbasin diversions move approximately 20 percent of the flow the Colorado River from the headwaters area to Colorado's eastern slope, where they make a significant contribution to both agricultural and urban water supplies. The sustainability of these transbasin diversions in the face of the impacts of a changing climate will depend not only on the physical changes in the volume and timing of runoff, but also on the details of the governance and infrastructural setting. Important factors include the seniority structure of the water rights for the transbasin diversions relative to the rights of western Colorado users, water marketing opportunities and constraints, the marginal value of water to each group of stakeholders, Interstate Compact obligations to downstream states, and the location and capacity of water storage and transport infrastructure relative to potential water demands. The project will make use information from the state of Colorado's hydrobase data base, published literature and legal documents to characterize the rules and limits governing transbasin diversions. Interviews with key stakeholders will provide information on the impacts of drought events, the use of climate information in long-term planning, and the drivers of policy innovations and contractual arrangements including the recently concluded Colorado River Cooperative Agreement between Denver and western slope water interests. The CSAP team will integrate this work with analyses conducted by other project participants to develop a spatial model of transbasin diversions under future streamflow scenarios for assessment and valuation studies.

FY13 plans also include further work on the dynamics of water governance institutions. Drs. Miller, Romero-Lankao and Hughes intend to collaborate on a paper on the evolution of water governance institutions. The goal of this effort will be to develop a theoretically-grounded framework for analyzing the dynamics of water-resource governance systems and for evaluating how vulnerability and adaptive capacity interact with that evolutionary process.

Dr. Miller also is working on a book proposal on: "Water Policies in the Context of Climate Change," to be co-edited with Douglas Kenney (CU School of Law) and Andrea Ray (NOAA Earth System Research Lab). This will be an invited contribution to a book series on: "Drought and Water Crises: Science, Technology, Management and Policy Issues for the 21st Century." The project is currently at the inception phase, and work is expected to extend over the following 18-24 months.

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https://nar.ucar.edu/2012/lar/ral/resilient-and-sustainable-cities Go

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society
  - Use and Value of Weather Information
  - Governance and Adaptation
  - Resilient and Sustainable Cities
  - Weather, Climate and Health
  - Geographic Information System (GIS) Program

Resilient and Sustainable Cities

Background

Urban areas play crucial roles in the arena of climate and environmental change, not only as key sources of carbon and other air pollutants, but also as hotspots of vulnerability to water scarcity, floods, heat waves, and other hazards that climate change is expected to aggravate. These roles create a unique opportunity for urban centers to prove their talents as sources of innovations, and laboratories for responses that help transition to more sustainable and more resilient pathways of urban development. The main goal of Resilient and Sustainable Cities (RS–Cities) is to integrate different disciplinary domains within NCAR and with other national and international organizations to:

- Explore the dynamics of urbanization and urban systems that shape urban emissions, vulnerability and risk
- Investigate urban populations' vulnerability to hazards and stresses
- Research how particular cities attempt to meet the challenges of reducing emissions while improving their response capacity (resilience) to environmental impacts
- Build capacity to foster urban sustainability and resilience through educational, mentoring and outreach activities at the science-policy interface

2012 Accomplishments

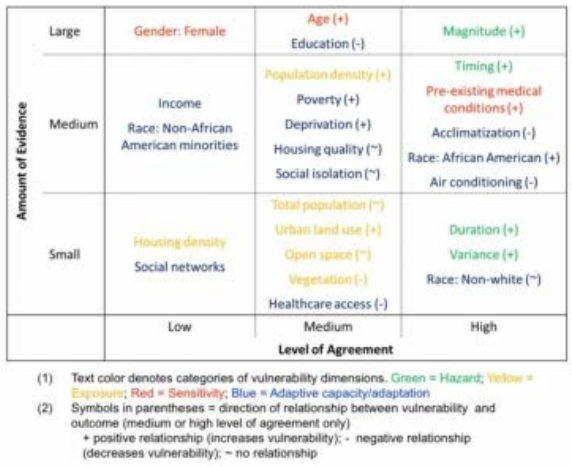
Dynamics of urbanization and urban systems that shape urban emissions, vulnerability and risk

An NSF Partnerships in International Research And Education (PIRE) Grant has been recently awarded to a team led by Anu Ramaswami (University of Minnesota), Marian Chertow (Yale), Ted Russell (Georgia-Tech), Paty Romero- Lankao (RS-Cities, NCAR), Chris Weible (University of Colorado Denver) and Rachelle Hollander (The National Academy of Engineering, NAE). Their project "Developing Low-Carbon Cities in the USA, China & India through Inter-Disciplinary Integration Across Engineering, Environmental Sciences, Social Sciences & Public Health" will a) evaluate three infrastructure interventions that can lower GHG emissions, enhance resource-efficiency and improve public health in cities; b) examine whether municipalities with different socioeconomic and infrastructure levels can be differentiated with respect to health risks; c) explore the extent to which local water-supply and public health concerns motivate the adoption of these low-carbon infrastructures; and d) identify the most effective political and institutional "nudges" that can facilitate such adoption in different city types.

Urban populations' vulnerability and risk

Four publications from ADAPTE led by Dr. Romero-Lankao explore vulnerabilities and risks among urban populations in the Latin American cities of Bogota, Buenos Aires, Mexico and Santiago through an empirical assessment of:

a. The health impacts of air pollution and temperature. We hypothesized that, on the intra-urban scale, health risks from air pollution and temperature in Latin American cities would not necessarily depend on socio-economic differentiations. Our results suggest that health risks from atmospheric conditions and pollutants act without boundaries or social distinctions within urban areas. For PM10, ozone and other criteria pollutants at the high concentration levels found in our study, populations in some of the least and the most socioeconomically vulnerable municipalities are at similar risks when simultaneously exposed



Determinants of urban vulnerability to temperature-hazards: levels of evidence and agreement

to air pollution and temperature change. These findings are contradictory to what would be normally predicted by the environmental justice literature.

b. The linkages among other components (e.g., sensitivity, capacity, perception and responses). Our findings on the risk of mortality among sensitive groups do not support existing literature, which tends to emphasize a universal physiological sensitivity to air pollution and temperature within vulnerable populations such as the elderly or women. On the contrary, we found inconsistencies in the data on how age and gender related to mortality risk. More empirical work on occupation, education, equity in access to resources, cultural roles and other factors could explain many of these inconsistencies.

Awareness of the urban risks and a suit of wellbeing-protection actions emerged as a fundamental component of adaptation responses. For example, households were asked how they deal with seasonal temperature changes in their homes. The varied answers depended on various factors, e.g., the latitude of the city, how much temperature variability people are exposed to, and availability of assets. While respondents in Buenos Aires use air conditioner to cope with hot and humid summers, respondents in Bogota do not use the heater in the winter as much as those in the other three cities, likely because it does not get as cold.

One product of the NSF Data Conservancy project was a meta-analysis paper published by Romero-Lankao, Qin and Dickinson on the determinants of populations' vulnerability to temperature-hazards in 222 cities. The results of the meta-analysis indicate that urban populations' vulnerability has mostly been examined using thirteen factors: hazard magnitude (i.e., temperature level), population density, age, gender, pre-existing medical conditions, education, income, poverty, minority status, acclimatization, and access to home amenities such as air conditioning and swimming pools. The vast majority of papers examining urban vulnerability to temperature-related hazards come from an *urban vulnerability as impact* approach. Cities from middle and low income countries are understudied.

Related publications

Abrutzky, R., Dawidowski, L., Matus, P., Romero Lankao, P. (2012) Health effects of climate and air pollution in Buenos Aires: a first time series analysis, Journal of Environmental Protection, 3 (3) 262-271

Romero Lankao, P., Qin, H., and Dickinson, K., 2012: Urban vulnerability to temperature-related hazards: A meta-analysis and meta-knowledge approach, Global Environmental Change, Available online 15 May 2012

Romero-Lankao, P., Qin, H., Hughes, S., Haeffner, M., Borbor-Cordova, M. (2012),"Chapter 10 Urban Vulnerability and Adaptation to the Health Impacts of Air Pollution and Climate Extremes in Latin American Cities", William G. Holt, in (ed.) Urban Areas and Global Climate Change (Research in Urban Sociology, Volume 12), Emerald Group Publishing Limited, pp. 247 – 275

Romero Lankao, P., Borbor-Cordova,M., Abrutsky, R., Günther,G., Behrentz, E. 2012: ADAPTE: a tale of four teams seeking to do integrated research, Environmental Science and Policy (Available on line).

Urban mitigation and adaptation responses

There is increasing interest in understanding the motivations behind cities' efforts to govern climate change, the strategies they employ, and their institutional capacity to enact the necessary policies and programs. A publication under review used interviews with governmental and nongovernmental actors and secondary data sources from the cities to better understand the political-economic determinants of institutional response capacity in Mexico City (a frontrunner) and Santiago de Chile (a laggard). We designed a framework to trace the political-economic construction of institutional response capacity: the actor-networks involved, the effectiveness of the legal framework, the use of information, and the inclusion of participation.

Romero Lankao, P., 2012: Governing climate change in cities: An overview of policy and planning challenges and options, European Planning Studies 20(1): 7-26

Romero-Lankao, P., Hughes, S., Rosas-Huerta, A., Borquez, R., Haeffner, M., "Urban Institutional Response Capacity for Climate Change: An examination of construction and pathways in Mexico City and Santiago", Special Issue of Environment and Planning C (in review).

Building capacity to foster urban sustainability and resilience

Paty Romero-Lankao has mentored two postdoctoral fellows and one graduate student. In collaboration with Roberto Sanchez (COLFEN, Mexico) Ricardo Jordan (CEPAL) and Marcella Ohira (IAI), she is developing a practical and useful guide to adaptation and mitigation experiences in Latin American cities. She is currently convening author of the IPCC-AR5 North American chapter and author of its Technical Summary and Summary for Policy Makers.

Plans for 2013

In 2012 Dr. Paty Romero-Lankao will conduct further research in the three areas described above with NCAR and international partners. The PIRE grant will start. A new research proposal is underway on three process of urbanization shaping exposure, sensitivity and response capacity in two cities. Dr. Romero Lankao will continue working with Dr. Miller on the analysis of the dynamics of governance arrangements for adaptive urban water management. And she will

publish a typology framework, along with 10 national and international colleagues from UGEC,**[1]** to examine urbanization characteristics, processes and indicators of vulnerability and emissions as they define different sets of mitigation and adaptation opportunities and challenges.

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[1] Solecki (CUNY), Seto (Yale), Balk (CUNY), Bigio (WB), Boone (ASU), Creutzig (TU-Berlin), Fragkias (ASU), Romero-Lankao (NCAR), Lwasa (MAK-UG), Marcotullio (CUNY), Zwickel (WGIII-TSU)

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society
  - Use and Value of Weather Information
  - Governance and Adaptation
  - Resilient and Sustainable Cities
  - Weather, Climate and Health
  - Geographic Information System (GIS) Program

Weather, Climate and Health

There is widespread scientific consensus that the world's climate is changing and that there will be a broad range of impacts on health through a variety of factors, including greater heat stress, air pollution, respiratory disease exacerbation, and changes in the geographic distribution of vector-, food- and water-borne disease. The complexity of such influences requires a multi-disciplinary approach to address climate-related public health challenges. The overall goal of this work is to research the complex interactions among weather and climate processes, ecosystems, and human health in order to improve our knowledge of climate impacts on human health and the health of the planet. Through collaboration within RAL (Barlage, Del Monache, Hopson, Monaghan, Wilhelmi), with other laboratories in NCAR (Morss - MMM, Oleson – CGD, Sain - Image), UCAR (Pandya), ACD (Wiedinmyer) with university partners (CSU, CU, KU, U of Veracruz, U of AZ), federal agencies (CDC, NASA, NIH, Environment Canada), and state and local agencies (AZ Department of Health Services, Maricopa County Health Department, Office of Border Health (AZ),Toronto Public Health (Canada), Monroe County Health Dept. (Key West, FL) and Houston Department of Health) the research will focus on:

- Investigating the complex relationships among weather, climate, human health and ecosystems
- Researching population vulnerability to human health threats
- Determining appropriate adaptation and mitigation strategies to tackle these issues
- Educating the next generation of scientists in these complex, yet interconnected areas

FY2012 Accomplishments

Health Risks from Extreme Heat

Our changing climate is predicted to increase the intensity and impacts of heat waves prompting the need to develop preparedness and adaptation strategies that reduce societal vulnerability. Work continues on our NASA funded project to develop a System for Integrated Modeling of Metropolitan heat Risk (SIMMER). The project focuses on understanding population vulnerability to extreme heat in Houston, TX, and, from the social science side, we are adopting a two-tiered approach to this. The household level survey of a cross-section of Houston residents and their adaptive capacity was undertaken in November 2011. Additionally, we conducted interviews of stakeholders to better understand response, preparedness and strategies for short and long-term adaptation and mitigation to extreme heat.

Human–Environmental Interaction and Risk for Dengue Fever

Dengue is an emerging arboviral disease with worldwide impact. Increasing numbers of cases of this disease in both the Americas and Asia necessitate an examination of changing human and vector ecology in order to better understand the dynamics of dengue transmission.

We successfully completed our second field season with funding from NSF to conduct a new program to address this world-wide human health threat. The program, "The vector mosquito *Aedes aegypti* at the margins: sensitivity of a coupled natural and human system to climate change", is designed to investigate and model dengue fever risk along an altitudinal gradient from Veracruz to Puebla, Mexico, in FY2011-13. We have established a highly successful working relationship not only with our collaborators at the University of Veracruz, but also with four high schools along the transect where mosquito and weather data are being collected. Early results for the first year will be presented at the annual meeting of the American Society of Tropical Medicine and Hygiene.

Additional funding for a one-year pilot has been received from the National Institutes of Health to conduct work on *Ae. aegypti* in Arizona and Florida. Work will begin on this project in early 2012.

A prototype Earth–gauging System Integrating Weather and Health Data to Manage Meningitis

This project supported by the Google Foundation aims to build and implement a prototype decision–support system that integrates two–to 14–day weather forecasts and epidemiological data to provide actionable information that can be used to

contain the spread of meningitis epidemics. In 2012 we continued to build our local partnerships in Ghana, undertook a site visit to conduct data analysis with our collaborators of a survey on knowledge, attitudes and practices (KAP) and cost of illness (COI) regarding meningitis in the Navrongo region of Ghana which was completed in early 2011. Results were presented at the American Society of Tropical Medicine and Hygiene annual meeting in December 2011 and at the American Meteorological Society meeting in January 2012. A manuscript detailing the knowledge, attitudes and practices of households in northern Ghana is currently under review. Work is ongoing to demonstrate weather–meningitis links, and develop and verify ensemble–derived forecasts for meningitis management.

Figure 1. Conducting a survey in Navrongo, Ghana

Integrating the Social and Physical Sciences to Reduce the Incidence of Plague in Rural Uganda

This project, sponsored by the Centers for Disease Control and Prevention and the U.S. Agency for International Development focuses on building links between weather variables and plague cases in order to develop an early warning system to allow limited resources for control of plague to be directed to the region. Additionally, we are working on enhancing surveillance for plague and assuring better access to health care for the residents of the West Nile region of Uganda by training traditional healers and village health workers to recognize plague symptoms and by providing them with cell phones so that they can call into the health clinics when cases are recognized. An evaluation of the program, which was begun in 2010, was conducted in 2011, and based on positive feedback, further training to an expanded traditional healer network was conducted in 2012.

Figure 2a. Traditional Healer in Rural Uganda

Modeling Plague in Uganda

The West Nile region in northwest Uganda is a focal point for human plague which peaks in boreal autumn and is spread by fleas that travel on rodent hosts. The U.S. Centers for Disease Control and Prevention is collaborating with the National Center for Atmospheric Research to quantitatively address the linkages between climate and human plague in this region. We hope to advance our knowledge of the climatic conditions required to maintain enzootic cycles and to trigger epizootic cycles, as well as how to use limited surveillance, prevention and control resources most effectively.

A hybrid dynamical-statistical downscaling technique was applied to simulations from the Weather Research and Forecasting Model (WRF) to generate a multi-year 2-km climate dataset for modeling plague in the West Nile region. The bias correction spatial disaggregation (BCSD) method of Wood et al. (2004) was applied to one year of dynamically downscaled 2-km resolution WRF simulations to extend the dataset out to ten years. Therefore, only 1-year of expensive dynamical downscaling was required to generate ten years of high-resolution climate data. Independent validation demonstrates that the statistically downscaled ("WRF-DS") fields reproduce the dynamically downscaled ("WRF") fields with high fidelity; an example is shown for near-surface

Modeling plague in Uganda

Figure 2b. Left Panels: 2-km domain WRF-simulated 2003 monthly T_{avg} (^{o}C) for August (top) and February (bottom). Middle Panels: Same as left panels, but for WRF-DS T_{avg}. Right Panels: Difference of WRF-DS minus WRF-simulated T_{avg}.

average temperature for the coolest (August) and warmest (February) months of the year. Additionally, the resulting dataset resolves the spatial variability and annual cycle of temperature, humidity, and rainfall in West Nile compared to satellite-based and *in situ* records (Monaghan et al. 2012). The WRF-based climate fields were successfully applied to develop an improved logistic regression model of human plague occurrence in West Nile, revealing robust positive associations with rainfall at the tails of the rainy season, and negative associations with rainfall during a dry spell each summer (MacMillan et al., 2012).

CDC-NCAR Postdoctoral Fellowship

Two new postdoctoral fellows began work at NCAR in the fall of 2010. In 2011, they have been trained in aspects of climate modeling and will move on for training in epidemiology in the second year of their appointments at the Centers for Disease Control and Prevention in Fort Collins, CO and Atlanta, GA. The goal of this program is to train the next generation of researchers in a multidisciplinary setting so that they are qualified to address the challenges of integrating health and weather/climate data. We anticipate having two new postdocs start in 2013 through this joint program.

Publications

de Sherbinin, A., Wilhelmi, O and **Hayden, M**. (2012) Exposure to Heat Stress in Urban Environments: Current Status and Future Prospects in a Changing Climate. In: Ecologies and Politics of Health, edited by Brian King and Kelley Crews, Routledge Press (in press)

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Lozano-Fuentes S, Welsh-Rodriguez C, **Hayden MH,** Tapia-Santos B, Ochoa-Martinez C, Kobylinski KC, Uejio CK, Zielinski-Gutierrez E, Delle Monache L, Monaghan AJ, Steinhoff DF, and Lars Eisen. (2012) *Aedes (Ochlerotatus) epactius* Dyar & Knab along an elevation and climate gradient in Veracruz and Puebla States, México. (accepted for publication - *Journal of Medical Entomology)*

FY 2013 Plans

Work will continue on the meningitis and plague projects with funding through FY 2013 from Google and the Centers for Disease Control and Prevention (CDC) respectively. New funding has been procured from the NSF to introduce clean cook stoves into the Upper East Region of northern Ghana in an effort to reduce negative health impacts of indoor open fire cooking and improve air quality.

We held a SIMMER project meeting in October 2012, involving our collaborators from KU, Houston Dept. of Health, Environment Canada, and Toronto Dept. of Health. A Houston wide survey on adaptive capacity to extreme heat was undertaken in November 2011 and stakeholders in Houston were queried about preparedness, response and adaptation to extreme heat. Efforts are currently underway to integrate

results from weather and climate modeling with survey data.

Year two field work was completed for the season in Mexico on our NSF funded project, and our NASA collaborators conducted a training workshop at the U of Veracruz in early 2012. We will hold a meeting with all our collaborators in May 2013 to disseminate results of our study.

Funding has been procured for continuation of the CDC post-doctoral program, and we expect to issue a new announcement of opportunity in November 2012.

Figure 3. Demonstration of a clean cook stove in the UER of northern Ghana.

Work was completed on a small NIH funded dengue project focused on Key West, FL and Tucson, AZ in the summer of 2012. A larger, newly funded NIH study also in collaboration with the U of AZ will begin along a transect from Tucson, AZ to Hermosillo, MX to investigate environmental determinants of dengue transmission.

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Log in

RAL Annual Report

- Director's Message
- Table of Contents
- Next Generation Air Transportation
- New and Emerging Applications
- National Security Applications
- Numerical Systems Testing and Evaluation
- Hydrometeorological Applications
- Climate, Weather and Society
  - Use and Value of Weather Information
  - Governance and Adaptation
  - Resilient and Sustainable Cities
  - Weather, Climate and Health
  - Geographic Information System (GIS) Program

Geographic Information System (GIS) Program

The Geographic Information System (GIS) program at the National Center for Atmospheric Research (NCAR) is an interdisciplinary effort to foster collaborative science, spatial data interoperability, and knowledge sharing with GIS. Working toward the definition, standards and interoperability of atmospheric information for usable science, the GIS program is: 1) conducting research integrating the Earth system and social sciences through spatial analysis and interoperability of georeferenced information; 2) supporting the use of GIS as both an analysis, and an infrastructure tool in atmospheric research; 3) improving usable science and knowledge sharing between science groups, educators and stakeholders; and 4) addressing broader issues of spatial data management, interoperability, and geoinformatics within the geosciences. Research progress in integration of geographic and atmospheric information allows GIS staff to lead and participate in a variety of research projects at NCAR, where spatial analysis and accurate georeferenced data are critical to answering complex interdisciplinary questions. With more than one hundred GIS users in all NCAR laboratories, the projects range from atmospheric chemistry to societal impacts of climate change to homeland security.

Current research activities in the GIS program occur in three thematic areas:

- Integrating physical and social science data in GIS
- Improving spatial accuracy and usability of atmospheric models for terrestrial and societal applications,
- Conducting GIS-focused educational activities at the science-society interface.

FY2012 Accomplishments

Integrating physical and social science data in GIS

Integration of quantitative and qualitative data for spatial assessment of local level vulnerability and adaptive capacity to extreme heat

This work is focused on theoretical and methodological advancements for assessing local level vulnerability and adaptive capacity to extreme heat. A research framework for extreme heat vulnerability assessment (Wilhelmi and Hayden 2010) has been adopted in several projects as well as in a broader context of societal vulnerability to weather extremes (i.e., NASA SIMMER project, Morss et al. 2011; Wilhelmi et al. 2012; Wilhelmi and Morss 2012, Hayden et al. 2011). More recently, the framework has been highlighted in the report by the NRC Committee on Urban Meteorology (NRC, 2012) as a model for connecting science to stakeholder needs.

Successful completion of the second year of the SIMMER project included the analysis of the household survey in Houston, Texas. The survey has been analyzed using multi-dimensional scaling and multi-level hierarchical statistical modeling techniques in order to better characterize adaptive capacity to extreme heat and determine response and adaptation strategies. Research on incorporation of the survey results, along with data on societal risk and vulnerability to extreme heat, into interactive GIS mapping system is currently underway.

Wilhelmi O.V. and Hayden M.H. (2010) Connecting people and place: a new framework for reducing urban vulnerability to extreme heat. Environ. Res. Lett. 5 014021. doi: **10.1088/1748-9326/5/1/014021**

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System for Integrated Modeling of Metropolitan heat Risk (SIMMER)

This large, multi-disciplinary and multi-institutional project (Figure 1) addresses the critical need for information at regional to local scales that are pertinent to public health decision-making in the context of global change. The primary goals are to: 1) advance methodology for assessing current and future urban vulnerability from heat waves through integration of physical and social science models, research results, and NASA data; and 2) develop a System for Integrated Modeling of Metropolitan Extreme Heat Risk (SIMMER) for building local capacity for heat hazard mitigation and climate change adaptation in the public health sector.

Figure 1. SIMMER research partners and study sites.

The SIMMER model is being developed for Houston, TX, however the methodology is intended to be transferrable to other urban centers. The robustness of the method and its transferability will be validated in Toronto, Canada. With the help of Canadian collaborators we will apply and validate the SIMMER model in assessing heat-related health risks and social vulnerability in Toronto. Involvement of public health sector stakeholders from Houston and Toronto ensures that relevant applications for the model in the context of climate change and human health are included. The SIMMER project is producing interesting results which will be synthesized during the third year of the project.

Global assessment of urban heat island effect and future heat waves: GIS applications in urban climate modeling

Empirical studies and model simulations suggest increasing health risks associated with climate change and extreme heat events in cities across the world. Global simulations of present-day and future climates from NCAR's Community Climate System Model, coupled with Community Land Model – Urban (CMLU) have been analyzed in a GIS with respect to the urban heat island effect and changes in extreme heat events. This project investigates spatial and temporal trends in future heat waves across the globe and examines potential impacts of combined effect of urban heat island and future heat waves on urban population. This project also involves development of methods for integrating climate model simulations with data on population projections, as well as geoprocessing techniques for working with the netCDF model outputs in a GIS. The goal of this analysis is to highlight potential changes in exposure of urban residents to extreme heat and the need for heat hazard mitigation and climate adaptation. A journal article is currently in preparation and will be submitted in early 2013. Additional analysis conducted in 2012 involved global, country-level assessment of extreme heat, population and economic projections.

Figure 2. Projected changes in extreme heat events as simulated by NCAR CCSM-CLMU

Analysis of the UCRB water demand

With the goal to provide information useful for managing current drought risks and for adapting to changing climate, this project aims to fill the gaps in the knowledge about the variations in water demand patterns in the Upper Colorado River Basin (UCRB) in response to climate variability. Specific objectives of the project included: 1) assessing knowledge gaps in the UCRB water demand information at the local scale; 2) analyzing spatial and temporal patterns in water demand across the study domain; 3) examining topological relationships among water users and their respective sources; and 4) linking spatial (and non-spatial) information on water demand to water supply to assess potential impacts of drought on water users. A major component of this activity focused on development of a method and a set of tools for spatially modeling water demand with available data at spatial scales to support decision making. The study resulted in a geodatabase and a data model (i.e., NIDIS Water Demand data model) that provides a scalable, flexible approach for estimation of water demand. This data model also supports explicit topological relationships among water users and their respective source or sources of water supply. To ensure transferability, the geodatabase and automated geoprocessing tools for estimating water demand and highlighting vulnerable water users have been tested in other basins in the state of Colorado. In 2012, state-wide study focused on the analysis of the water rights seniority as a potential factor of drought vulnerability. The analysis included spatial and statistical (i.e. extreme value theory) analysis. The results are currently being summarized in a journal article.

Improving spatial accuracy and usability of atmospheric models for terrestrial and societal applications

In 2012, the GIS program continued working to improve the spatial accuracy and usability of atmospheric models for

terrestrial and societal applications. The GIS program researchers have been developing methods and tools to facilitate climate- and weather-related policy and decision making. Climate Change GIS data portal (http://www.gisclimatechange.ucar.edu) provides GIS-compatible user access to CCSM AR4 global and the downscaled U.S. simulations. Over 4000 users from 137 countries have accessed the CCSM-3 climate predictions through the GIS data portal. In 2012, scientists and engineers at NCAR's Research Applications Laboratory (RAL) and Computational Information Systems Laboratory (CISL) updated the site to add a host of new features. Now, GIS users can not only access their choice of dates, variables, and formats (shapefile or text) from the CCSM simulations, but pre-processed data such as long-term averages and climate model anomalies are also now available. The site redesign offers a much smoother user experience with user registration, the ability to provide more data, and an implementation of web service technologies, which accelerate data retrieval and on-the-fly conversion. The site also includes extensive documentation regarding the appropriate use of climate model data along with an educational tutorial. In our effort to make climate change data more useful and easily accessible, climate change anomalies and climatologies are being distributed as Open Geospatial Consortium (OGC) web services.

The distribution of data through these open protocols allows more flexibility in data retrieval and visualization. We are exploring the capabilities and limitations of using a THREDDS Data Server as the web server and Web Map Services (WMS) and Web Coverage Service (WCS) as the access protocols. Along with data distribution we are also exploring the appropriate metadata needed in order to comply with OGC and ISO metadata standards for data distribution and data discovery. Issues of uncertainty, data lineage, and statistical methodologies have all been explored in order to best explain the climate products to non-climate scientists.

Methods of conversion between sphere-based models and ellipsoid-based data for GIS analysis have been tested, under the SIMMER research umbrella, to determine the full potential of the sphere-ellipsoidal shift and its impacts upon the output positional accuracy for numeric weather models as well as, the use of these models to determine impacts upon society, and infrastructure (Monaghan et al. 2012)

Andrew J. Monaghan, Michael Barlage, Jennifer Boehnert, Cody L. Phillips, and Olga V. Wilhelmi, "Overlapping interests: The impact of geographic coordinate assumptions on limited-area atmospheric model simulations of datum assumptions in input datasets" submitted to Monthly Weather Review in November 2012

GIS education at the science – policy interface

In 2012, Wilhelmi, Boehnert and Hayden conducted several interdisciplinary, interactive training workshops focusing on the science of climate change, societal vulnerability and Geographic Information Systems (GIS). Workshop participants included faculty and students from Tribal Colleges. This training was part of the funded activity "Preparing Indian Country for Climate Change through Technology, Education and Research", conducted at Haskell Indian Nations University. The workshop included presentations, hands-on GIS exercises, and group discussions. The participants were introduced to climate change science, modeling and scientific uncertainty. They learned about climate impacts, vulnerability and adaptation. Workshop addressed top-down and bottom-up approaches to conducting integrated vulnerability assessments across geographic regions and economic sectors. Other efforts in GIS education and training included several NCAR-hosted workshops, including RETI and the Diversity Workshop. The diversity workshop, "Enhancing diversity in climate change science and applications: from models to adaptation" engaged student (undergraduate and graduate) and faculty teams from minority-serving institutions, including Historically Black Colleges and Universities.
http://www.ral.ucar.edu/csap/events/diversity/

Figure 3. GIS education and training workshop, "Enhancing diversity in climate change science and applications: from models to adaptation"

FY2013 Plans

Work will continue in the three focus areas described above. A new version of the climate change portal is expected to be updated with AR5 model simulations. We will continue making progress in developing research frameworks and spatial methods for integration of diverse, multidisciplinary datasets, which are both quantitative and qualitative and exist at different spatial and temporal scales. Ongoing, externally funded projects in this area of research are focused on extreme heat and human health, as well as on drought and water use. Previously developed educational materials that link GIS, climate science and societal vulnerability and adaptation will be adjusted for a variety of training programs and workshops, the IAI-NCAR colloquium on Knowledge Integration at Science-Policy Interface to be conducted in Dominican Republic in FY2013. Training modules will use open source GIS software (i.e., QGIS, GRASS). Several papers are currently in preparation and are expected to be submitted for publication in 2013.

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