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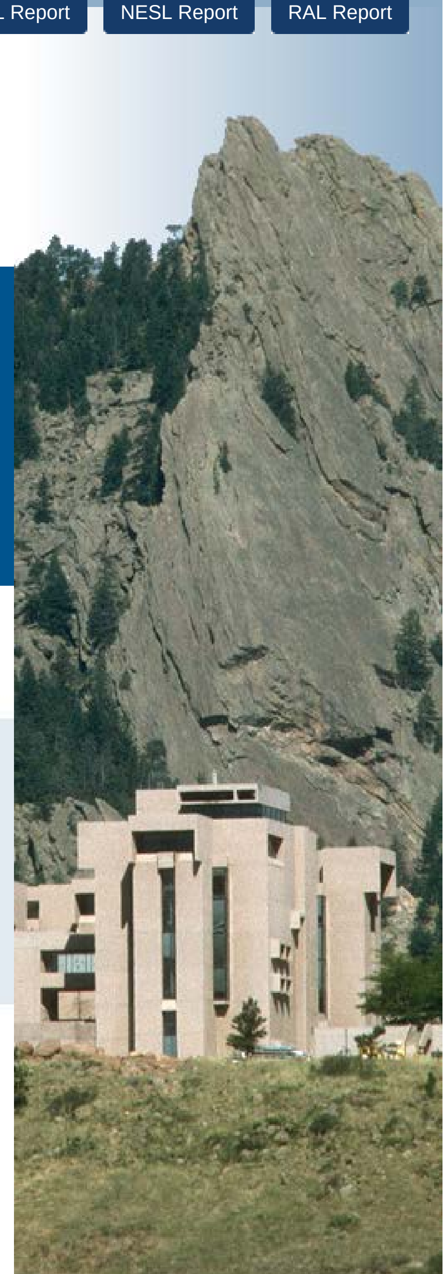

National Center for Atmospheric Research

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A Message from the Director »

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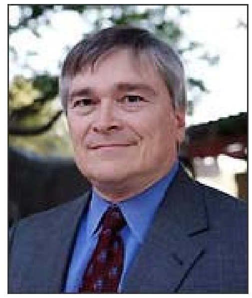
A Message from the Director



Fiscal Year 2009 (FY2009) was an exciting one, as NCAR continues to be a crossroads for scientific interaction and collaboration. The heightened interest in climate by decision makers, funding agencies and society as a whole is reflected in many of the stories included in this annual report. Our focus — and that of the National Science Foundation — on ways in which science can serve and improve societal welfare also features significantly, as does work being done by the universities, government laboratories, and international and national research institutions that we serve. By focusing on five themes—**Accelerated Scientific Discovery**, **U.S. Western Water and Environment**, **Science Serving Society**, **Taking Science to the Field**, and **Cutting-edge Research**—we provide a snapshot of NCAR competencies, facilities, and the community-wide accomplishments achieved in Fiscal Year 2009. Additional details on the support, tools, and research efforts being pursued within NCAR's four Laboratories can be found in the Laboratory Annual Reports.

I invite you to delve further into the NCAR Annual Report, as well as the Laboratory Annual Reports, to learn more about these and our many other FY2009 efforts.

Best wishes,
Eric Barron

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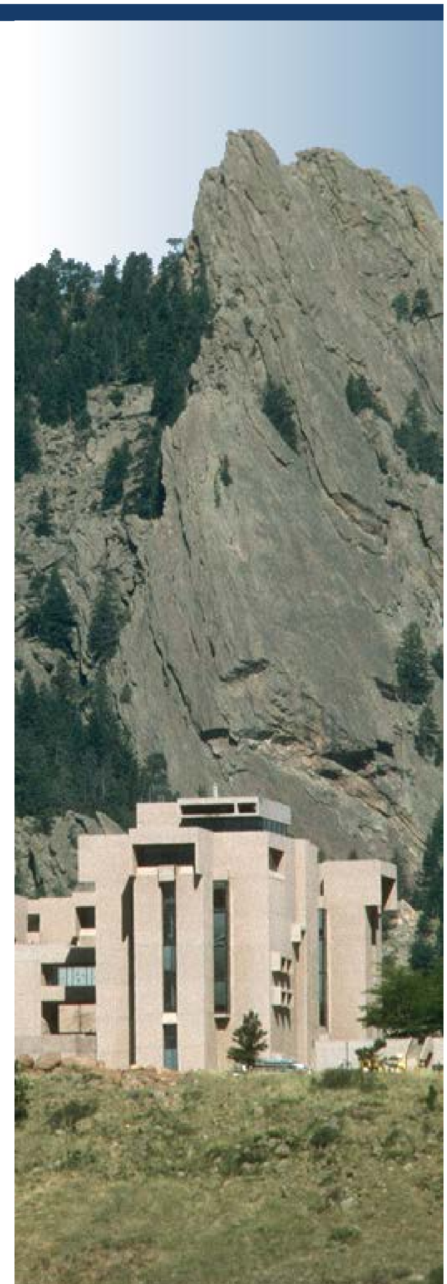

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Accelerated Scientific Discovery

During the first three months of FY2009, nearly 40% of bluefire, NCAR's latest supercomputer, was dedicated to the Accelerated Scientific Discovery (ASD) initiative, which provided a number of production-ready projects with the opportunity to make accelerated progress on important scientific problems. In the subsequent months of Fiscal Year 2009, NCAR's Computational and Information Systems Laboratory (CISL) dedicated smaller portions of bluefire to NCAR and university scientists to address select challenging problems. Highlights related to some of these projects are featured in the following pages. Also see **CISL's Laboratory Annual Report** for additional project details.

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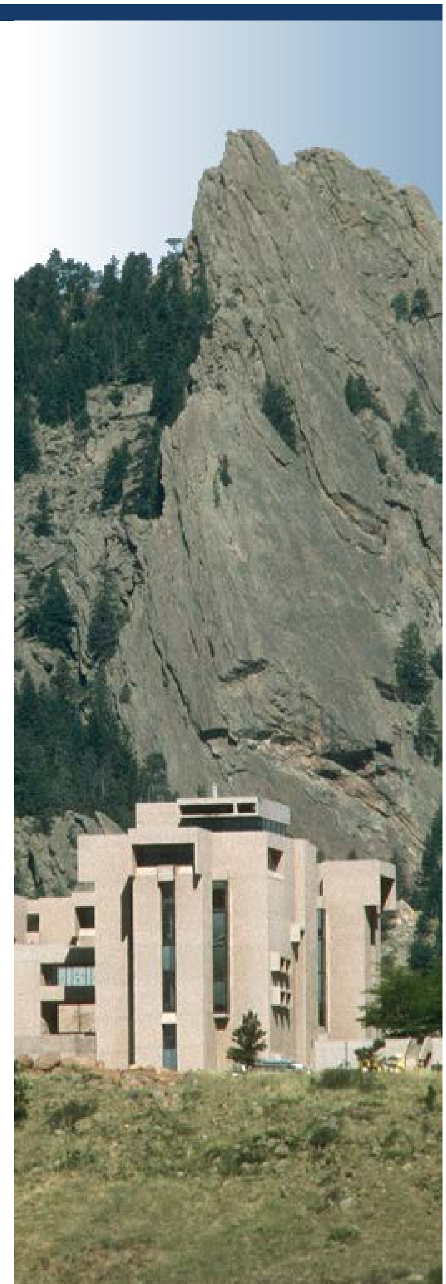

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Slicing into the future of hurricanes: Insurers get a sharper look at potential trends

Like individuals, industry faces safety and financial risk related to extreme weather events. Reinsurers — insurers of insurance companies — want to understand how changing climate might affect the strength and frequency of extreme events. Similarly, energy companies that have infrastructure (oil rigs, refineries) and personnel located on and near coasts clamor for ever-more accurate weather forecasts and climate change impact information to aid evacuation planning and infrastructure design efforts, as well as to address bottom-line concerns.

In the case of hurricanes in the Caribbean and U.S. Gulf Coast, forecasts of future storm activity — hurricane path, intensity, distribution — in the next 50 to 100 years have traditionally been made using statistical models based on historical data.

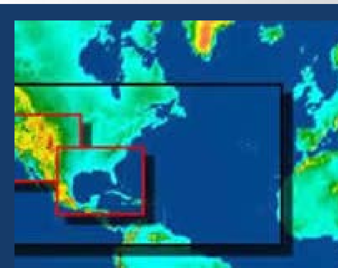
In the case of hurricanes in the Caribbean and U.S. Gulf Coast, forecasts of future storm activity — hurricane path, intensity, distribution — in the next 50 to 100 years have traditionally been made using statistical models based on historical data. But, because of the long life of many greenhouse gases (50 to 100 years in the case of carbon dioxide), ongoing climate warming is effectively built into the system. This means that historic hurricane data are not likely to be useful predictors for future hurricane trends during the next 50 years. As a result, industry leaders are turning to scientists for help in predicting how climate might affect their business in coming decades.

Wanting to capture both global climate dynamics and the behavior of a single hurricane, a group of researchers from NCAR, the university community, federal agencies and industry looked at combining the Weather Research and Forecasting (WRF) model and the Community Climate System Model (CCSM). The Nested Regional Climate Model (NRCM) was the result, offering the benefit of both global and regional perspective.

Funded by NSF's Accelerated Scientific Discovery, which allocates windows of computing time to study science questions, and by the Willis Research Network and the offshore oil industry, the researchers looked at the effects of warming climate and hurricane genesis for 1995 through 2055. Because of the intensive computing power and time required to generate high-resolution (36 km) model output, the team generated time slices for three decades — 1995-2005, 2020-2030, and 2045-2055 — and used statistical analyses to fill in the missing data points. While other research groups have used similar nesting techniques, these efforts haven't been done at such a high level of resolution or for this duration of time.

The study's focus honed in on tropical areas — especially over Africa and the North Atlantic — so as to capture the disturbances in pressure, temperature, wind and other variables, known as easterly waves, as they travel from Africa to the Caribbean. Approximately 60% of all North Atlantic basin tropical cyclones and 80% of strong hurricanes develop from these easterly waves. Of particular interest to the team and its funders were high resolution views of hurricane formation in the Caribbean and Gulf of Mexico.

The baseline climate was generated by CCSM using an Intergovernmental Panel on Climate Change CO2 emissions scenario: the A2 'business-as-



Zooming in on future climate. NCAR scientists are using a combination of weather and climate computer models to simulate the atmosphere in three dimensions at resolutions ranging from about 20 miles across a large part of the Northern Hemisphere to as fine as 2.5 miles in targeted areas of North America (red boxes). This strategy enables scientists to forecast future climate in detail for specific regions without overloading existing supercomputing resources.(Contrast between coarse and fine resolution has been increased for illustrative purposes; image by Steve Deyo, �UCAR.)

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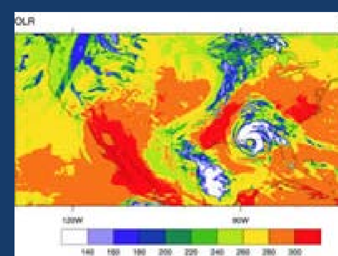

Nested Regional Climate Model Landfalling Cat 4 Simulation. October 10, 2046. Image is color enhanced Outgoing Long Wave Radiation in W/m2.

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usual' scenario based on moderate economic growth. By nesting the higher resolution WRF inside the lower resolution CCSM, model output reflected both large-scale and smaller, hurricane-scale dynamics. The scientists noticed that the NRCM didn't represent tropical cyclones as well as it should, but by incorporating NCAR-NCEP (National Centers for Environmental Prediction) Reanalysis data, improved NRCM accuracy in depicting regional atmospheric phenomena.

Already, insurance companies are using this work to identify the level of risk faced by coastline development. These initial runs are being analyzed to address the reinsurance and energy organizations' immediate needs, even as NCRM work continues. Among the planned model improvements is an enhanced ability for 2-way telescoping of data. Currently, NRCM scales down to regional dimensions effectively, but with improved scaling from regional up to global, users would gain more nuanced understanding of the small-scale effects of wind, precipitation, humidity, etc. on global climate; this would enhance the realism with which global climate is replicated in general circulation models.

A fully coupled regional and global modeling system offers a practical approach to high-resolution climate modeling, yet the knowledge of how best to achieve this is still in its infancy. The NRCM provides a powerful tool from which we can learn from and satisfy an urgent need to provide useful forecasts of changes in high-impact weather.

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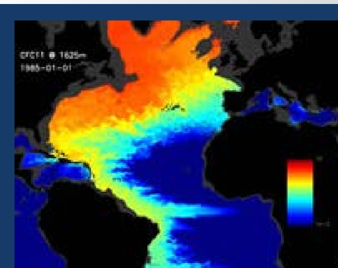
Modeling Ocean Transport Pathways

by Agatha A. Bardoel



Nested Regional Climate Model Landfalling Cat 4 Simulation. October 10, 2046. Image is color enhanced Outgoing Long Wave Radiation in W/m2.

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Oceans play a critical role in the Earth's balance of heat and water, and in the uptake and redistribution of chemicals such as carbon dioxide (CO2) and chlorofluorocarbons (CFCs). After absorbing chemicals from the atmosphere at the surface, the ocean can store substances for hundreds to thousands of years, circulating them through the 319 million cubic miles of water around the globe. This ventilation process influences climate in multiple, still-to-be-determined ways. Difficult to measure directly, it can be inferred from observations of dissolved chemical compounds, or tracers. One particularly useful class of chemical tracers for seeing how chemicals are moved through the ocean are CFCs, which human activity has introduced to the atmosphere in known quantities since the 1930s.

Using Jaguar, the Cray XT computer system at Oak Ridge National Laboratory, and the National Center for Atmospheric Research's (NCAR) blue fire super computer, NCAR's Synte Peacock and Frank Bryan, and Mathew Maltrud at Los Alamos National Laboratory (LANL) , for the first time carried out a 100-year global eddying ocean simulation run. The model carried CFCs, as well as a host of other tracers that have yielded valuable information about ocean ventilation pathways and timescales. By comparing the measured CFC concentration at a point deep in the ocean to the surface concentration, scientists can estimate how long it has been since a water parcel was last at the surface. However, because CFCs have been in the atmosphere for only tens of years (not thousands), this age metric has an inherent bias. To better understand ventilation timescales, a number of highly idealized age tracers were also transported by the NCAR/LANL ocean model. Together with simulated CFCs, these have provided new insights into transport processes and timescales.

Due to the limits of computational power, most previous ocean model studies of tracer distributions have used fairly coarse resolutions (grid spacing greater than 100 kilometers), for which some important transport activities are poorly resolved. To begin to resolve features such as narrow currents and mesoscale eddies (circular loop-like features with diameters of less than 200 kilometers), researchers need a model with a finer grid resolution — kilometers to tens of kilometers. Thanks to powerful supercomputers such as Jaguar and blue fire, it has been possible to perform studies of the ocean uptake of CFCs and other trace gases using global fine-resolution (eddying) models. The NCAR/LANL model is among the most realistic global eddying models ever run, Maltrud says, and the only one to simulate such a large set of tracer distributions. A standard way to assess the accuracy of the model's eddy strength is to compare model sea-surface height changes with measurements from satellite altimeters (signals bounced off the sea surface to detect local changes in the height of the water). The close agreement between altimeter readings and the size and distribution of the model eddies is unprecedented in this type of ocean model.

While much has been learnt about transport processes by studies such as the one described above, there is still a great deal to do, says Peacock. While the observational data are as yet too sparse to characterize concentrations of these tracers on space and time scales associated with turbulent eddies, computational modeling is bringing researchers closer to a realistic assessment. Eddy-resolving ocean models are now providing sufficiently realistic proxies of ocean transient tracers, Peacock continues, which researchers can begin to use to provide a realistic picture of how, and on what timescales, the ocean is ventilated. "This will help researchers better understand the role of the ocean in uptake and redistribution of gases such as anthropogenic (man-made) CO2, which will increase understanding

of the role that the ocean plays in climate change."

For more information read ***Tracking CFCs in a Global Eddying Ocean Model*** (published by Oak Ridge National Laboratory).

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Scaling down to understand climate effects on severe storm formation

Observations show global warming is resulting in both rising temperatures and increased moisture in the Earth's lower atmosphere. Both are basic components in thunderstorm generation. As climate warms, therefore, it seems likely that thunderstorms and other severe weather events could grow in number. As part of an effort to identify trends related to such events, and to better understand how climate change is affecting severe storm formation in the United States, a team of Purdue University scientists received computing time on NCAR's blue fire supercomputer as part of the National Science Foundation's Accelerated Scientific Discovery (ASD) program.

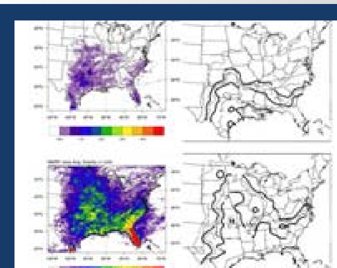
Led by Jeff Trapp, the team developed a 10-year climatology of high-resolution weather forecasts. The scientists dynamically downscaled coarse-resolution models (scales of 100s of kilometers) to create finer resolution (scales of a few kilometers) model output capable of reproducing local-scale atmospheric phenomena such as thunderstorms. The dynamical downscaling tool was the Advanced Research WRF (ARW) model, run initially using the temperature, humidity, winds, etc. from the NCAR-NCEP (National Centers for Environmental Prediction) Reanalysis Project (NNRP). These data, Trapp says, represent well the observed global atmosphere.

Using NNRP data from April through June for the years 1991 to 2000, the researchers generated a sequence of single-day high-resolution model forecasts rather than a continuous 90-day forecast; doing so eliminated potential error in the modeled output resulting from, for example, a storm mistakenly located in an area outside the observed location. In such a situation, inaccurate representation of a single characteristic, such as soil moisture content, in turn affects representation of heat transfer, humidity and temperatures in the lower atmosphere, cloud formation, etc.

Trapp and his colleagues used the ASD computing time to generate a decade of model runs, which they then compared to observed data to get an idea of how the simulations/climatologies compared to reality. With initial analysis showing the modeled data accurately replicating observed atmospheric dynamics, the team next moved on to running the ARW with the Community Atmospheric Model as input, thereby generating two different sets of climatologies.

"The ASD project gave us a jump start on model runs, data comparisons, and climatology development," says Trapp. "Next we'll focus our efforts on further analysis of the NNRP results to understand the spatial distribution of storms producing severe weather to see how well the modeled simulations work both over time and spatially."

Since creating its climatologies, the team has begun looking at severe storm trends. Identifying trends in thunderstorm generation is a trickier prospect, Trapp explains, because a variety of factors can be introduced into the observational record. For instance, thunderstorm reporting happens with good accuracy in populated areas, but in less-populated regions, storms can be under-reported, reported incorrectly or not reported at all. In addition, changes in reporting procedures also affect reporting accuracy. A trend needs to be both recognized and attributed, which can be difficult for reasons listed above, before definitive correlation of increasing thunderstorm activity can be correlated with growing greenhouse gas concentrations. To aid this effort, the team will develop a longer — 20 or 30 years — time series, which will provide longer, more reliable statistics from which to work on trends.



Monthly mean occurrences of hourly > 1 in hr. [left] from the NNRP-forced WRF runs, over the period 1991-1999; [right] from Brooks and Stensrud (2000), based on the period 1948-1993.

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"By correlating observed and modeled data we can assess how well the models are doing and potentially use these to identify and better understand storm trends," says Trapp.

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CCSM Progress Report

The Community Climate System Model (CCSM) will be included as one of more than a dozen general circulation models providing data to the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report. In preparation for this report, CCSM development has been frozen. The latest version, CCSM4, boasts a variety of updates to all its components — atmosphere, land, ocean, and sea ice — compared to the previous wide-release version, CCSM3; CCSM4 will be made widely available to the climate research community in spring 2010.

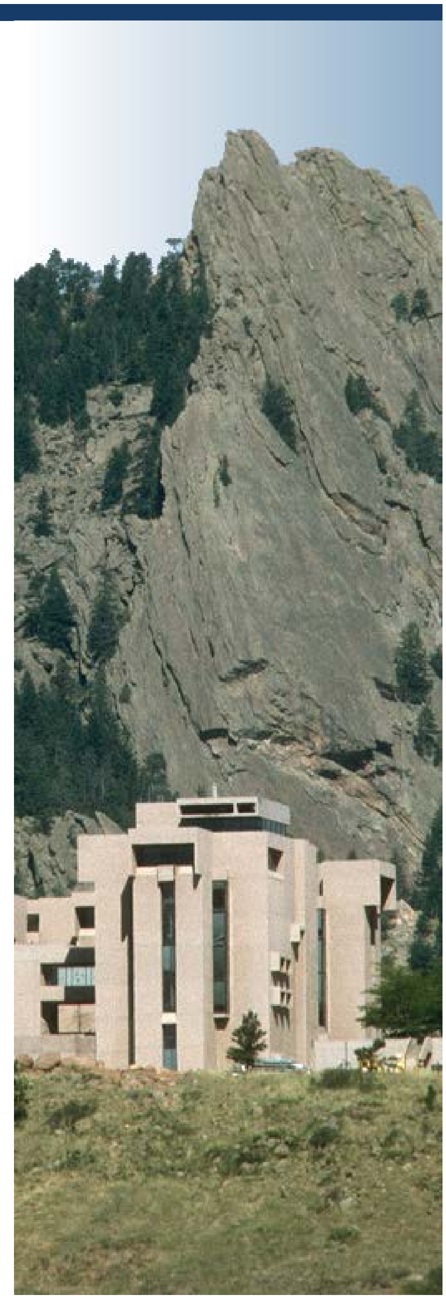
CCSM4 advances include a variety of new developments in the ocean model, such as increased vertical resolution. The new sea ice component contains improved radiative transfer and albedo schemes, a surface melt pond parameterization, and radiative effects and cycling of dust and black carbon aerosols. Another exciting enhancement is the coupling of a terrestrial carbon/nitrogen-cycle component to the Community Land Model (CLM4).

IPCC run preparations are moving ahead full steam, with a longer than 1000 year, 1850 control run complete for the chosen resolution of 1o in all the components. An ensemble of 20th century runs, which go from 1850 to 2005, are now underway. An ensemble of 21st Century runs from 2005 to 2100, using different projections for future levels of carbon dioxide in the atmosphere, will be made in 2010. In addition, the CCSM project is working with NCAR's Data Assimilation Research Testbed (DART), an open-source community facility that allows atmospheric scientists, oceanographers, hydrologists, chemists, and other geophysicists to build state-of-the-art **data assimilation systems**.

The CCSM4 ocean component is being used to assimilate a new set of ocean observations collected since 2003 by the Argo program, part of the Integrated Ocean Observing System. Argo data provide greater detail on ocean characteristics, including salinity and temperature, which will provide a more realistic ocean state using the DART assimilation system. These ocean states will be used as initial conditions for decadal forecasts using the CCSM, which are a new class of climate predictions that will be submitted to the IPCC Fifth Assessment Report.

In addition, two atmospheric chemistry components have been developed for the CCSM4. One version includes a very large number of chemical compounds, which will provide researchers with detailed information on, for example, pollution levels in urban areas. However, because of its comprehensive chemistry capabilities, the model requires significant computing resources. Consequently, a second, pared down version was created for users who need less exhaustive atmospheric chemistry, and simply want to understand how basic chemistry will affect future climate scenarios.

Other CCSM developments include significant progress on the **CCSM land-ice model**. Using the Community Ice Sheet Model, scientists will soon run future climate scenarios that include an interactive Greenland ice sheet; this will provide insights on the effects of glacial run off on sea level and the North Atlantic Ocean thermohaline circulation. In addition, an updated version of the Whole Atmosphere Community Climate Model (WACCM) based on the CCSM4 will soon be available. The updated model will allow a better representation of ozone, which is important as the "ozone hole" over Antarctica recovers during the first half of the 21st century.



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US Western Water and Environment

With population growth in the U.S. West among the fastest in the nation, a clear understanding of the effects of climate on health, natural resources, and societal welfare becomes increasingly important. Because of this, and because we are located in the U.S. West, these issues have particular interest to NCAR scientists. Below is a snapshot of some of the projects that our researchers and community focused on in FY2009.

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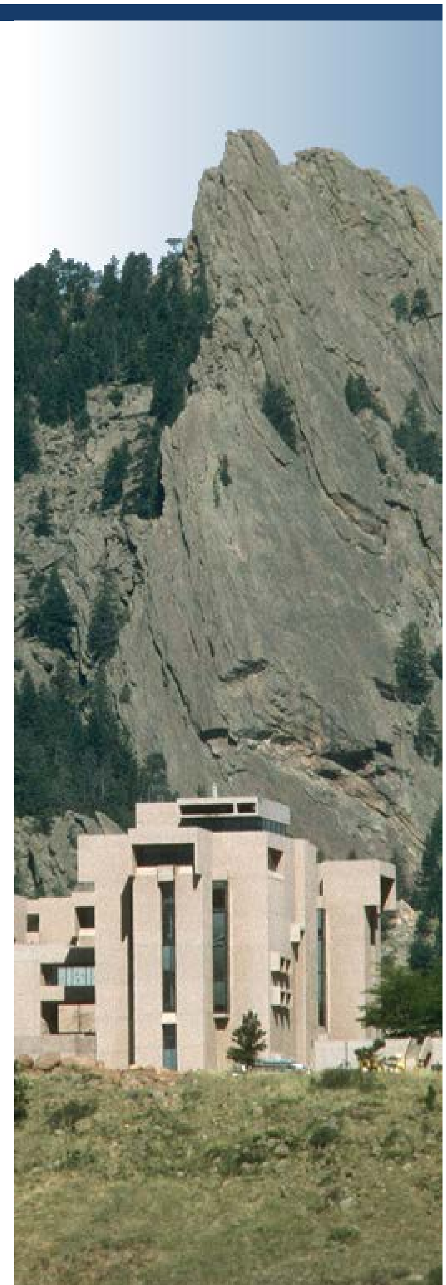
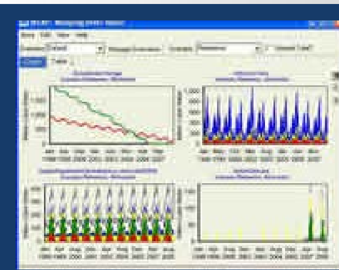


Climate change and moisture: Giving water managers a better sense of tomorrow's supply

Water managers have historically made resource projections assuming that past climate predicts future trends. With regional climate changing, these assumptions are less accurate and in worst case scenarios incorrect conjecture will leave resource managers — and water users — high and dry. NCAR's David Yates and Stockholm Environmental Institute (SEI) researchers retrofitted SEI's Water Evaluation and Planning System (WEAP) to address some of these planning needs



WEAP allows users to design a bird's-eye view that highlight key indicators in a water-resource system.

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In 2001, responding to a call by the U.S. Environmental Protection Agency for new water resource forecasting tools that could factor in climate change, the team received funding to advance WEAP's algorithms. Originally created to in 1988 to evaluate sustainability of water demand and supply patterns, the team updated WEAP to include parameters such as humidity, wind, precipitation, temperature, etc. — key information for forecasting long-term future water scenarios. WEAP now transforms these parameters into practical hydrologic properties, like streamflow and runoff, which resource managers rely on to assess current and future climate conditions as they relate to flow forecasts.

> ***With several thousand licensed users around the world, many have come to depend on the WEAP decision support system.***

With several thousand licensed users around the world, many have come to depend on the WEAP decision support system. This input has been essential to informing software revisions and improvements; working directly with users is important for ensuring ongoing innovation and utility. California water planners — who face some of the most demanding water issues in the United States — have been among those instrumental in putting WEAP development through its paces.

Among the organizations that rely on WEAP is the California Department of Water Resources, which uses the tool to generate data and scenarios used in its annual five-year water-plan update. WEAP lets planners evaluate water supplies, estimate agricultural, environmental, and urban water uses and demand — quantifying gaps between water supplies and uses — and assess options for meeting future water needs. Eldorado Irrigation District staff worked with University of California, Berkeley to devise a drought plan; they used WEAP to look at potential water delivery cut backs, including how and where these might be imposed under various drought stages, from Stage 1 (15% water use reduction from normal), to Stages 2 (30% reduction) and 3 (50%-plus reduction).

Many international water resource specialists have added WEAP to their water resource/climate change planning arsenal. In Peru, a tunnel is being drilled through the heart of the Andes' to transport up to 2 billion cubic meters of water from the lush Amazonian side of the continental divide to agricultural lands on the dry Pacific coast. As part of the process of considering how future climate change might affect water availability and climate patterns on both sides of the tunnel, Yates is working with project planners to use WEAP as part of their analysis process.

The next likely frontier for WEAP, says Yates, is the energy-water nexus; in California, 20% of energy use is tied to moving water from north to south. WEAP, with planned modifications, will soon help managers assess

tradeoffs between energy use and costs, water costs, demands, needs, and availability in coming years. WEAP provides water agencies and decision makers with a means to make considered resource choices, which will be ever more essential as water becomes an ever more pressing concern to society.

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Neighborhood by neighborhood: Using GIS to assess how people deal with heat waves

In Phoenix, Arizona state and county public health personnel work diligently to ensure citizens are ready and able to deal with the city's frequent extreme heat events. Despite having a wide variety of programs and preventative information in place and publicly available, many preventable heat-related deaths and illnesses occur in Phoenix every summer. Scientists from NCAR, working with researchers from Arizona State University (ASU), and county and state public health service personnel, headed up a pilot project to better understand societal vulnerability and adaptive capacity to extreme heat in several Phoenix neighborhoods threatened by effects of summer-time heat events. Through their efforts, the team hopes to pinpoint characteristics of the most vulnerable populations for more targeted health interventions and extreme-heat preparedness programs. If successful, results will be extrapolated for use in other cities facing similar heat health issues.

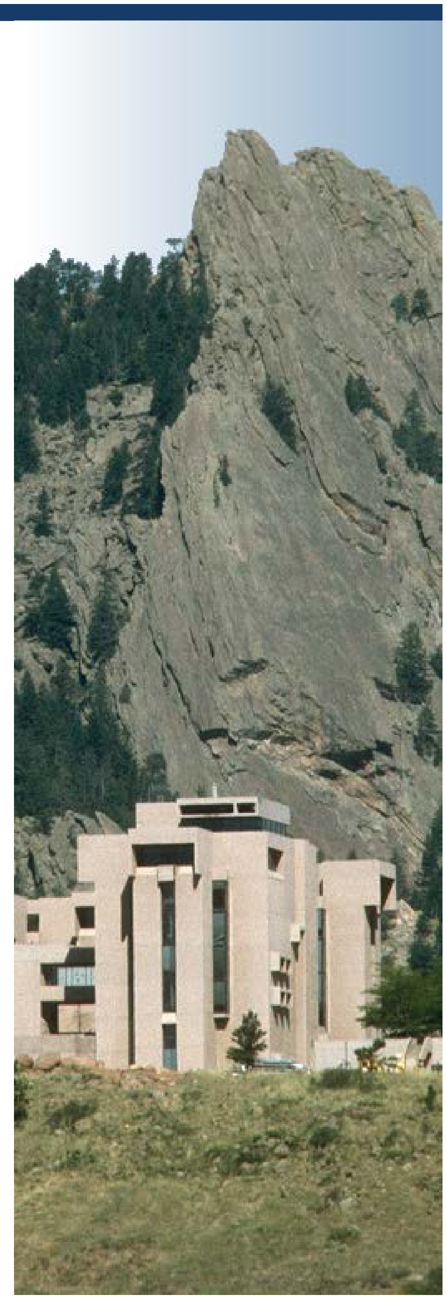
Typically, census data (income level, race, age, etc.) are used to assess a population's ability to cope with and adapt to extreme events. However, these data often gloss over adaptation capabilities at individual and neighborhood levels. In studying the demographics of heat wave mortality in Phoenix, for instance, the number of relatively youthful heat-related fatalities surprised the scientists — generally, heat affects older populations. Equally important is understanding why some neighborhoods fare better than others in extreme weather. For example, work done by Eric Klinenberg in Chicago shows that areas with strong community networks have reduced likelihood of injury and death related to heat exposure because neighbors check on each other's well being. In less interconnected neighborhoods, fatalities increase because individuals must cope with extreme weather largely on their own.

> ***Mapping spatial distribution of heat-related health outcomes and identifying links to neighborhood demographics was a first step.***

To identify study neighborhoods, the team mapped zones of higher vulnerability to heat waves across the city. Researchers used previous heat mortality cases and 911 heat distress calls, provided by ASU, and census-based socio-economic and demographic data, aggregated by neighborhood.

Mapping spatial distribution of heat-related health outcomes and identifying links to neighborhood demographics was a first step. Local public health experts and ASU researchers helped narrow the study to three neighborhoods that varied in terms of income level, and ethnic and cultural diversity. Researchers and a team of students from ASU and the University of Arizona conducted door-to-door surveys, gathering detailed information to assess household-level vulnerability to extreme heat, as well as adaptive capacity. Correlating geographic location with responses, the scientists will incorporate spatial components that relate neighborhood characteristics directly to coping capabilities and mechanisms as they vary by site. With this knowledge, the scientists hope to discover ties between the socio-economic, cultural and behavioral patterns that have — or might — influence neighborhood heat-wave coping strategies.

In addition to providing the foundation for future modeling of spatial adaptive capacity characteristics of a neighborhood and its residents to generate a



wider context of heat health vulnerability, the outreach provided neighborhood residents with practical information for effectively dealing with future heat wave issues. Because of this study, ties between residents and public health officials have strengthened, allowing health services personnel to more effectively meet their public mandate. And that's not a bad way to begin.

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Assessing winter precipitation in the Colorado Headwaters region

Snow provides a significant portion — up to 75 percent — of the U.S. West's water supply. The amount of water supply from snowpack varies dramatically from year to year, depending on a variety of factors ranging from total precipitation to soil moisture content, to effects of wind and wind patterns, etc. With millions of users depending on this water for hydropower generation, irrigation, recreation, and other uses, accurate prediction of snow melt and runoff is critical.

In generating annual water resource plans, decision makers rely on both direct observations, culled from a vast array of data collection sites located throughout the West, as well as climate models. In situ data provide information on snow water equivalent, precipitation and temperature for discreet areas, however, in mountainous areas individual sites do not always accurately reflect the collective snowpack characteristics for the region because of the highly heterogeneous terrain. Ideally, climate models can help interpolate snow characteristics between sites, but because many models have resolution on scales of 100s of kilometers, they too miss the nuance of the West's geography, and therefore poorly replicate snowfall patterns, and snow accumulation and melt processes. As a result, model results often don't match observations.

A recent Advanced Scientific Discovery (ASD) effort, funded by the National Science Foundation and supported by NCAR's Computational and Information Systems Laboratory, offered a way to improve model output that should provide water resource managers with better information from which to assess annual snowpack. The ASD award gave the Colorado Headwaters project team, which is looking at snow cover in the Colorado River headwater region, with computing power to run high-resolution regional climate simulations of cold-season snowfall, snowpack, and evapotranspiration across this area of complex terrain.

The Colorado Headwaters project received 500,000 computer GAUs — units charged for computing use — to run the high-resolution Advanced Research WRF-ARW model in assessing winter precipitation, snowpack, and runoff processes from Colorado's headwater basins. This region is particularly important because about 85 percent of the stream flow for the Colorado River comes from snowmelt in this area, and the Colorado is the primary source of water for much of the arid U.S. Southwest.

While diagnostic analysis of the simulations are still in progress, results so far show that the high-resolution regional model is able to reproduce observed SNOTEL (Snowpack Telemetry) precipitation amounts to within 10 percent of observations from 111 SNOTEL sites for all four simulated years; model simulation of spatial patterns of precipitation also shows excellent agreement with SNOTEL observations.

"The simulated strong dependence of snowfall and snowpack on grid resolutions illustrates the importance and usefulness of high-resolution models in improving the future climate projections by global climate models," says project lead, Roy Rasmussen, a senior scientist at NCAR. "Future work will focus on analysis of the future climate runs and conducting nested regional climate runs."

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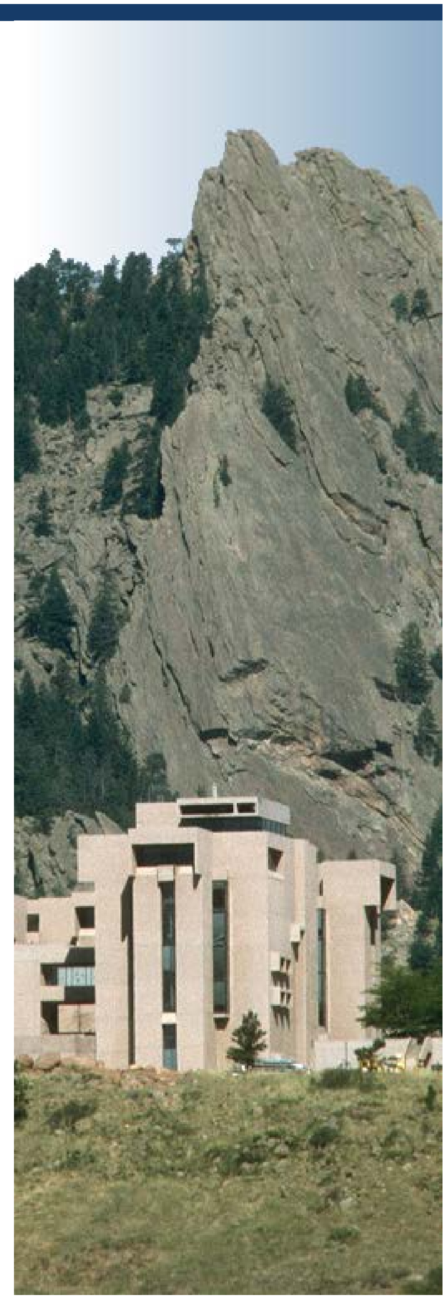

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Science Serving Society

Among NCAR's missions is fostering transfer of knowledge and technology for the betterment of life on Earth. From improving prediction of severe weather both on Earth and in space, to providing health care workers with insights on disease outbreaks, those within the NCAR science community are breaking new research ground to better serve society.

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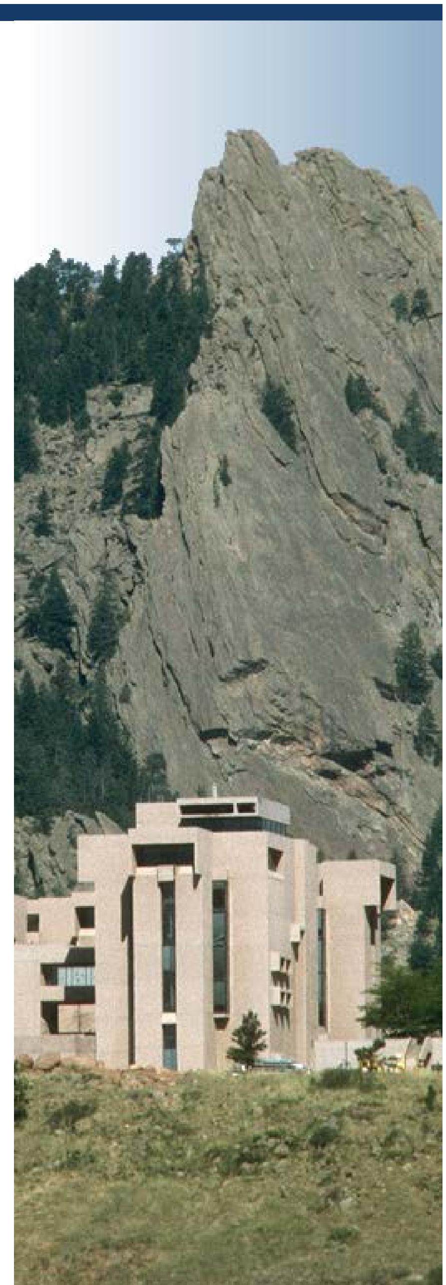
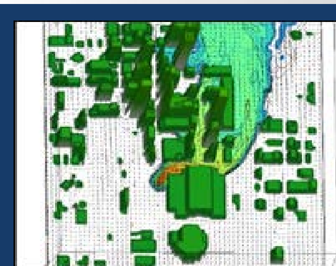


Bright models, big cities: Simulating urban weather in new detail



Coupling the Weather Research Forecasting Model with a large-eddy simulation model (Eulerian/semi-Langrangian fluid solver), scientists can simulate urban canyon thermodynamical fields (for example, temperature and pressure) and transport fields to simulate transport of a contaminant from its source through an urban area.

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More than half of the world's humans already live in cities, and urban growth seems likely to continue apace. United Nations (note to Rachel: verify this source) experts suggest that by 2015, the globe will have as many as 60 cities with populations of 5-million-plus. For these and many other reasons, scientists are looking at how cities affect local and global climate.

> ***Researchers rely on the WRF-Urban modeling system to investigate and address a variety of environmental issues. Efforts include studying formation and evolution of urban heat islands and associated boundary layer structures in rapidly developed urban regions in Asia; examining effects of urbanization on summer precipitation in the Beijing and its implication in local water resources; and investigating impact of urban land-use change on regional air quality under future climate change scenarios.***

Combined factors such as high heat emissions from building climate-control, pollution resulting from industry and transportation, and a preponderance of paved surfaces, create urban heat islands (UHI) where day-time temperatures are 2º to 5ºF warmer than rural areas; during summer nights this difference climbs even higher — up to 12ºF. UHIs considerably influence local and regional weather, affecting wind regimes, precipitation, and humidity, for example. In turn, urban weather characteristics affect efficient dispersion of heat and pollution, human health, water quality, and energy consumption and greenhouse gas emissions.

Weather models provide one way of better understanding UHI effects on local and regional climate. With increasingly fine grids — resolutions of 0.5 km in some cases — these models offer a way of estimating and understanding urban weather in detail.

Fei Chen, an NCAR scientist in the Research Applications Laboratory, has studied UHI effects all over the world, looking at air quality in particular. Chen and other NCAR researchers and university and agency colleagues are developing an integrated urban modeling framework for the Weather and Research Forecasting (WRF) model. By coupling WRF — or other fine-scale weather models like the Pennsylvania State University/NCAR MM5 — to land surface (LSM) and urban canopy models, they can more accurately replicate urban weather dynamics. The Noah LSM, for example, hones the UHI perspective by providing details on city characteristics such as building type, height and density, land use, surface type, anthropogenic heating, heat and moisture exchange between indoor and outdoor atmosphere — details critical for accurately capturing and understanding the influence a city has on weather.

"We are applying WRF to look at various urban problems, such as the effects of urbanization on air pollution, public health, and how land-use changes affect climate change," says Chen.

HongKong, one of several cities Chen is studying, suffers from temperature inversions. As a result, during summer nights heat relief generated through mixing of cooler land air and warmer ocean air occurs less frequently because urban air temperatures often do not cool enough to instigate

mixing. And, lacking the land breeze, pollution can languish in the city, resulting in human health problems related to respiratory issues, heat-related mortality and general discomfort.

Like HongKong, many urban areas contend with the effects of higher night-time temperatures in summer, which make looking at seasonal UHI effects a significant focus. Chen will soon take a more in-depth look at the impact of winter-time UHI on weather and climate. Less noticeable in its impact on human health and mortality, Chen expects this research will provide valuable new insights on urban weather regimes.

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It's all related: Linking people, policy, and land use with a changing climate

Individuals, governments and industry clamor for a view on the effects of changing climate tens to scores of years down the road. To answer their questions and investigate options for responding to climate change, more and more scientists and policy makers are turning to integrated assessment models (IAMs). These models merge climate science, economics, demographics, land use, and policy analysis under a single umbrella.

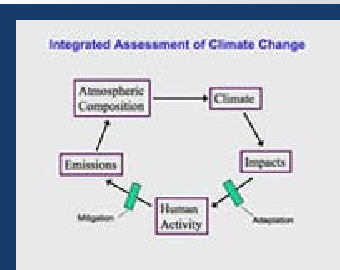
IAMs are used to address applied policy questions such as, what might it take to cap greenhouse gas emissions at a given level? What role might land use play in driving future emissions or mitigation efforts? How might different rates and levels of climate change impact societies in the future? Is it better to act now or postpone some of our efforts until later? Answers to these and similar queries require decision makers to know how climate scenarios relate to non-climate factors such as economic growth projections, energy and land use changes, and global and regional demographics, among other parameters.

> ***The team is exploring ways to make iPETS the latest addition to NCAR's suite of community models.***

NCAR is among those U.S. research organizations that have a strong — and growing — IAM team addressing such questions. Starting at the global and national level their model, the Integrated-Population-Economy-Technology-Science (iPETS) model, currently focuses on answering emissions-related questions. Led by Brian O'Neill, the team is using iPETS to look at how future demographic change may affect emissions, and how viable achieving particular emissions reduction goals might be. Over time the group expects to focus on the role of land use and to do more impacts-related work, which would include assessing adaptation strategies in collaboration with the community of researchers studying climate impacts, adaptation and vulnerability (IAV). NCAR's IAM group is also part of a consortium of research teams involved in developing a new round of integrated scenarios to be used as part of the Intergovernmental Panel on Climate Change's Fifth Assessment Report.

The team is exploring ways to make iPETS the latest addition to NCAR's suite of community models. The group plans to make the iPETS model accessible through a web interface and to make model code publicly available. Users will be welcome to contribute modifications and suggestions related to iPETS development. In addition, NCAR hopes to link its IAM to general circulation models like CCSM. Until recently, this cross-model integration was hampered by slow computing speeds and limited demand for integrated assessment output. However, in both areas, this reality has changed.

Despite IAMs being in vogue as a means of answering pressing climate questions, the need for continued work and refinement of GCMs remains critical. Climate science/model uncertainties like cloud and precipitation issues need to be resolved so as to further bolster IAM efficacy. NCAR's climate science and IAM groups will work together to participate in achieving this end.



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The storms between Sun and Earth: Looking for more lead time on damaging space weather

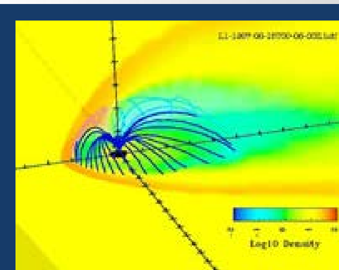
Beyond providing Earth with its predominant source of heat and light, the Sun affects the planet and human society in a variety of other ways. For instance, effects from storms propagating from the solar corona outward through space, can seriously impact aviation, electrical grids, and satellite performance on Earth, often impinging on daily societal function directly. Due to distance from the Earth and few observing instruments, solar storms cannot currently be predicted. But, once observed, researchers can monitor a storm's progress, tracking it through space, into the magnetosphere, Earth's outermost protective boundary. To isolate and identify storm characteristics and better forecast future events, scientists are turning to the Coupled Magnetosphere Ionosphere Thermosphere (CMIT) model developed by HAO scientists in collaboration with the NSF-funded Center for Integrated Space Weather Modeling.

Extreme space weather events include coronal mass ejections (CMEs). Not unlike hurricanes in space, CMEs expel a plasma of charged particles and elements like helium, iron, and oxygen, and cause the coronal magnetic field to propagate outward from the Sun, toward Earth. Despite the magnetosphere, which acts as a gatekeeper, protecting the lower atmosphere from solar winds by harnessing the energy and momentum of incoming ions and magnetic forces, CMEs can have serious repercussions on Earth.

> ***Not unlike hurricanes in space, CMEs expel a plasma of charged particles and elements like helium, iron, and oxygen, and cause the coronal magnetic field to propagate outward from the Sun, toward Earth.***

In particular, aviation faces significant challenges during strong space storms. Pilots flying above 85 degrees latitude are outside the range of satellite communications and therefore must rely on radio communications for navigation. However, severe space weather disrupts radio transmissions; ionized particles and heightened magnetism affect radio wave propagation. A highly ionized atmosphere can also disrupt Global Positioning System (GPS) signals, throwing off the required triangulation of points that allows correct location of an object — such as an airplane — by GPS receivers. The more ions present in the atmosphere, the longer a signal takes to triangulate between points, so precise information on ionization level (the total electron content of the upper atmosphere) helps assess GPS accuracy. Also, the global wide area augmentation system (WAAS) provides the aviation industry with direct connection to GPS units. Capable of providing GPS calculation corrections in most circumstances, under extreme atmospheric ionization events, WAAS capabilities can be severely curtailed if not completely debilitated.

CMIT couples a magnetospheric model (Lyons-Fedder-Mobarry) with NCAR's Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIE-GCM). CMIT can simulate ionosphere activity by driving magnetophseric dynamics; these dynamics, in turn, are driven by the solar winds. The CMIT framework connects these linked systems and allows scientists to compare modeled outcomes with observed space weather events and characteristics. In doing this, new insights are being gained on the cascading effects of solar activity on Earth, which is particularly important for regions acutely affected by space weather.



This scientific visualization shows results from the CMIT model depicting the impact of a shock at the head of a coronal mass ejection on the magnetosphere. The visualization clearly shows the inward motion of the magnetopause and compression of the magnetosphere at the arrival of the shock which is modeled from solar wind observations and throughout of the coupled magnetosphere - ionosphere - thermosphere system. Accurate modeling of these types of events is essential for creating reliable space weather predictions.

Click here to view movie +

Observational data obtained from satellites like NASA's Advanced Composition Explore (ACE), provide researchers with information about solar wind — temperature, composition characteristics, speed, etc. — and geomagnetic storm observations back to Earth within an hour of storm onset. Feeding these observations into the CMIT drives magnetospheric dynamics, which are used to drive — and better understand — ionospheric activity. In doing so, CMIT isolates what causes for many of the Earth-bound anomalies. Causes can range from variation in atmospheric chemistry to motion of ionospheric plasma.

CMIT is not currently used in real time — and therefore cannot be used operationally to forecast space weather events — but over the long term, scientists hope to use the model in a predictive capacity. Right now CMIT is an effective research model, providing an improved view on Sun-Earth interactions as well as in assessing how the two models do individually and as a coupled unit.

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How strong a hurricane? New modeling brings fresh angles to a perennial problem

Tracks of Katrina generated from high-resolution forecasts performed for the Hurricane Forecast Improvement Project (HFIP). The dates in the upper right corner are initialization times of each of the six numbered forecasts. Intensity is also indicated along the track by color code at bottom left.

Click here to enlarge +

The stronger the near-ground winds in a hurricane, the greater the damage to infrastructure and the higher the risk to human lives. A hurricane's inner core drives storm intensity, however little is known about inner core dynamics because few direct observations have been made; lacking observational data, scientists have only slightly improved hurricane-intensity forecasts in 30 years. Hoping to advance and enhance such predictions, the National Oceanic and Atmospheric Administration (NOAA) recently launched the Hurricane Forecast Improvement Project (HFIP), providing funding for both in-the-field research and hurricane modeling efforts. The field observations will not only help scientists refine understanding of processes occurring in the hurricane's eye wall, where the strongest wind and rainfall occur, they will provide a means of testing and improving weather-model output.

Model output evaluation is critical. The inner core of a hurricane spans a limited geographic area (at its widest, the eye wall is perhaps 10 miles wide), and evolves quickly in time and space. The time it takes a hurricane to spin up from a tropical storm can be as little as 24 hours. These characteristics complicate the modeling effort, requiring high-resolution models that can predict hurricane intensity changes and that are agile enough to resolve the attendant weather on times scales of hours.

NOAA initiated its HFIP effort asking researchers at participating modeling centers to look at hurricane development at varying spatial and temporal resolutions to assess a given model's forecast capabilities. NOAA chose to focus on 2005 and 2007 hurricanes, were both difficult to predict at the time and had a significant societal impact.

Led by Chris Davis, NCAR's Mesoscale and Microscale Meteorology (MMM) Division participated in HFIP using the Advanced Hurricane-research WRF (AHW) model. Davis and colleagues wanted to see how changing the AHW's horizontal resolution — that is, the individual cell blocks within the model — affected model output, comparing forecast data generated at a grid size of 12 km to data generated with the addition of a smaller, moving 1.33-km grid that followed the storm. Not least, NCAR's scientists wanted to determine if costs incurred from increasing computing time and power as a result of running higher resolution models could be balanced against potential forecast improvements. NCAR's HFIP results indicated a measurable improvement due to increasing resolution, and were the only modeling results among the many HFIP participants to find such a benefit.

Davis believes that among the reasons for this result, MMM and AHW have the advantage of a long history and modeling experience at high resolution, and AHW development benefits from significant scientific community input. As result, AHW is more nimble than other models, particularly in terms of nesting higher resolution grids within lower resolution grids to generate hurricane intensification predictions. Furthermore, collaboration with Ryan Torn at the University at Albany (State University of New York) allowed the use of a more sophisticated method of initializing the forecasts. This method, generally termed ensemble data assimilation, reduced the imbalance that is sometimes introduced into the initial state of models and provided more realistic storm structures than can be obtained with more traditional initialization methods. At a minimum, NCAR's HFIP results suggest a place for fruitful cross-center collaboration to begin. In future, MMM and other centers hope to run similar experiments in real time. With a quiet 2009 hurricane season, HFIP participants look forward to 2010 as the season to advance this goal.

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Forecasting for Disease Prevention in Africa's Meningitis Belt

Periodically, epidemics of bacterial meningitis break out across a stretch of sub-Saharan Africa. This region, dubbed the meningitis belt, reaches across the continent from Senegal to Ethiopia. During the world's largest recorded outbreak of epidemic meningitis in 1996 and 1997, more than 250,000 Africans fell ill and 25,000 died. Dry, dusty conditions seem to be correlated with the disease, while onset of the summer rainy season sees epidemics end. With limited vaccine available to combat the disease and difficulties related to getting vaccines to those in remote areas, health officials and scientists combating the disease hope to use weather forecasts to concentrate efforts on regions most at risk, while pulling back from areas about to get rain.

In November 2008, an international team of health and weather organizations and experts launched a project to provide weather forecasts to medical officials in Africa to help minimize outbreaks of meningitis. The forecasts will allow local health providers to target vaccination programs.

Meninges, the thin linings that surround the brain and spinal cord, are affected by the fatal disease. Researchers do not completely understand the relation between dry and dusty conditions and meningitis. Some theorize that mucous linings in people's respiratory systems are irritated by dusty conditions, while others suspect changes in social behavior might be to blame as residents tend to stay indoors during the dusty season, which facilitates spread of the disease.

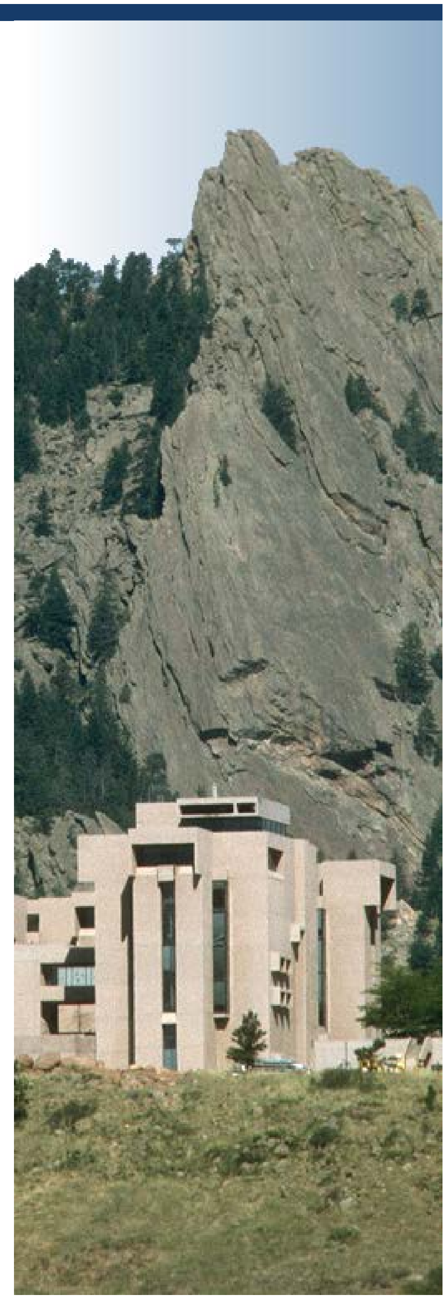
"Working with meteorologists in Africa, we're developing more accurate and more useful weather forecasting to assist health care officials on the front lines of this disease," says Rajul Pandya, director of the University Corporation for Atmospheric Research�s Community Building Program (UCAR is NCAR's managing body).

By targeting forecasts in regions where meningitis is a threat, we may be able to help vulnerable populations, continues Pandya. Ultimately, we hope to build on this project so that local and regional meteorological services can provide information to public health programs battling weather-related diseases in other parts of the world.

Over the next year, project leaders will focus on Ghana, a country hard-hit by past meningitis outbreaks. NCAR and African meteorologists will use computer models run by agencies such as the European Centre for Medium-Range Weather Forecasts and the U.S. National Centers for Environmental Prediction. To make reliable predictions, the meteorologists are using statistical techniques to zero in on the meningitis belt, giving greater weight to models generating the most accurate forecasts under specific conditions. At the same time, the forecast team will also make use of an Africa-focused implementation of NCAR's own WRF model, which is being lead by former NCAR post-doctoral fellow Benjamin Lamptey, now a faculty member in Ghana.

In the next two years, the team will work closely with health experts from several African countries to design and test a decision support system that will provide health officials with useful meteorological information. Some of the biggest challenges will be disseminating the forecasts to health officials on the ground and helping African Meteorological services.

"Working closely with both the meteorologists and local public health officials will allow us to more effectively target vaccines to at-risk populations in areas with limited resources," says Mary Hayden, a medical anthropologist at NCAR.



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Taking Science to the Field

As part of our mission to serve the science community, NCAR supports NSF-funded field campaigns, providing equipment, services and staff. Field campaigns are an essential part of basic scientific research; the resulting in situ observations improve our understanding and ability to predict — and hindcast — Earth system processes and dynamics.

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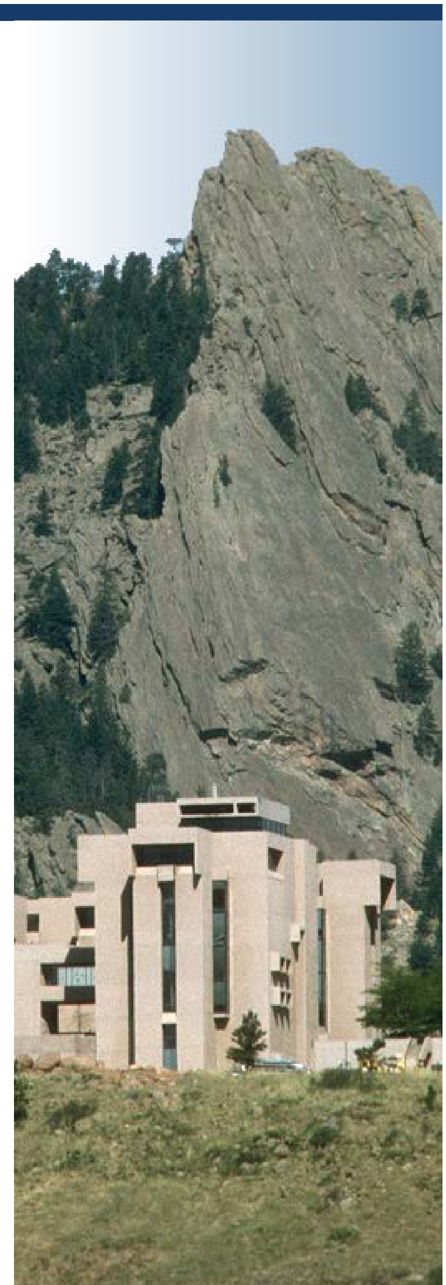

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Sunrise at the OASIS: Springtime's light triggers sharp changes in Arctic air chemistry

More than simply ushering in a promise of spring, increasing late-winter Arctic sunlight corresponds with depletions in the region's atmospheric ozone and mercury. During the winter's cold and dark, newly formed sea ice provides a reactive surface on which chemical species involved in ozone- and mercury-depletion events such as bromine oxide (BrO) form. In a recent, Barrow-based research campaign, scientists gathered to hone in on finding answers to questions of how and why these events occur, how BrO fits into the Arctic's ozone and mercury depletion picture, and at what scale and for how long these reactions are occurring.

Typically atmospheric ozone depletion events occur over distinct regions for periods of up to several days.

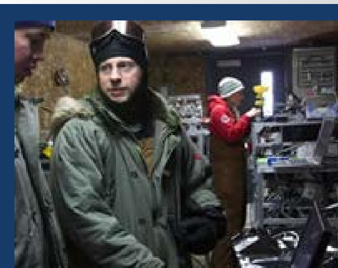
Depletion of both ozone and mercury has significant environmental impacts. Such low levels of ozone are not common in unpolluted regions, and serve to alter the chemistry as well as influence biota. In the case of mercury, deposition from the atmosphere onto the sea ice, snow and ocean surfaces introduces this toxic substance to the biosphere. With the chemical and physical exchange processes poorly understood, a number of universities led a field campaign — the Ocean-Atmosphere-Sea Ice-Snowpack (OASIS) — as part of the International Polar Year to boost scientific comprehension of the drivers behind these processes.

Run between February and April 2009, OASIS scientists designed and carried out a thorough set of experiments measuring atmospheric chemical composition and chemical fluxes to and from snow and ice surfaces using a variety of sensors. Results will shed light on the influence, life-span and interactions between naturally occurring chemical species in the Arctic. Findings will also help to fine-tune chemistry and climate models that try to replicate these interactions.

Typically atmospheric ozone depletion events occur over distinct regions for periods of up to several days. With experiment results currently under analysis, the scientists also hope the OASIS program results shed light on the variety of possible effects of anthropogenic pollutants on the ecosystem, and provide insight on possible interactions between the region's quickly changing climate and regional chemical dynamics.

Among its unique characteristics, multiple universities initiated and led OASIS, including Purdue University and University of California, Davis. With a nucleus of scientists and research foci in place, additional researchers, including individual university investigators, science organizations and government agencies asked — and were asked — to participate. This broad community collaboration helped the 2009 OASIS campaign generate a wide-ranging set of measurements at a level unprecedented by anything done before in a similar research setting.

Sought out by OASIS principal investigators because of skills and expertise in field studies of this nature, NCAR scientists and staff coordinated many project logistics, and ran 10 different experiments that provided the backbone for the gas-phase component of the study. With a high number of ozone-depletion events observed during the campaign, the weather cooperating, all instruments operating as expected, and observations of



OASIS researchers inside one of the modules in Barrow, Alaska. The OASIS (Ocean-Atmosphere-Sea Ice-Snowpack) field project made some of the most extensive measurements ever on the chemical exchanges between polar air, snow, frost, brine, and sea ice. Part of International Polar Year, OASIS tackled a number of standing questions in polar chemistry, with the emphasis on the life cycle of pollutants that drift into the Arctic.

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Little known outside the world of polar research, frost flowers haven't been studied much till recently. They're highly salty, which makes them potentially important in the chemistry of depletion events. This image shows an OASIS researcher working with equipment involved in the study of a freshly formed batch of frost flowers atop a patch of ice cleared the day before. The OASIS (Ocean-Atmosphere-Sea Ice-Snowpack) field project made some of the most extensive measurements ever on the chemical exchanges between polar air, snow, frost, brine, and sea ice. Part of International Polar Year, OASIS tackled a number of standing questions in polar chemistry, with the emphasis on the life cycle of pollutants that drift into the Arctic.

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anticipated chemical compounds secured, OASIS scientists have high expectations of exciting results from their two months of field work.

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To the tropopause: Capturing fast-changing air at high-flying altitudes

Our planet's climate is influenced by the atmosphere's chemistry. How chemicals interact, how chemicals are distributed, and how many and the types of chemicals present in the atmosphere all play a role in influencing the Earth's climate. Much of the chemistry influencing climate occurs in the atmospheric layers closest to the surface — the troposphere and the stratosphere. But it is the boundary between these layers — the UT/LS (upper troposphere/lower stratosphere) region — that has a particularly large influence in terms of generating climatic effects.

Scientists have learned much about the chemistry of the atmosphere from remote sensing instruments placed on Earth-orbiting satellites. These instruments continually probe the atmosphere, providing global-scale observations of a limited number of gases and particles. Measurements of gases such as water vapor (H2O), ozone (O3), and carbon monoxide (CO) provide critical information on global atmospheric chemistry and air transport. However, measurements from satellites tend to miss the fine detail that is often important in unraveling the actual processes that control chemical distributions. And the chemical composition that can be determined is limited. This lack of detail becomes especially important in the UT/LS region, where changes in chemistry can occur over very short time and space scales.

> ***AWAS's detailed chemical measurements help scientists by providing first-hand observations of faster-acting chemical reactions in addition to the longer-lived chemical species obtained during START08. START08 mission results from all of the chemical sensors loaded on the GV will be used to generate a detailed map of chemical species location in and around the stratosphere/troposphere boundary region. These observations, placed in context of global-scale satellite measurements, offer a critical link to advancing modeling and atmospheric and climate science efforts in the future by providing observations against which model output can be compared and verified.***

Understanding the UT/LS role in the climate system requires extensive and detailed knowledge of chemical processes and distributions — processes and distributions that can occur over a range of scales, from minutes up to decades. To better understand these phenomena, it is essential to take in-situ measurements within the UT/LS. One obvious solution is to collect air from this region and bring it back to the lab to determine which chemical components are present. Until recently, no airplanes — the most obvious measuring platform — could fly high enough to achieve this. With NSF's Gulfstream V (GV), the platform became available.

Elliot Atlas (University of Miami), and Donald Blake and Eric Saltzman (University of California, Irvine) proposed creating a new instrument designed to fly on the GV and collect in-situ samples. The resulting instrument — the Advanced Whole Air Sampler (AWAS) — incorporates the investigators' years of research experience and provides a tool that they and the wider science community can use to sample the UT/LS region for the first time.

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Once on the ground, AWAS air samples can be taken to a controlled laboratory environment, and run through multiple instruments to generate high-precision chemical analyses. Typically more than 50 individual trace gases can be measured from the AWAS, providing chemical fingerprints of industrial emission sources, biomass burning, and/or natural emissions from land plants or the ocean surface.

In its first scientific mission, Atlas used the AWAS on the GV during the START08 (Stratosphere-Troposphere Analyses of Regional Transport 2008) experiment. Of special interest, he and his colleagues wanted to determine how chemicals with different atmospheric lifetimes were distributed in the UT/LS region. Because of the wide range of chemicals that the AWAS can measure, it is possible to obtain fine-scale information on original sources of air in the UT/LS, and on how air mixes across the troposphere/stratosphere boundary.

Among the exciting discoveries of START08, AWAS and the suite of instruments included in the GV payload provided the first in-situ observations of the chemistry of a deep intrusion of tropospheric air into the lowermost stratosphere. Combined with meteorological analyses, the source of the intrusion could be pinpointed to the upper troposphere in the tropics over India.

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A tale of two continents: Why does Eurasia outpace North America in spring warming and melting?

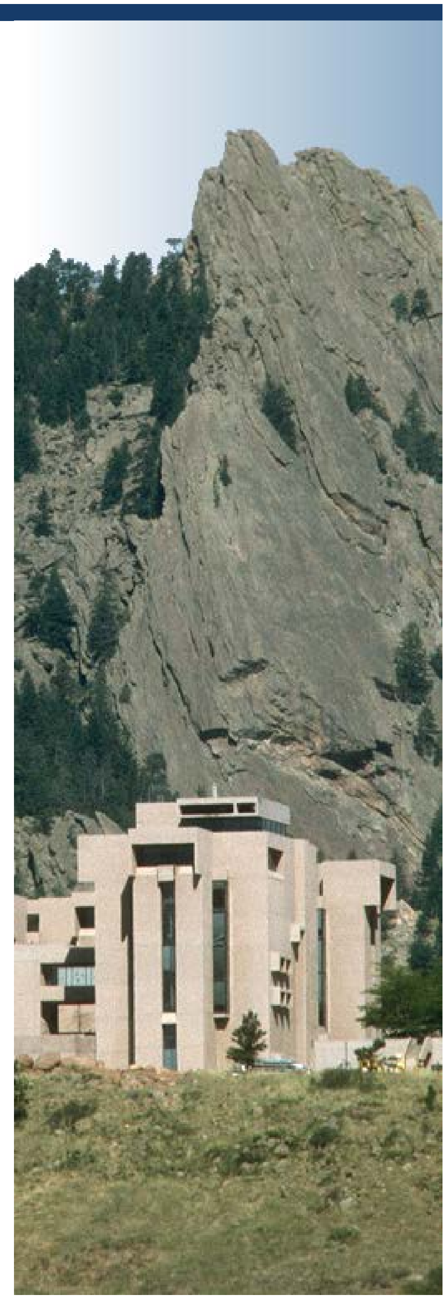
Observations show Eurasian spring-time snow melt and warming proceeding at a faster rate during the past 30 years than has occurred in North America. Mark Flanner, a recent NCAR Advanced Study Program graduate, led a study that estimates that warming rates and snow cover decline in Eurasia are two times as great as those in North America. In the same study, Flanner and his colleagues also point out that climate scenarios generated by all but one of the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report general circulation models (GCMs) fail to reflect this trend; most IPCC model runs show the regions having similar spring-time temperatures and snow-melt rates. The scientists suspect aerosols — particularly black carbon and organic matter such as dust — might be responsible for the difference in modeled versus observed climate.

> ***While this research does not fully explain why springtime land temperatures and snow cover are changing so much faster over Eurasia than North America, it does suggest that snow darkening from black carbon,a process lacking in most climate models, is playing a role.***

Generated by human activity, dust storms, and forest fires, Asia produces high levels of both types of aerosols. Blown across the Eurasian land mass, black carbon and organic matter affect the surface and nearby atmosphere in a variety of ways. Black carbon tends to warm the atmosphere by absorbing incoming solar radiation. In addition, aerosols reflect incoming solar energy, potentially cooling the underlying surface. However, particulates that fall to the surface reduce snow's reflective qualities, causing more radiation to be absorbed. Overall, the amount of heating is greater than the amount of cooling over snow surfaces. Northern Hemisphere spring-time snow cover is unique both because of its widespread distribution and because the relatively intense incoming solar radiation makes the snow more vulnerable to atmospheric aerosols' effects. Flanner and colleagues hypothesize that higher concentrations of organic matter and black carbon typically found in the atmosphere and on the snow-covered surfaces in Eurasia might account for regional snow-cover differences. By including black carbon and organic matter aerosols as GCM parameters, they thought the models might more effectively match spring-time observations.

To test their hypothesis and better understand why most IPCC GCMs don't reflect the observed spring-time response, the team ran a number of modeling scenarios to see if the issue might relate to ocean-based effects. They began their study here because if oceans proved to be playing a leading role, their hypothesis would likely be incorrect, which would lead to identifying alternate explanations. But, after constraining the oceans' effects, the GCMs continued under-predicting land-surface temperature trends. This indicated that a land effect had to account for the discrepancy between observed and modeled warming and melt trends.

Having eliminated ocean effects, they experimented with enhancing the GCMs with snow-darkening characteristics (i.e., deposition of materials darker than the pristine snow surface). In doing so, the models generated



increased spring-time Eurasian warming.

Next, the researchers compared the models' springtime climate responses to CO2 and black/organic carbon aerosols. The scientists found as much reduction in Eurasian spring snow cover caused by black carbon and organic materials currently emitted from fossil fuels and biofuels as from human-produced CO2. But over North America, CO2-induced snow cover loss was greater.

"While this research does not fully explain why springtime land temperatures and snow cover are changing so much faster over Eurasia than North America, it does suggest that snow darkening from black carbon,a process lacking in most climate models, is playing a role," says Flanner. Ultimately, Flanner continues, the magnitude of Earth's climate response to CO2 and other human-generated products depends on feedbacks. Changes in snow cover amplify initial climate changes and constitute one of the most powerful feedbacks. Because snow covers much of the Northern Hemisphere during spring, Flanner and his colleagues expect to see some of the strongest climate change signals in northerly regions during local spring.

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Storm Chasing: Tracking Tornadoes in the U.S. Midwest

Approximately 60 deaths occur each year in the United States as a result of the roughly 1,000 tornadoes generated each year. Tornadoes have long been studied, but questions remain as to why, how and under what circumstances tornadoes form. To better answer these questions, more than 100 scientists and staff gathered in the U.S. Midwest in late spring 2009 to study supercell — isolated thunderstorms characterized by strong, rotating updrafts that are the precursors to tornadoes — and tornado generation.

This work, funded largely by the National Science Foundation and the National Oceanic and Atmospheric Administration, expands on an initial Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) run in the mid-1990s. The 21st century effort involves researchers — including a significant contingent of graduate students — from around the world who spent a month as nomads, tracking tornadoes using a fleet of mobile radar and other ground-based instrumentation. Identifying likely supercells, they gathered in-depth information on tornado formation processes.

"We still do not completely understand the processes that lead to tornado formation and shape its development," says Roger Wakimoto, director of NCAR's Earth Observing Laboratory and a principal investigator for VORTEX2. "We hope VORTEX2 will provide the data we need to learn more about tornado development, which in time will help forecasters provide the public more advance warning before a tornado strikes."

Despite an unusually quiet tornado season in 2009, the team captured critical information from several severe storms that will bolster knowledge related to supercell and tornado genesis, life span, and death. Equally important, scientists also had an opportunity to observe supercell development that didn't result in tornado generation, despite seemingly ideal conditions. With a second month-and-a-half-long study to look forward to beginning in May 2010, scientists are currently assessing the 2009 data to refine study approaches and questions for the final stage of VORTEX 2.

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VORTEX2 vehicles stop by the side of the highway as they track the Goshen Country storm in Wyoming on June 5, 2009. Two vehicles are equipped with roof-mounted weather stations. VORTEX2 is designed to improve our understanding of tornado formation, which ultimately will better allow us to assess the likelihood of tornadoes in supercell thunderstorms and possibly tornado intensity, longevity, and cyclic behavior.

Click here to enlarge +

National Center for Atmospheric Research
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Cutting-edge Research

By its nature, scientific discovery is exciting. Taking existing understanding to the next level is the goal of every researcher. Below are some areas where the NCAR scientific community is leading the charge to take existing knowledge and apply it in new ways to address both age-old questions and existing and burgeoning issues.

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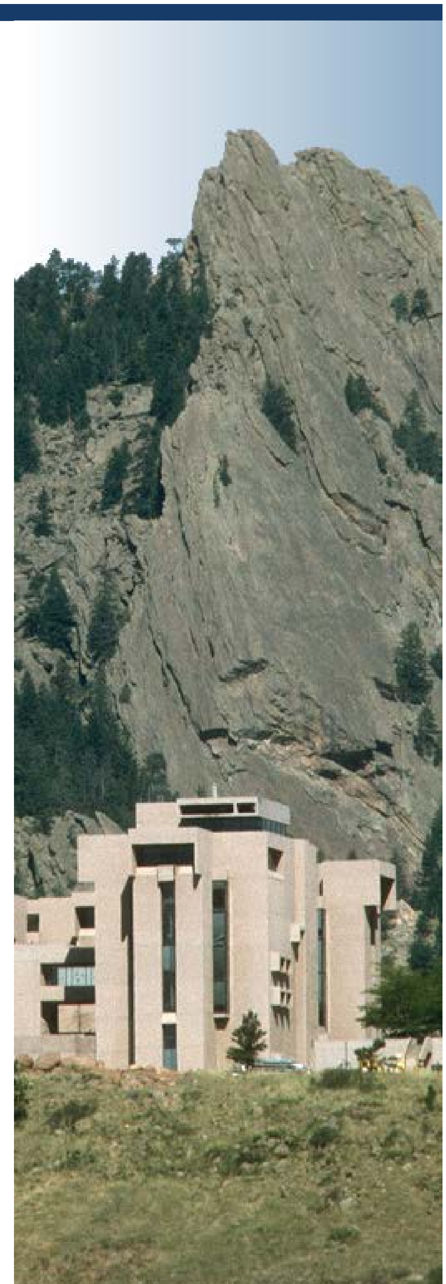


Plasma that packs punch: Spaceborne telescope finds a possible cause of the solar corona's heat

The 2006 launch of Hinode changed the picture of the Sun for astrophysicists. A satellite that includes a high-resolution telescope, Hinode captures images of the Sun in unparalleled detail without interference from the Earth's atmosphere. Among the regions observed by Hinode is the solar chromosphere, the area separating the Sun's surface — the photosphere — from its extended atmosphere — the corona. This advance in imaging allows scientists to measure smaller features missed by older, ground-based telescopes. With these new, better images in hand, several scientists found tantalizing clues that led them to a new wayof addressing the age-old question of why the solar corona is millions of degrees hotter than the photosphere.

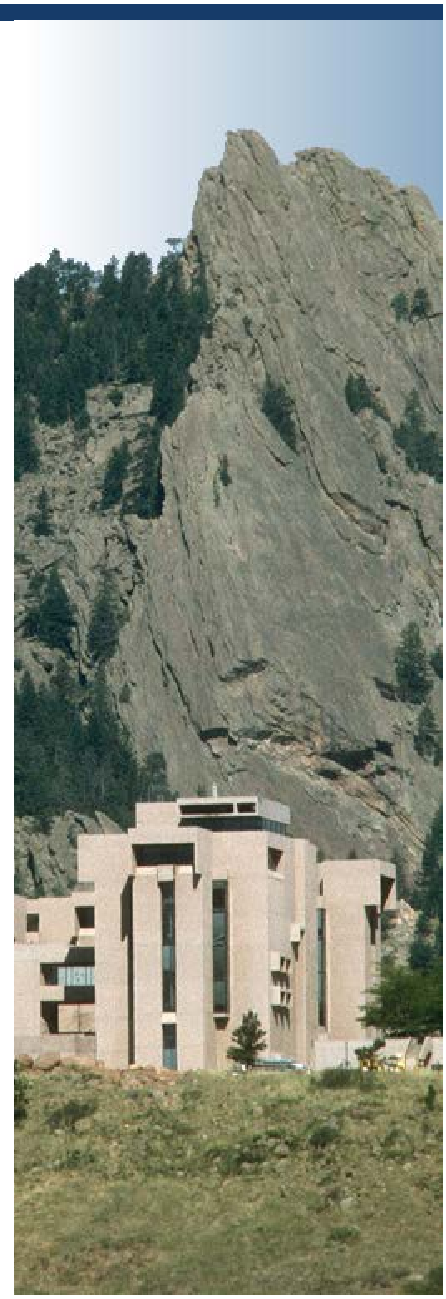
Intuitively, the Sun's atmosphere should get cooler with distance from the Sun's surface, but reality doesn't match supposition. Using Hinode imagery, Bart De Pontieu of Lockheed Martin's Solar & Astrophysics Laboratory and Scott McIntosh of NCAR's High Altitude Observatory were able to see differences between "classic" Type-I spicules — jets of dense plasma that shoot up from the chromosphere — and a new type of spicule. These Type-II spicules — that McIntosh and De Pontieu have recently dubbed "radices" — are hotter, shorter lived and faster moving than their Type-I brethren.

> ***In the imagery, radices appeared to shoot upward, disappearing into the corona.***

In the imagery, radices appeared to shoot upward, disappearing into the corona. The researchers observed radices (or a single radix) moving at speeds often in excess of 100 kilometers per second. The jets likely contain plasma that ranges in temperature from 10,000 to several million degrees Celsius, and have a life span of no more than 10 to 100 seconds. While astrophysicists — including NCAR founder, Walter Orr Roberts — have long studied Type I spicules, it is known that the material in those does not reach coronal temperatures of 1 million degrees Kelvin, which eliminates a connection to coronal heating.

At a 2008 Hinode meeting, when a colleague discussed seeing the presence of a very subtle 100-km-per-second upward velocity component in a coronal region of very strong magnetic field, McIntosh and De Pontieu looked at each other, and wondered if they were possibly seeing the coronal signature of radices. After an intense search for the "ideal" Hinode data set, they traced the columns of plasma ejected from the chromosphere into the corona. Each approached the task from a different perspective. McIntosh, with spectroscopic expertise, studied the coronal observations while De Pontieu, who has studied a host of chromospheric events in high-resolution ground-based observations, dealt with the chromospheric dynamics. Comparing their investigations, the two realized that the locations of the radices and the upward velocity signature were the same. They also found that the velocities of the chromospheric jets and those of the coronal events matched extremely well.

Based on this evidence, De Pontieu and McIntosh estimate that radices play an important role in supplying and replenishing the hot mass of the solar corona and wind. Based on their calculations, radices can fill the



corona with hot plasma even if only one to five percent of the chromospheric radices' mass reaches coronal temperatures.

Interestingly, the location of radices in regions of strong magnetic field, combined with their role in heating the middle solar atmosphere means that they may play an important role in dictating the ultraviolet (UV) output of the solar atmosphere. For Earth, this is important because it implies that their presence and distribution over the solar surface plays an important role in governing the UV radiation that impinges on the Earth's atmosphere, in turn affecting the production and destruction of stratospheric ozone impacting climate dynamics and evolution.

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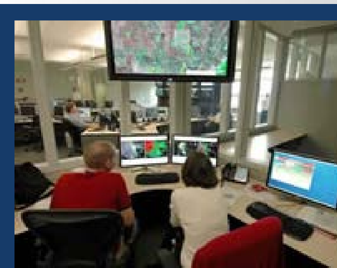
The Joint Numerical Testbed: A collaborative proving ground for cutting-edge models

Numerical models are the workhorses of U.S. weather prediction systems. Working behind the scenes, weather forecasters interpret model output; many real-time weather forecasts that the public has come to rely on are generated based on this output. Making these workhorses better, stronger, faster and — most importantly — more useful and reliable is the focus of NCAR's Joint Numerical Testbed (JNT). Working closely with the research and operational communities, the JNT takes research models' leading-edge capabilities and, through testing and evaluation, helps ensure that they meet operational needs.

> ***While the JNT came into being to serve the weather forecasting community, its facilities can be used for a variety of testing and evaluation activities in other areas, including climate. JNT service to the scientific community also includes tutorials on models and tools and workshops that bring together modeling experts and users to discuss critical modeling issues, and how the JNT might assist scientists in dealing with these issues. In addition, it runs an annual program that invites researchers to work with JNT and NCAR staff, as well as staff at operational modeling centers on innovative and new modeling questions. Selectively chosen based on project proposals, researchers work at NCAR for up to a month with those interested in similar research issues; direct collaboration continues for a year. Not only does this encourage cross-institutional connections, the JNT benefits from a fresh infusion of ideas, and the community benefits from the research questions under scrutiny.***

Research and operational requirements vary significantly when it comes to weather model output. Operational forecasters (the National Weather Service, for example) have direct links to society, generating as-accurate-as-possible forecasts in real time. Not only do operational forecasters have to-the-minute time constraints, they must also contend with limited computing power and space; if anything goes awry with model runs, forecast delivery schedules can be left in tatters and operational forecasters caught flat-footed during potentially serious weather events. As a result, this community tends to be leery of using model code that hasn't passed a rigorous litmus test. Researchers work with fewer of these pressures and have greater flexibility when it comes to testing out new model functionality — and generally demand cutting-edge model capabilities. While both communities may use a single same model, output and public requirement differences mean that all jointly used tools must address disparate user needs.

The Weather Research Forecasting (WRF) model provides a good example of where the two worlds meet. While tackling each community's set of requirements may seem straightforward, achieving the required capabilities demands a high degree of model sophistication. And, having an agent — a neutral group without a horse in either race — assists model enhancement, validation and development, which was how the JNT came into being at NCAR. While born into the Mesoscale and Microscale Meteorology (MMM)



The figure above shows the 0.1-degree-latitude Parallel Ocean Program (POP) model simulated Chlorofluorocarbon-11 concentration (on a logarithmic scale) at 1625m depth in the North Atlantic Ocean on January 1st 1985.

Click here to enlarge +

Among the Joint Numerical Testbed capabilities are model evaluation tools, state-of-the-art software provided to the meteorological community for forecast verification. This example demonstrates the use of MODE - an object based diagnostic tool that evaluates the performance of forecasts by measiring meaningful attributes such as the displacement between forecast and observed storms, rather than focusing only on agreements between gridpoint values, as is done with traditional verification methods.

Click here to enlarge +

division, home of WRF, NCAR's Research Applications Laboratory took on this effort so as to avoid perception of a conflict of interest within the wider WRF community.

In developing operational models from research versions, the JNT queries users from both communities to identify a model that would benefit from JNT code evaluation and testing skills. For instance, a particular aspect of a model — such as 1-day hurricane intensity forecasts — or intercomparison of models with similar forecast objectives might be assessed. Testing begins after choosing a representative period of model operations, including a variety of times, seasons, forecast lengths, times of day to ensure the desired level of thoroughness is met. Evaluation outcomes lead to new insights on model performance; these insights can be rolled into future model improvements that serve the public, government, private, as well as research interests.

The JNT's four components — the Developmental Testbed Center (DTC), the Data Assimilation Testbed Center (DATC), the Tropical Cyclone Modeling Testbed (TCMT), and the Applied Statistics and Verification Research project (ASVR) — provide users with a breadth of services. The DTC, funded with support from NSF, NOAA, and the Department of Defense, is part of a national program supporting access for the research community to operational models and testing of next-generation numerical forecasting systems in the United States. The TCMT efforts center on testing and evaluating numerical weather prediction (NWP) systems used to predict tropical cyclones. And the ASVR project concentrates on developing statistically meaningful advanced verification tools for the assessment and comparison of the performance of NWP and other forecasts. Through its efforts, the JNT is helping bridge the gap between operational and research forecasting.

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Gaining Stellar Insights

Scientists are gathering unprecedented quantities of solar and stellar data from sophisticated ground-based networks and space-based missions. Designed to take a closer look at global oscillations of the Sun and other stars to deduce their internal structure, the sheer volume of data creates a scientific challenge of its own: finding an efficient way to process and analyze vast amounts of information. Supercomputers provide an answer to this problem, and scientists are using the National Science Foundation's TeraGrid resources at NCAR's Computational and Information Systems Laboratory (CISL) and the Texas Advanced Computing Center (TACC) to delve deeper into stars' properties.

TeraGrid is a national cyberinfrastructure for open scientific research that includes 11 academic supercomputing centers, including TACC and NCAR. Hayden Planetarium counts itself among TeraGrid's beneficiaries, using celestial data, as well as visualization resources and tools to create a new planetarium show that takes viewers on a journey through the universe's early formation. Journey to the Stars explains how dark matter's gravity gathered the primordial gas in the universe to form the first stars, and how these massive stars exploded, seeding the galaxy with new stars and the chemical elements that made life possible.

The show's centerpiece, and the most difficult sequence to depict scientifically, is a flight into the center of the Sun. These visual sequences, created based on the research of Juri Toomre, a professor of astrophysics at the University of Colorado at Boulder, were run on TACC's Ranger supercomputer.

"It's not enough to know what comes out of the surface [of the Sun]," Toomre says. "We would like to understand how the magnetic engine of a star works, how it churns away and how it builds orderly fields. This is one of the top 10 questions in physics."

Toomre's doctoral student Benjamin Brown used VAPOR (Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers), a tool developed by NCAR in collaboration with the University of California, Davis, and Ohio State University, to generate visualizations of the Sun and the image sequences for the movie. In addition, NCAR's Matthias Rempel, a scientist in the High Altitude Observatory, contributed to the movie using his numerical sunspot model to visualize the connection between the magnetic field in the solar interior and sunspots on the visible surface of the Sun. He customized a simulation for Journey to the Stars, processing approximately a terabyte of solar data on TACC's Ranger supercomputer.

"The results are beautiful," says Ro Kinzler, the show's producer. "No one has seen the Sun in this way, and the software from NCAR and computational resources from TACC made it possible."

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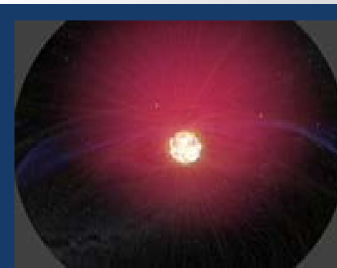


The centerpiece of Journey to the Stars is a flight into the center of the Sun, complete with narration and music composed for the show. This silent clip features a visualization created with VAPOR, the NCAR-based Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers. In 30 seconds it provides a small window into what visitors to the Rose Center for Earth and Space experience on the Hayden Sphere's 87-foot, seven-million-pixel dome. (� 2009, American Museum of Natural History)

Click here to view movie +

NCAR Launches Green Energy Initiatives

Researchers from NCAR's Research Applications Laboratory (RAL) are collaborating with university researchers, US Department of Energy labs, and other NCAR entities to develop methods to more accurately analyze and predict wind energy to support the renewable energy industry. Among the early efforts that RAL has focused on is a joint project with Xcel Energy to advance research and develop technologies that allow Xcel to increase the amount of wind-generated energy in its energy portfolio.

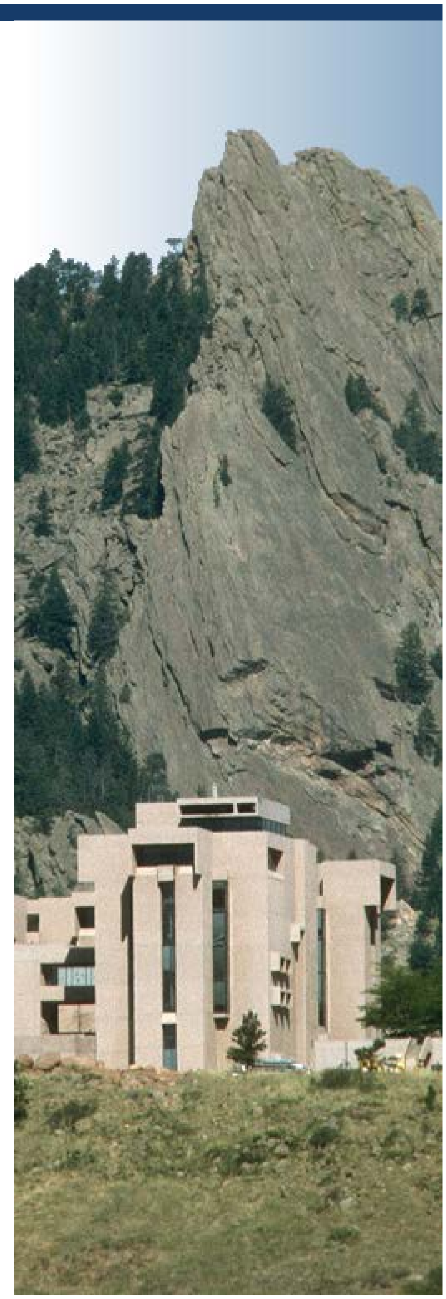
"One of the major obstacles that has prevented more widespread use of wind energy is the difficulty in predicting when and how strongly wind will blow at the wind farms," says William Mahoney, the NCAR program director overseeing the project. "These forecasts are a critical step in getting more energy from wind."

NCAR scientists are providing Xcel Energy with highly detailed, localized weather forecasts to enable the utility to better integrate electricity generated from wind into the power grid. The forecasts will help operators make critical decisions about powering down traditional coal- and natural gas-fired plants when sufficient winds are predicted, allowing the utility to increase reliance on alternative energy while still meeting its customers' needs. In turn, Xcel Energy and NCAR are analyzing the forecasts to identify areas of forecast success as well as areas requiring improvement, which will be used by NCAR to identify areas that need additional research and development.

DOE's National Renewable Energy Laboratory (NREL) is also supporting the project, developing mathematical formulas to calculate the amount of energy that turbines generate when winds blow at various speeds. The wind generation "sweet spot" occurs when winds blow between 10 and 20 miles an hour — at speeds below about six miles per hour, the turbine blades don't turn, above about 25 miles per hour, blades reach the maximum speed that their design can handle without compromising the turbine infrastructure.

"The entire issue of our forecasting is to get the wind speed right when it's between about 10 miles an hour and 20 miles an hour," says David Johnson, a RAL scientist. "Getting an accurate wind forecast within a couple miles an hour of that range makes a dramatic difference in our power forecast,"

Using its suite of tools and models, NCAR is issuing high-resolution wind energy forecasts for wind farm sites every three hours. The prediction system has already proven successful for Xcel Energy, and is saving the company significant costs. With this success, says Mahoney, it seems likely that other wind forecasting companies may adopt the technology as a means of helping utilities in the United States and overseas transition away from fossil fuels.



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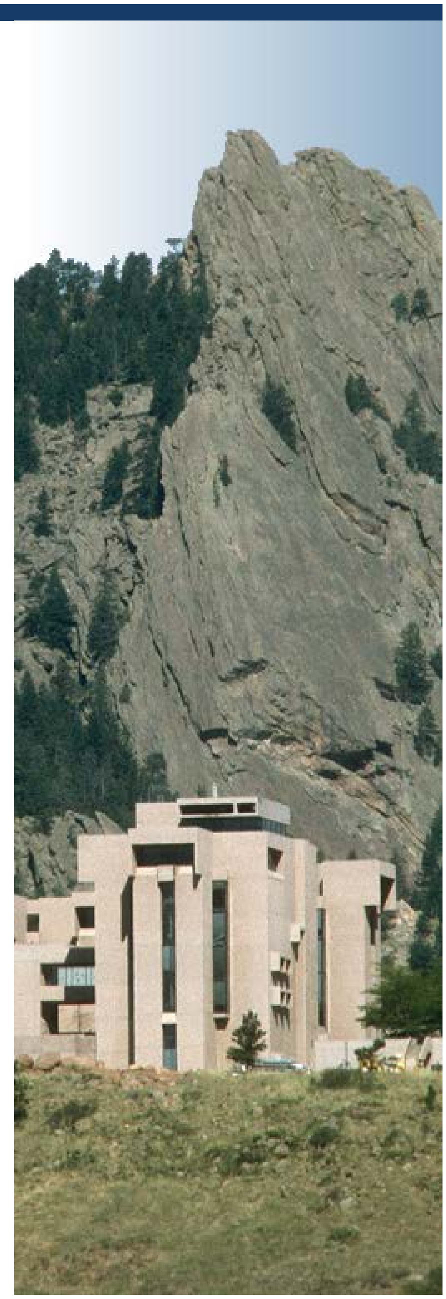

Metrics

These metrics are qualitative and quantitative measurements and assessments of the productivity, quality, and impacts of NCAR programs and activities.

Field Campaigns

(top)

Collecting field data has always been 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 campaigns (field-based observing missions or experiments) ensure successful data collection.

NCAR led or participated in 56 field campaigns in 14 countries and the United States. Locations ranged from the Amazon to the Arctic, and included more than 1,100 participants.

Editorships

(top)

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

Sixty-one NCAR staff served in 82 different editorial roles in 56 journals. Publications included top tier journals such as Journal of Geophysical Research - Atmospheres and Atmospheric Environment to targeted journals such as Radio Science.

External Committee Service

(top)

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

More than 145 NCAR staff served in a multitude of roles on 435 external

committees for national and international scientific, education, and governmental organizations, including organizations such as the Intergovernmental Panel on Climate Change, the American Geophysical Union (AGU), and the American Meteorological Society (AMS). Positions ranged from Chair of the Board of Directors to Committee Advisor.

Scientific and Technical Presentations

(top)

NCAR Staff give formal scientific and technical presentations about data, models, theories, hypotheses, reviews, and results around the world.

Over 80,000 people were in the audience when 239 NCAR staff made over 1,400 scientific and technical presentations across the country and around world, from Kona, Hawaii to Ilulissat, Greenland. Examples range from Bill Mahoney's (RAL) presentation on optimizing wind power using wind power forecasts in Houston, Texas to a presentation on regional climate models, spatial data and extremes by Doug Nychka (CISL/IMAGe) in Eindhoven, Nederlands.

Colloquia & Symposia

(top)

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 75 colloquia in Boulder and abroad. Participants per session averaged out to 33, for a total audience of more than 2,400 peers and students. Some of the co-hosts include Rutgers University, DOE, NOAA, NASA, and the Max Planck Institute.

Workshops

(top)

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 99 workshops and conferences in seven countries and nine U.S. states. We partnered with sponsors from the university community, such as the California Institute of Technology and Boston University, government agencies including NOAA, DOE and NASA, as well as with non-profit partners like the World Meteorological Organization and the American Statistical Association. In total, these workshops and conferences reached just under 6,000 participants, a 20% increase over last year.

Teaching Appointments

(top)

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 47. Seventeen percent of these appointments occur in seven countries around the world; 83% took place in 13 U.S. states including NCAR's Super Computing partner, the University of Wyoming. The longest term is 24 years and counting and the current cumulative commitment adds up to over 190 years of service.

Graduate Advisors

(top)

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

Of the 100 graduate students that have NCAR staff serving as graduate advisors, 25% hail from Colorado institutions; 31% attend schools in 16 other states. The remaining 44% study at schools in 19 countries around the world, including six students from the University of Eastern Finland who

are advised by James Smith.

Thesis committee

(top)

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

Twelve Master students and 96 PhD candidates work with 56 NCAR staff as they pursue their degrees from universities in 19 U.S. states; this includes 43 students from Colorado institutions. Twenty-four students come from 17 countries, with Korean students leading the international count at four.

NCAR Student Appointments

(top)

Students also enjoy NCAR-based appointments.

In FY09, there were 63 student appointments: five Graduate Students, five Graduate Research Assistants and 35 undergraduate Student Assistants appointments. There were also 18 student internships coordinated through the Summer Internships in Parallel Computational Science (SIParCS) program, **http://www.cisl.ucar.edu/siparcs/index.jsp** and the EOL Undergraduate Engineering Internship program at **http://www.eol.ucar.edu/about/work/eng-internship**. These students hail from home institutions ranging from Denver's Metro State College to Louisiana State University. NCAR also awarded 38 postdoctoral fellowships to talented staff through the Advanced Study Program at **http://www.asp.ucar.edu/** and other laboratory visitor programs **http://www.ucar.edu/opportunities/postdocs/**.

Special Appointments

(top)

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 3 year terms. This appointment is particularly suitable for parties who desire an extended, close-working relationship on scientific problems of mutual interest. Currently 36 hold appointments including Dr. Lance Bosart of State University of New York/Albany whose current research projects focus on observational and modeling studies of synoptic and mesoscale phenomena from a multiscale perspective. Dr. Bosart collaborates with MMM.

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 11 with the recent appointment of eminent HAO scientists Ray Roble and Peter Gilman.

K-12 Outreach

(top)

staff across NCAR 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.

Twenty-one NCAR Staff worked with K-12 students from 32 schools. Activities included mentoring, lectures, tours and field trips reaching 14 different communities.

Informal science education and presentations

(top)

NCAR scientists participate in educational activities by contributing to the development and provision of informal science education resources. Examples range from serving on an exhibit advisory committee, to providing and vetting science content in Web sites and modules, to supporting

community outreach at local community events, including judging at a science fair and supporting Super Science Saturday.

This year's count totaled more than 61 events. Among the highlights: Kate Young (EOL) led a balloon launch at Meadow View Elementary School in Castle Rock, CO; Matthias Rempel (HAO) developed a special display on sunspot simulation at the Rose Center for Earth and Space in New York City and Sarah Gibson (HAO) led Solar Week for Girls in the Boulder schools.

Awards

(top)

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

Thirty-six staff received special recognition for their work in FY09. Marcia Politovich (RAL) was selected as a Fellow of the American Meteorological Society (AMS) for her outstanding contributions to the atmospheric or related oceanic or hydrologic sciences or their applications during a substantial period of years. Simona Bordoni (ASP/NESL/MMM)was selected for the AGU James R. Holton Junior Scientist Award. This award was established by the AGU Atmospheric Sciences section in 2004 and is given to an outstanding junior atmospheric scientist within 3 years of their Ph.D. The award is to honor James Holton, who was a pioneer in atmospheric dynamics and an inspiration to young scientists. Art Richmond (HAO) was selected as the 2009 AGU Joint Assembly AGU Bowie Lecture Series--Nicolet Lecturer. The AGU Bowie Lecture Series was inaugurated in 1989 to commemorate the 50th presentation of the William Bowie Medal, which is AGU's highest honor and is named for AGU's first president. His presentation on the upper atmosphere's response to the magnetosphere is available at **http://www.agu.org/meetings/ja09/lectures/**.

Fellowships

(top)

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

Natasha Flyer was granted a fellowship at the Oxford Center for Collaborative Applied Mathematics (OCCAM), situated in the Mathematical Institute at the University of Oxford. The objectives of OCCAM are to develop innovative mathematical and computational methods for application to biology, engineering, geoscience, and industry. During her stay, Natasha's research focused on the development of radial basis functions, a novel mesh-less computational method, for three dimensional modeling of geophysical phenomena.

Aaron Andersen continued his fellowship at the Uptime Institute. Using benchmarking, abnormal incident data, and industry Best Practices collected from members of its knowledge communities, The Uptime Institute, Inc. (the Institute) has distilled uptime management into scientific disciplines and practices which can be confidently applied. The synergy of a knowledge community encourages more to be shared so that more is known, and then there is even more to be shared. This exponential increase in knowledge is facilitated by the Institute and its faculty of Distinguished Fellows. **http://www.upsite.com/TUIpages/tuihome.html**

Carl Drews graduated in August 2009 from the University of Colorado at Boulder (CU) with a Master's Degree in Atmospheric and Oceanic Sciences. The CU Department of Atmospheric and Oceanic Sciences (ATOC) awarded him a travel fellowship in the amount of $1,000 to travel to the Symposium of the Office of Naval Research (ONR) in Chicago, Illinois and present the results of his thesis research into wind-driven storm surge. Mr. Drews used the Regional Ocean Modeling System (ROMS) to model storm surge in Manila Bay, forced by WRF wind fields over a range of possible typhoon tracks. The conference provided the opportunity to meet and discuss his research results with other oceanographers funded by the ONR.

Scientific and Technical Visitor Appointments

(top)

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.

Visit Length		Number of Scientific and Technical Visits in FY09
1-7 Days		213
8-14 Days		88
15-30 Days		109
1-2 Months		87
3-6 Months		228
6 Months - 1 Year		36
Total		761

Scientific and Technical Visit Types		Headcount in FY09
Visits by visitors on Payroll		50
Visits by NCAR funded Visitors		335
Visits by visitors funded externally		376
Total		761

NCAR Visitors hailed from 317 institutions, located in 46 different U.S. states and 42 different countries.

Publications

(top)

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 referred and non-referred publications lists for the period October 1, 2008 to September 30, 2009. Search for recent NCAR publications by author, date, keyword or status please go to the NCAR Publications database at: **http://www.essl.ucar.edu/publications/index.php**

For excellent library resources please go the NCAR Library Web site at: **http://www.ucar.edu/library/**

NCAR Refereed Publications: 550 (**download PDF Bibliography**)

550 Publication(s) for the time period 2008-10-01 to 2009-09-30
Group(s): ASP, ISP, NCARLIB, CISL, EOL, HAO, NESL, RAL
Class: Refereed; Status: All; (most recent first, AMS format)
Author Collaborations Summary:

UCAR Only: 86
UCAR & University: 176
UCAR & Other: 67
UCAR, University, & Other: 188

FY09 UCAR Outstanding Publication Award awarded to Bill Skamarock of NESL/MMM
This award is given for the published results in the past five years of original research, review papers, or pedagogically oriented books that contribute to the atmospheric sciences. Publications are judged on four criteria: (a) importance of the subject to atmospheric science broadly defined, including work connecting atmospheric science with other disciplines or matters of

public policy; (b) importance of the paper's contribution to its specific subject area; (c) evidence of creativity and originality; and (d) clarity of exposition.

Skamarock, W.C., 2004: Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra. Monthly Weather Review, 132, 3019-3032.

This publication tackles the very difficult problem of assessing the ability of numerical weather forecast models to accurately represent important weather features that occur at smaller scales. The author proposes a new approach, utilizing the characteristic behavior of observed kinetic energy spectra to evaluate the ability of numerical weather prediction (NWP) models to properly represent the behavior of weather disturbances and to quantify the effective resolution of the numerics of these models.

Partners

(top)

NCAR defines collaborators using the National Science Foundation's definition of partner organizations as being "academic institutions, other nonprofits, industrial or commercial firms, state or local governments, and schools or school systems that have been involved with NSF base-funded projects." Partner Organizations may provide financial or in-kind support, supply facilities or equipment, collaborate in research exchange personnel or otherwise contribute project support.

NCAR Collaborators come from 868 institutions, which are located in all 50 states, and 60 countries. Institutions range from the American Wind Energy Association (AWEA) to Yale University.

For a full list of each metrics topic, download **NCAR 2009 Metrics Details.xls**

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National Center for Atmospheric Research
2009 ANNUAL REPORT

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About NCAR

The National Center for Atmospheric Research (NCAR) is a federally funded research and development center devoted to service, research and education in the atmospheric and related sciences. Our primary sponsor is the National Science Foundation, with significant additional support provided by other U.S. government agencies, other national governments and the private sector. NCAR's mission is to understand the behavior of the atmosphere and related physical, biological and social systems; to support, enhance and extend the capabilities of the university community and the broader scientific community — nationally and internationally; and to foster the transfer of knowledge and technology for the betterment of life on Earth.

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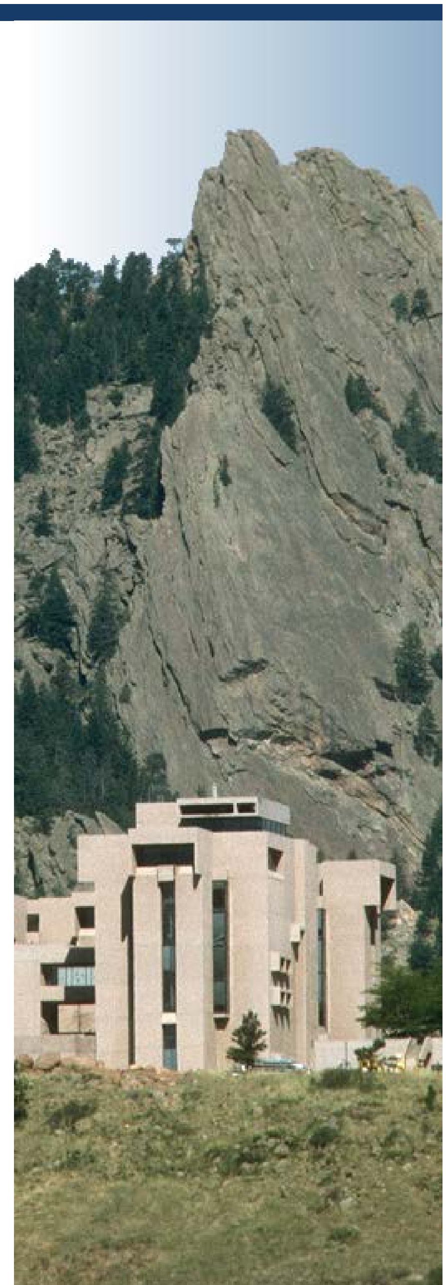

ASP Annual Report 2009

DIRECTOR'S MESSAGE


ASP Director Maura Hagan

The Advanced Study Program (ASP) helps NCAR and the scientific communities that it serves to prepare for the future by engaging in human and institutional 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 young 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 component Graduate Visitor and Faculty Fellowship Programs, 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 15 new postdoctoral fellowships in spring 2009 (up from seven last year). These new fellows have already begun to arrive and to participate in ASP activities, providing a boost to the ongoing program. In September 2009 second-year postdoctoral fellow, Song-Lak Kang, kicked off ASP's new pilot program with NCAR Historically Black Colleges and Universities (HBCU) partners when he arrived at Howard University to teach and do research for the fall semester.

The Faculty Fellowship Program provided support for five faculty fellows with three accompanying students to do research at NCAR. The FFP also sponsored one member of the NCAR staff to spend four months at University of California at Berkeley, working in collaboration with university faculty there.

The ASP also hosted 13 graduate students through the Graduate Visitor Program. These students spent time in residence at NCAR in support of their thesis research. Most of these awards also included support for at least one two-week visit for their thesis advisors.

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

FY2009 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. Directeur Jean-Dominique Creutin (Laboratoire d'étude des Transferts en Hydrologie et Environnement) will visit in November 2009 and Professor John Seinfeld (California Institute of Technology) will visit in April 2010.

The annual ASP Colloquium series will include two events in summer 2010 on the topics of "Forecast Verification in the Atmospheric Sciences and Beyond" and "Asia in the 21st Century". The Colloquium on "Asia in the 21st Century" will be co-sponsored by the newly established Integrated Science Program (ISP) at NCAR.

ASP will also provide organizational support for the NCAR Software Engineering Assembly and the newly established Technology Innovation Forum, along with the activities of the Early Career Scientists Assembly (ECSA), including the Junior Faculty Forum on Future Scientific Directions.

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

ASP Annual Report 2009

Postdoctoral Fellowships

NCAR is sponsored by the National Science Foundation.

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-four years and has sponsored over 435 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 FY09, the ASP appointed 15 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 FY2009, the ASP held monthly 'socials' that often included an education or career development aspect. Socials during the past year included a panel discussion on tenured and permanent positions with early career scientists and professors, an interactive presentation on communicating science, and an opportunity to interact with journalists. These socials 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 FY2009, ASP plans to continue the core elements of the program, including monthly seminars, bi-weekly research reviews, monthly socials, and the Thompson Lecture Series along with the annual research planning sessions and on-going mentoring that ASP postdocs receive.

The ASP postdoctoral program receives its funding from the National Science Foundation.

Front row, left to right: Shannon McNeeley, Cecile Piret, Marielle Saunois, Maura Hagan, Lulin Xue, Julie Theriault, Saewung Kim, Jia Yue, Kathleen Barney.
Back row , left to right: Charles Bardeen, Jacob Fugal, Lars Rippe, Ethan Gutmann, Hannah Brenkert-Smith, Clark Evans, Paul Winkler, Scott Briggs.

Postdoctoral Fellowships

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ASP Annual Report 2009

Faculty Fellowship Program

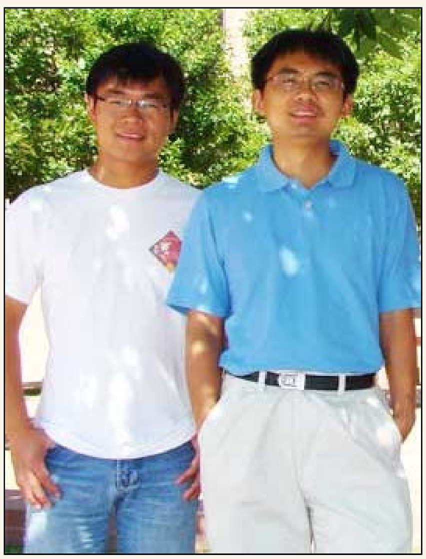
BUILDING PARTNERSHIPS WITH UNIVERSITY FACULTY

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 FY09, applicants submitted proposals and budgets for 3- to 12-month visits that occurred between 1 June 2009 and 31 May 2011. ASP received seven viable applications. Five applicants were extended offers for visits that either occurred in FY09 or will take place in FY10. The FFP supported 11 university faculty visitors and eight student visitors during FY08. One NCAR scientist received support for his long-term visit to a U.S. university.

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. The ASP plans to continue this program at the same level as FY09 in FY10.

Participant Feedback of the Faculty Fellowship Program



Jun Wang wrote about his visit: *We had many important outcomes as a result of our FFP-supported visit in NCAR. First, we, in particular, my student, learned CCSM in great detail, and are now in an advanced level to modify the model. ...Second, the visit enhanced the research collaborations between my research group and Dr. Gettelman's research group as well as between NCAR and UNL in general. A collaborative proposal with Dr. Gettelman has been discussed, and is anticipated to be submitted to NSF by the end of this year. ...Last but not least, the visit will greatly benefit my graduate student's, research and career. In my opinion, the support of FFP for the advisor to bring the graduate student to work on the research project with scientists in NCAR is an excellent idea because it provides a golden opportunity for students to see the excitement of being a professional researcher (such as in NCAR), and motivates students to continue pursuing their careers in atmospheric and other related sciences. By participating in regular meetings, seminars and scientific discussions, the students also learn how to communicate and collaborate with colleagues in research settings. Personally, I see that my student showed much higher motivation and working efficiency after this visit in NCAR, and his scientific view of our field is broadened and deepened significantly, all of which will help him develop his career in long run.*

Andrew Conley wrote of his visit to University of California at Berkeley: *The combination of being able to work daily and share our understandings in person made this collaboration possible. Without the daily interaction, the implementation, testing, and design would have been nearly impossible. In addition, we were able to be creative about possible theoretical advancements of the algorithms that are fundamental to radiative transfer codes. The rapid interchange, ability to draw rough pictures for each other, and share incomplete thoughts was facilitated by working in person together. Out of this creative environment we have been able to formulate a number of possible improvements to algorithms which we wish to test. We hope that over the next several years some of these will turn out to be useful for climate models.*

The trip reinvigorated an ongoing collaboration, introduced me to a number of people working in associated fields (carbon cycle, methane clathrates, representations of shortwave scattering, economics of climate change, regional climate change, satellite observations and comparisons with models), allowed us to test a number of aspects of the new radiation code, and allowed us to design tests to diagnose the changes to CCSM. I also had the joy to meet and work with a number of young faculty and postdocs.

Personally, it was a joy to be able to explore a range of potential avenues for advancement of the science of climate change with an expert in the field.

The Faculty Fellowship Program is sponsored by the National Science Foundation and by all the Universities and Institutions who co-host the fellows' NCAR visits, including Florida State University, National Central University, Taiwan, University of California –

Berkeley, University of Nebraska – Lincoln, Virginia Polytechnic Institute and State University.

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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 fourth 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.

Inputs, Outputs and Outcomes for FY2009

ASP received 16 applications for Graduate Visitor Program visits between January 2009 and January 2010. Of those applications, 13 students were funded, and most of those included or will include at least one visit by their faculty advisor. The ASP office conducts the application and selection process for this program, working closely with the NCAR laboratories and divisions who host the students.

Many NCAR scientific staff members who hosted graduate visitors indicated that important work was completed during the students' visits. Almost all hosts agreed that the time spent at NCAR contributed significantly to their visitor's thesis research, and that most would be returning to their home institution to write and publish papers based on their work at NCAR. Several of the graduate student visitors and their advisors indicated that their NCAR visits provided access to resources and facilities that they do not have at their home institutions.

Projected Inputs, Outputs, and Outcomes for future years

The Graduate Visitor Program is still too new to measure or understand its full impacts. Yet, 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.

Feedback from 2009 GVP Participants

Matthew Norman (North Carolina State University)

My experience during this recent 10-month ASP visit was truly invaluable. In my time at NCAR, I worked on finite volume methods based on characteristic decomposition which showed promise in terms of high-order accuracy, scalability, and efficiency. This will serve as the foundation for my further Ph.D. research. I worked under Dr. Ram Nair who helped guide me though the research, spent a great amount of time discussing the project, and introduced me to several great opportunities outside the ASP visit itself. During my visit, I had the opportunity of interacting with many of the top names in atmospheric modeling.

...

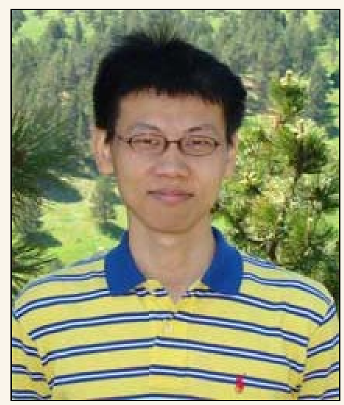
I am grateful to the ASP program for inviting me for the 10-month visit, and I honestly consider it the best opportunity for learning and experience I have had thus far.

Alexandra Jonko (Oregon State University)

In general, I am pleased with the outcome of this visit. It has provided me with the opportunity to exchange ideas with many interesting and relevant people. I was able to learn a lot from them and our interactions, and to broaden and solidify my knowledge on issues pertinent to my research. This process has made me reflect a great deal on my research goals, and review them more critically. I feel that my ideas about it have become more mature, giving my project a better defined direction.

Matthew Beals (Michigan Technological University) *Taking part in the development and initial testing of the probe was a great benefit to me. My future research (and potentially career) will involve use of the HOLODEC II probe and by taking part in the initial testing and assembly of the probe, I have a much better understanding of what the probe is doing and how it is doing it. This gives me better insight into the resulting data and prepares me for future field work involving the instrument. I also gained valuable experience in the process of developing and debugging a holographic instrument, which has already turned out to be useful to another project that I was involved with at my home institution. ...*
In short, I think the visit was really an invaluable experience for my research and my career.

Xin Qui (Nanjing University)
Xin Qui indicated that he had benefited greatly from his discussions with scientists at NCAR. Not only did he receive many scientific insights, but due to these discussions his work has become known to a broader research community. According to Mr. Qui, this exposure is very important to the early career of a young researcher and more meaningful than a scientific paper.



Graduate Visitor Program

NCAR is sponsored by the National Science Foundation.

BRINGING EARLY CAREER FACULTY AND NCAR SCIENTIFIC STAFF TOGETHER

Speakers and Participants - 2009 ECSA Junior Faculty Forum on Future Scientific Directions: Connecting Weather and Climate in Theory, Models and Observations

In 2003, the Advanced Study Program and the Early Career Scientist Assembly (ECSA) began hosting an annual forum at NCAR on future scientific directions. The objective of this forum is to bring together early career faculty and NCAR scientific staff to discuss selected topics in the Geosciences. This forum is open to non-tenured faculty at universities who are within five years of their first professorial academic appointment and to Level I and Level II NCAR scientific staff. In addition to promoting scientific discussion, an intended goal of the forum is to encourage development of professional relationships between members of the ECSA and UCAR institutions.

The Forum targets specific topics of interest based on feedback from early career staff from NCAR and the university community. In FY2009, the theme was Connecting Weather and Climate in Theory, Models and Observations. A total of 30 participants and 4 external speakers from across the nation, as well as a few international participants, attended the 2009 Forum and presented posters and made plans to write papers on the theme. The organizers plan to submit a summary of the Forum to the Bulletin of the American Meteorological Society.

Proposal topics for the 2010 Junior Faculty Forum have already been solicited and should be determined by the end of 2009.

The Junior Faculty Forum on Future Scientific Directions is funded by the NSF.

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ASP SUMMER COLLOQUIA

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 FY09, the ASP hosted two colloquia. The first program *Exploring the Atmosphere: Observational Instruments and Techniques* was developed by scientists in EOL, University of Wyoming, and Colorado State University. A total of 27 students from four countries and more than 70 professors, scientists, and staff members from NCAR, Colorado State University, University of Wyoming, NOAA, University of Illinois, University of Alabama, University of Vienna, and University of Virginia, participated in this two-week colloquium, which included lectures, tutorials, and hand-on field projects.

The student-led two-day mini-field experiment component of this colloquium, involving major NSF observing facilities from University of Wyoming King Air, Colorado State University CHILL radar and NCAR/EOL, was unprecedented. After four days of intensive courses on observing facilities, this group of talented and enthusiastic students designed experiments, deployed these facilities in mini-field campaigns, analyzed the resultant data, and presented impressive results on 10 different scientific topics.

Organizers, Speakers and Students of the "Exploring the Atmosphere: Observational Instruments and Techniques" Colloquium

The program for the second ASP Colloquium on *Marine Ecosystems and Climate: Modeling and Analysis of Observed Variability*, was developed by scientists in NCAR CGD and their partners from Rutgers University, University of California - Berkeley, and NOAA/ESRL. An invited group of 18 international experts worked closely with 26 students from the climate, marine ecosystem and impact communities during this two-week colloquium in August, 2009.

Lecture topics included the response of benthic, coastal and open-ocean ecosystems to climate change; modes of tropical and extratropical climate variability; statistical analysis techniques; earth system and regional ocean modeling; and fisheries, marine protected areas, and other socio-economic issues. An accompanying set of computer-based tutorials was designed to give the 26 students an in-depth understanding of the models and analysis methods available to tackle cross-disciplinary research problems. An important portion of the colloquium was devoted to four hands-on projects that allowed the students to put into practice the research approaches introduced in the lectures and tutorials.

Organizers, Speakers and Students of the "Marine Ecosystems and Climate: Modeling and Analysis of Observed Variability" Colloquium

The 2009 Summer Colloquia were sponsored by the National Science Foundation with additional support from the World Climate Research Programme (WCRP), and the Global Ocean Ecosystem Dynamics (GLOBEC) and Climate Variability and Predictability (CLIVAR) projects.

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RESEARCH CATALOG

- Charles Bardeen
- Clark Evans
- Song-Lak Kang
- Jasper Kok
- Lars Rippe

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CHARLES BARDEEN - NCAR EARTH SYSTEMS LABORATORY ATMOSPHERIC CHEMISTRY DIVISION

Meteor Smoke

In *Hervig et al*. [2009], we report the first remote observations of meteor smoke particles from the Solar Occultation for Ice Experiment (SOFIE) satellite instrument. Figure 1 shows a result from this paper in which the seasonality of the meteor smoke seen in the SOFIE data is found to be similar to simulations of meteor smoke using WACCM/CARMA [*Bardeen et al*., 2008]. WACCM/CARMA is an extension of the NCAR Whole-Atmosphere Community Climate Model (WACCM) that includes sectional microphysics from the Community Aerosol and Radiation Model for Atmospheres (CARMA). WACCM/CARMA is a framework for size resolved cloud and aerosol models that was developed by Charles Bardeen.

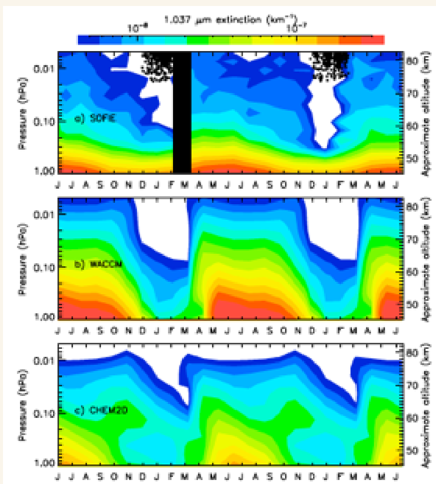


Figure 1. a) SOFIE MSP extinction versus time and height for the Southern Hemisphere. Black dots indicate NLCs, and the black bar represents missing data. Smoke extinction from the b) WACCM and c) CHEM2D and models calculated using the refractive index for Mg0.4Fe0.6SiO3. The abscissa is labeled by the first letter of each month for June 2007 through June 2009. All results are monthly zonal averages and white regions represent extinction below $5x10^{-9}$ km^{-1}. Note that the altitude scale is approximate because the altitude of a pressure surface changes seasonally.

Polar Mesospheric Clouds

In *Bardeen et al*. [2009], we report the first three-dimensional microphysical simulations of polar mesospheric clouds (PMC) using an explicit source of meteor smoke ice nuclei. As shown in Figure 2, these WACCM/CARMA simulations for the Northern Hemisphere are found to compare well with PMC observations from SOFIE and from the Cloud Imaging and Particle Size Experiment (CIPS) (not shown). The simulations are very sensitive to the temperature profile created by tuning the WACCM gravity wave parameterization, but are surprisingly insensitive to the details of the heterogeneous nucleation parameterization. Subsequent work is attempting to improve the tuning of the gravity wave parameterization to provide a more realistic simulation of the polar winter and of the Southern Hemisphere polar summer mesopause region. Additional experiments with added temperature variability from sub-grid scale gravity waves overcome the number density bias seen in the initial simulations, indicating that heterogeneous nucleation of ice upon meteoric smoke particles alone could be sufficient to explain the SOFIE and CIPS PMC observations. This work is being prepared for submission to *Geophysical Research Letters*.

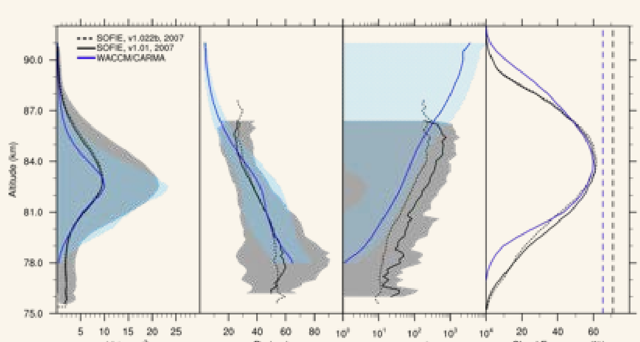
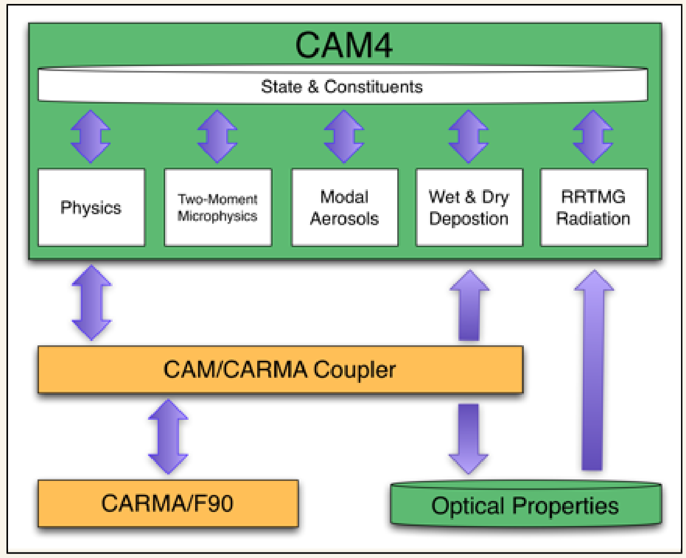


Figure 2. The average vertical profiles for mass density, effective radius, number density and the frequency of clouds with an extinction greater than $1x10^{-7}$ km^{-1} from SOFIE for the 2007 Northern Hemisphere season and for the control run. The shaded areas indicate one standard deviation from the average. The dashed vertical lines indicate the frequency of a cloud occurring anywhere in the column.

Sectional Microphysics in CAM4

The CARMA code based used in WACCM/CARMA is written in Fortran 77, is not thread safe, does not provide consistent answers across restarts and is not designed to be embedded with another model. Charles Bardeen is developing a new version of CARMA that fixes these limitations and adds additional capabilities. The new CARMA code is ~90% complete and is being integrated with CAM4 by Charles Bardeen and with GEOS-5 by Pete Colarco of NASA Goddard. CARMA is intended to be included in future versions of CAM and WACCM as an optional component. A prototype of the new CAM4/CARMA coupled model is being tested. Figure 3 shows a block diagram of the CAM4/CARMA model.

Figure 3. The CAM4/CARMA block diagram shows that the new Fortran 90 CARMA code is fully interactive with CAM and provides support for radiatively active particles via integration with RRTMG.



Simulations of TTL Cirrus

A new model of thin cirrus clouds in the tropical tropopause layer (TTL) is under development using CAM4/CARMA. As shown in Figure 4, the ice phase of the Morrison-Gettelman two-moment microphysics is being replaced by a bin representation using CARMA. This allows for a more detailed representation of the ice size distribution and hopefully will result in a better simulation of ice clouds and a more accurate calculation of the radiative effects of these clouds. A preliminary version of this model is complete, and while the CAM4 code needs to be updated to the latest CAM4/Track5 code and further tuning is needed, the initial spatial distribution of ice clouds in the TTL appears to have been improved over the standard simulation.

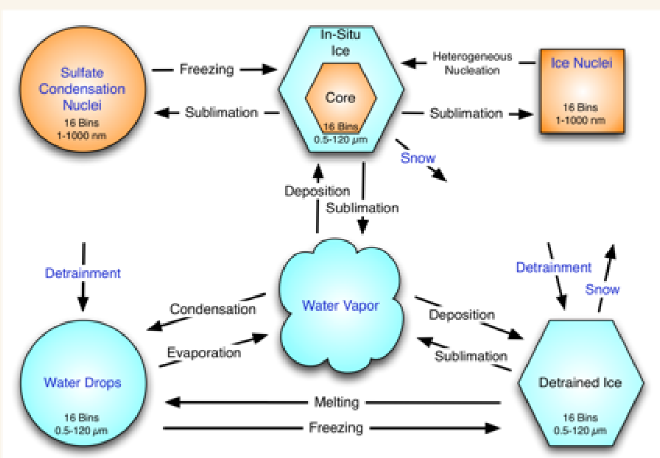


Figure 4. CARMA microphysical model for TTL cirrus. CARMA adds prognostic variables (black) for in-situ and detrained ice size bins, while interactively interfacing with existing (blue) water vapor and detraining ice and modal descriptions of water drops, snow, sulfates and ice nuclei.

Publications

Bardeen, C.G., Toon, O.B., Jensen, E.J., Hervig, M.E., Benze, S., Marsh D.R., Randall C.E. and Merkel A.W., Numerical simulations of the three-dimensional distribution of polar mesospheric clouds, *J. Geophys. Res.*, In Press.

Bardeen, C.G., O.B. Toon, E.J. Jensen, D.R. Marsh, and V.L. Harvey (2008), Numerical simulations of the three-dimensional distribution of meteoric dust in the mesosphere and upper stratosphere, *J. Geophys. Res.*, 113, D17202, doi:10.1029/2007JD009515.

Hervig, M.E., L.L. Gordley, L.E. Deaver, D.E. Siskind, M.H. Stevens, J.M. Russell, S.M. Bailey, L. Megner, C.G. Bardeen (2009), First Satellite Observations of Meteoric Smoke in the Middle Atmosphere, *Geophys. Res Lett.*, 36, L18805, doi:10.1029/2009GL039737.

Research Catalog

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CLARK EVANS - NCAR EARTH SYSTEMS LABORATORY
MESOSCALE & MICROSCALE METEOROLOGY DIVISION

Clark Evans began at NCAR as an ASP postdoctoral fellow in August 2009 after completing his Ph.D. in meteorology at Florida State University in Summer 2009. His research interests include tropical cyclone and mesoscale convective system structures, dynamics, and evolutions on scales ranging from the mesoscale to the climate-scale. His research primarily utilizes theory in conjunction with available observations and numerical modeling, particularly ensembles, to obtain physical and dynamical insight into these features. His current research focuses upon a wide array of topics, including but not necessarily limited to the following:

The extratropical transition of tropical cyclones, including the structural evolution of the cyclone's thermodynamic profile & wind field

Starting with his M.S. work at Florida State University, Clark has been and continues to be interested in the extratropical transition (ET) of tropical cyclones, particularly in terms of the structural evolution of the cyclone's thermodynamic profile and wind field. Specifically, during ET, the thermodynamic structure of the tropical cyclone transitions from warm, with winds decreasing with increasing altitude, to cold, with winds increasing with increasing altitude, with the timing of this evolution currently poorly captured by numerical models. The evolution of the thermodynamic structure during and after ET has significant impacts upon the intensity and structure of the post-tropical cyclone, potentially resulting in significant impacts to higher latitude locations and activities. Also during ET, the tangential wind profile of the cyclone expands radially outward throughout the depth of the troposphere, particularly equatorward of the track of the cyclone, resulting in an increased areal extent to the cyclone's impacts. Ongoing research is aimed at identifying and quantifying the synoptic-scale and mesoscale factors that cause these evolutions to occur.

The role of tropical cyclones in climate, particularly tropical-extratropical interactions

Motivated by the aforementioned work on the thermodynamic evolution of tropical cyclones during ET, Clark is interested in understanding the role of tropical cyclones in climate. For over forty years, it has been believed that tropical cyclones and the resultant energy and heat transport from the tropics to higher latitudes accounts for approximately 10% of the energy and heat transfer within the Earth's general meridional circulation. However, the variability in this value from cyclone to cyclone, year to year, and basin to basin has never been quantified, nor have the larger-scale and longer-term impacts of the tropical cyclones that lead to the heat transport. Utilizing mesoscale and climate models, Clark aims to resolve both the tropical cyclone's and general circulation's structure and evolution on large time scales, attempting to explain some of the aforementioned variability to better understand how tropical cyclones modulate climate (and vice versa).

Atypical tropical cyclone evolutions, including the overland reintensification of Tropical Cyclone Erin (2007)

In August 2007, a relatively benign tropical cyclone, Tropical Cyclone Erin (2007), made landfall on the central Texas coastline. Three days later, as it moved from the Texas Panhandle eastward into Oklahoma, it briefly but dramatically reintensified to an intensity approximately 10 hPa greater than was observed throughout its entire time over the warm waters of the Gulf of Mexico. How and why this occurred remain a mystery. Current research aims to solve this mystery, linking tropical cyclone and mesoscale convective system theory with a land-surface property-based ensemble of high-resolution mesoscale model simulations to quantify the factors responsible for this reintensification. Preliminary results suggest the importance of the nocturnal lower tropospheric jet across the southern Great Plains and of soil properties upon boundary layer thermodynamic and moisture fields that modulate the convective environment near the remnant cyclone.

Vortex dynamics on multiple scales, particularly associated with the development of mesolows with mesoscale convective systems

As an offshoot from the aforementioned studies of Tropical Cyclone Erin (2007), Clark is interested in the broader question of mesolow formation and dynamics associated with mesoscale convective systems, particularly in terms of the organization of convection and convective structures. Currently, he is studying the evolution of the mesolow that formed during the 8 May 2009 derecho event across the Central Great Plains and Mississippi River Valley, utilizing vorticity/circulation budgets and trajectory analyses from a high-resolution model simulation of the event to garner insight into the dynamics of the mesolow and its formation. Further research efforts are aimed at comparing the evolution of this and other convectively-driven mesolow features to tropical cyclones, including the aforementioned Tropical Cyclone Erin (2007).

Diagnosis and verification of tropical cyclone structures within real-time NWP models

In collaboration with the real-time Advanced Hurricane WRF (AHW) simulations conducted by the hurricane modeling group in of the Mesoscale and Microscale Meteorology (MMM) division of NCAR, Clark is interested in diagnosing and verifying simulated tropical cyclone structures from the genesis period through the completion of ET. Goals in this research are two-fold: one, to provide a means of verification of the real-time hurricane model (e.g. is it getting reasonable results for the supposedly right

reasons?) and to identify areas for improvement within the AHW, and two, to better understand the environmental conditions that lead to genesis and ET in order to better understand the role of climate in modulating tropical cyclones and vice versa.

Evaluating the utility of physics- and initialization-based mesoscale ensembles

Over the past three years, Clark has been running a real-time, twice-daily eight to sixteen member ensemble of Advanced Research Weather Research & Forecasting (WRF-ARW) model simulations across the southeast United States. During his time at NCAR, he has added a real-time, once-daily eight member ensemble of WRF-ARW model simulations across the entire United States to his research efforts. Research activities associated with these simulations focus upon diagnosing and analyzing the uncertainty of model forecasts of high impact weather events, including forecasts of severe convective storm environments, heavy rainfall and snowfall events, and tropical cyclone tracks and intensities. Forecasts and brief case studies using the ensemble modeling systems are available online at http://moe.met.fsu.edu/~acevans/ensemble/ and http://moe.met.fsu.edu/~acevans/usensemble/.

Publications in preparation:

Evans, C., R. Schumacher, and T. J. Galarneau, Jr., 2010: The overland reintensification of Tropical Storm Erin (2007). Part I: Land-surface property sensitivity. Mon. Wea. Rev., in preparation.

Evans, C., R. Schumacher, and T. J. Galarneau, Jr., 2010: The overland reintensification of Tropical Storm Erin (2007). Part II: Dynamical evolution and physical mechanisms. Mon. Wea. Rev., in preparation.

Evans, C. and R. E. Hart, 2010: The thermodynamic evolution during the extratropical transition of Tropical Cyclone Bonnie (1998). Mon. Wea. Rev., in preparation.

Service activities:

Reviewer, Monthly Weather Review
Reviewer, Journal of Geophysical Research-Atmospheres
Member, ASP Seminar Organizing Committee

Active collaborators:

Lance Bosart (State University of New York, Univ. at Albany)
George Bryan (NCAR)
Chris Davis (NCAR)
Tom Galarneau, Jr. (State University of New York, Univ. at Albany)
Bob Hart (Florida State Univ.)
Russ Schumacher (Texas A&M Univ.)
Morris Weisman (NCAR)

SONG-LAK KANG - RESEARCH APPLICATIONS LABORATORY

Investigating structures and processes of Atmospheric Boundary Layer (ABL) over heterogeneous land surfaces for a better numerical weather prediction (NWP) system

Nowadays, numerical weather prediction (NWP) system is used not only for daily weather forecast but also for weather-related businesses such as water management, air pollution control, and wind power forecast. The atmospheric boundary layer (ABL) that is by definition directly influenced by the earth's surface is parameterized in an NWP system. The ABL parameterization has been built based on the horizontal homogeneity assumption. Thus, the parameterization may fail to simulate the ABL over the mesoscale surface heterogeneity that is strong enough to induce temporally fluctuating horizontal flows (Kang and Davis 2008; Kang 2009). Given that the ABL is one of the critical components in the atmosphere and the ABL parameterization significantly affects NWP results, the limitations of the ABL parameterization built on the horizontal homogeneity assumption should be clearly perceived in various surface and weather conditions.

In Kang (2009), a theoretical approach suggests that the surface heterogeneity on a scale of tens of kilometres can generate mesoscale motions that are not in a quasi-stationary state. The starting point of the theoretical approach is the equations of horizontal velocity and potential temperature that are low-pass filtered with a mesoscale cutoff wavelength. The transition of the generated mesoscale motions from a quasi-stationary state to a non-stationary state occurs when horizontal advection is strong enough to level out the potential temperature gradient on the surface heterogeneity scale. Large eddy simulations (LES) suggest that the convective boundary layer (CBL) transitions to a non-stationary state when forced by surface heat flux variation with an amplitude of 100 W m-2 or higher and a wavelength of the order of 10 km. Spectral analysis of the LES reveals that when the mesoscale motions are in a quasi-stationary state, the energy given by the surface heat flux variation remains in organized mesoscale motions on the scale of the surface variation itself. However, in a non-stationary state, the energy cascades to smaller scales. The cascade extends down into the turbulence scale, when the wavelength of surface heat flux variation is on a scale smaller than 100 times the CBL height. The energy transfer from the generated mesoscale motions to the CBL turbulence results in absence of the spectral gap between the two scales. The absence of an obvious spectral gap between the generated mesoscale motions and the turbulence raises questions about the applicability of mesoscale models for studies on the effect of high-amplitude surface heterogeneity on a scale of tens of kilometers.

In addition to the temporal oscillation onsets, in the CBL over strongly heterogeneous surface, turbulence characteristics is different from those of the turbulence in the horizontally homogeneous CBL (Kang and Davis 2008). For example, in the non-stationary CBL, mixed-layer similarity (e.g., Lenschow et al. 1980) is violated, the inter-scale flux can be comparable to turbulence flux (Kang and Davis 2008), and the turbulence intermittency abruptly increases (Kang et al. 2009). Given these finding, an NWP system employing a 1-D ABL ensemble mean scheme may fail to appropriately simulate CBL structures and processes over strongly heterogeneous surface – in particular on a scale of 10s of km.

REFERENCES:

Kang, S.-L, D. Lenschow, and P.P. Sullivan, 2009: Temporal change of wind speed induced by mesoscale surface heterogeneity: an implication for wind speed ramp events. in internal review

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Kang, S.-L., and K. J. Davis, 2008: The effects of mesoscale surface heterogeneity on the fair-weather convective atmospheric boundary layer. J. Atmos. Sci., 65, 3197-3213.

Lenschow, D., J. Wyngaard, and W. Pennell, 1980: Mean-field and second-moment budgets in a baroclinic, convective boundary layer. J. Atmos. Sci., 37, 1313-1326.

Research Catalog

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JASPER KOK - NCAR EARTH SYSTEMS LABORATORY CLIMATE AND GLOBAL DYNAMICS DIVISION

Since the beginning of my NCAR ASP appointment in late August 2009 I have worked on unraveling the complex physics of the emission of mineral dust aerosols from arid regions. In particular, I have focused on determining the size distribution of emitted dust aerosols by using a combination of theory, numerical modeling, and the use of published measurements. I expect this line of research to yield a publication in the first half of 2010. I have also worked towards developing a physically-based expression of the quantity of emitted dust aerosols as a function of wind speed and surface parameters, such as soil moisture, the soil size distribution, and the presence of vegetation. The results of both research projects will likely be used to improve dust emission parameterizations in regional (e.g., WRF-Chem) and global (e.g., NCAR's Community Climate System Model) atmospheric models.

In addition, I have worked on determining the total mass flux in wind-blown sand, which is the source of dust aerosols, as a function of wind speed and surface parameters. Moreover, I have submitted a publication on the occurrence of a large hysteresis effect in wind-blown sand on Mars. The manuscript reports that, once initiated, wind-blown sand on Mars can be sustained at wind speeds an order of magnitude less than required to commence it. This large hysteresis effect allows sand transport to take place for much lower wind speeds than previously thought possible and has important implications for the formation of dust storms, sand dunes, and ripples on Mars. The bulk of the work for this publication was performed during my Ph.D. and a subsequent brief postdoctoral position at the University of Michigan.

LARS RIPPE - EARTH OBSERVING LABORATORY

Lars Rippe's research at NCAR is aimed at developing and adapting broadly tunable laser sources for atmospheric trace gas detection. The broad tunability enables many gases to be measured with one instrument. Traditional technology requires one instrument for each gas. Broadly tunable lasers are enabling technology for versatile instruments, which is attractive for many applications e.g. airplane platforms, where space is limited.

A demonstrator based on a broadly tunable (35 nm) telecom laser has recently been constructed. It can simultaneously measure acetylene, carbon dioxide, carbon monoxide and methane. The gases are measured sequentially, with a 5.5 ms long frequency scan per species, followed by 0.5 ms dead time to move to the next species. During the dead time the laser can jump 10's of nanometers, with very little to no degradation of the sensitivity. The gases are measured in a multi-pass cell with 34 m optical path length.

This demonstrator has shown relative absorption sensitivity below 1 part in a million in one second. The system has partly been constructed and tested together with Märta Lewander, Lund University, Sweden.

The long term goal is to use this technology as a part of a widely tunable, multi species, difference frequency generation trace gas detection instrument.

Message from CISL Director Al Kellie

Welcome to CISL's FY2009 Annual Report. This report organizes our accomplishments and plans according to our strategic plan that was issued in March 2009. For reference, *Computational and Information Systems Laboratory Strategic Plan: Service, Science, and Education, 2009-2014* is published on the CISL website.

Al Kellie with one of the 65% design documents for the NWSC.

Using high performance computing and information technology for simulation and prediction, data analysis, and visualization is an essential component of 21st century Earth System science research. To support NCAR's discipline-specific mission, CISL marshals and adapts the facilities, equipment, software, numerical methods, and intellectual resources necessary to support the ever-expanding scientific goals of the research community and its complex, ever-changing workflows. CISL continually prepares for the future by tracking and testing new technologies, developing algorithms and tools, and providing educational opportunities that serve the growing needs of our community and cultivate the future workforce in applied HPC.

CISL's identity is rooted in three essential roles: CISL functions as a computing laboratory that provides end-to-end services, a science laboratory that conducts research, and an education laboratory that trains and mentors. Each aspect is essential to CISL's effective operation: no single role can survive in isolation. Therefore CISL structured its strategic plan and this annual report according to these three roles, describing the Imperatives and Frontiers for each. Our organizational Fabrics – aspects of our workplace environment and philosophy that contribute to institutional achievement and excellence – are presented in a fourth section. The fifth and final section of this annual report is the research catalog that highlights selected research performed by individual CISL scientists in the past year. Throughout all our planning, we align our work with NSF strategic priorities as articulated by the NSF Strategic Plan and its Cyberinfrastructure (CI) Vision for the 21st Century.

CISL is a computing laboratory

CISL provides world-class supercomputing and data services to its user community. The configuration of these services is dynamic: scientific demands and underlying technologies require continual monitoring, refinement, and evolution. For example, CISL foresees providing fewer standalone services in the future. Over time, services will increasingly be virtualized and federated with other resource and service providers. Another macro-trend will be to provide more flexible and customized services such as through sophisticated science gateways tied to data repositories or computational resources, rather than the current paradigm of "batch" access.

I invite you to read about our accomplishments and plans as a computing laboratory in the Computing Services section of this annual report.

CISL is an interdisciplinary science laboratory

To support sustained progress in using simulation to advance science, CISL develops and tests new techniques to exploit emerging technology trends that will support new scientific goals. Because of its unique juxtaposition of computer science, applied mathematics, statistics, and geosciences domain expertise, CISL is strongly positioned to function as a leading interdisciplinary computational science laboratory that advances Earth System science simulation.

The CISL Science and Research Catalog sections of this report highlight our progress and plans as an interdisciplinary science laboratory.

CISL is an education laboratory

CISL teaches the mathematical and computational science concepts and the practical skills needed to make effective use of advanced cyberinfrastructure. Furthermore, CISL's mission of supporting 21st-century computational Earth System science research can succeed only if CISL and NCAR replenish themselves with a diverse and talented staff. Therefore CISL must encourage students to embark on careers in supercomputing and the computational sciences as applied to atmospheric science.

Please review our FY2009 educational advances in the CISL Education section.

CISL's Fabrics

CISL defines Fabrics as shared values that become daily habits so ingrained that they guide our actions and bind us together as an organization. CISL has identified these Fabrics as the most crosscutting, key contributors to our success as a laboratory:

- Service to support NCAR's science mission
- Innovation to facilitate scientific and technical progress
- Leadership to recognize critical future challenges and take timely action
- Collaboration to fill gaps in resident expertise, infuse new ideas, and amplify impact
- Mentorship to improve communication and leadership skills, develop and retain talent, preserve organizational knowledge, and facilitate the professional growth of everyone involved
- Diversity to improve the breadth of perspectives, approaches, and experience in solving problems

CISL strives to measure and inculcate these Fabrics throughout the organization, and an overview of this work appears in the Fabrics section of this report.

Looking ahead

Our plans for the future are organized by our three paths into the era of petascale science: facilities and infrastructure, science and research, and education of the future workforce. Our ongoing ambition is to provide a balanced computing environment that supports our traditional science community while sharing our resources via distributed facilities and new partnerships. CISL provides levels of support for Earth System science that are without peer anywhere in the country.

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. As you read this report, I hope you share our sense of expectation for significant progress in the future.

Please review our accomplishments and plans in this FY2009 CISL Annual Report.

Director's Message

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CISL Fabrics

CISL Research Catalog

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Computing Imperative: 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 Earth System sciences. Consistent with NCAR's environmental mission, CISL continually enhances the capability and capacity of NCAR's supercomputing facilities while maximizing their efficiency. We continue a two-pronged approach to meeting this challenge.

Mechanical engineers and technicians fine tune the balancing of the chilled water header for Bluefire. Tuning the balance of the loop improves pump performance and optimizes the energy use to cool the IBM Power 575 system.

The Mesa Lab computing facility continued operating throughout FY2009 at nearly 100% of its electrical power capacity. CISL continues to improve and tune the operation of the facility to recover some electrical and mechanical capacity that could be used for continued upgrades to computing and data services equipment. Further tuning of the mechanical systems continues with good results.

FY2009 also furthered considerable work on the NCAR-Wyoming Supercomputing Center design efforts. Specific lessons learned from the Mesa Laboratory have been applied, and target efficiencies for the Wyoming facility will be truly state of the art and demonstrate maximum efficiency for a supercomputing center. Climatic conditions in Cheyenne were evaluated as part of the design and will allow for "free" cooling for much of the calendar year.

For FY2010 CISL will continue to optimize the Mesa Lab facility, in particular by adding chilled water storage that will allow NCAR to experiment with raising the chilled water set point to a warmer temperature. This will be done systematically and should result in further improvements. Considerable effort will also be applied toward finalizing the design for the Wyoming facility. Pending NSF approval, construction will begin in FY2010.

This work is supported by NSF Core funding.

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The NCAR-Wyoming Supercomputing Center

Artistic rendering of the NCAR-Wyoming Supercomputing Center (NWSC), courtesy of H+L Architecture, as of the 65% design completion in July 2009. Administrative/public spaces will be in the two-story, glass-walled section shown in the middle of the image, and the data center and mechanical and electrical support areas are depicted on the right. This graphic illustrates the progress that was made in FY2009 to develop the facility design, and it gives a sense of the planned scale and architectural style of the facility.

In partnership with the University of Wyoming (UW), the State of Wyoming, Cheyenne LEADS, the Wyoming Business Council, and NSF, NCAR continues making plans to build the NCAR-Wyoming Supercomputing Center (NWSC) in Cheyenne, Wyoming. The primary purpose of the NWSC is to meet the rapidly growing high-performance computing (HPC) needs of Earth System scientists and to encourage broader participation in this scientific enterprise. In support of both NCAR's and the UW's strong commitment to environmental stewardship, the NWSC will be energy efficient and as green to build and operate as practicable.

The vision for the project is well aligned with the NSF Strategic Plan and the NSF vision for cyberinfrastructure (CI). The project is motivated by the scientific needs of the Earth System sciences community and is being proposed in direct response to geosciences researchers' increasing needs for both capability and capacity HPC resources. Whether because of a need for greater model resolution, increased model complexity, better statistics, more predictive power, longer simulation times, or a combination of these factors, Earth System scientists are calling for petascale computing, data analysis, and visualization resources combined with exascale data management capabilities.

The provisioning of such capabilities requires the availability of a large-scale computing center capable of handling the multi-megawatt heat loads of future systems. The basic size and infrastructure requirements for the NWSC have been established in accordance with these power demands.

Plans for developing the NWSC are fully aligned with NSF's larger CI vision and will directly contribute to the creation of a national petascale cyberinfrastructure. As proposed, the NWSC 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 multi-disciplinary, one-petaflop-sustained Track-1 facility.

In FY2009, NCAR staff worked with NSF and project partners in Wyoming to develop the NWSC design. Using funding advanced by the University of Wyoming (UW), the initial facility design effort was formally launched in February 2009 with the selection of the architecture and engineering team for the project. Schematic (or 30%) design of the NWSC was completed in April 2009, and the initial design phase was completed on schedule in July 2009 with the delivery of 65% design materials (also referred to as construction documents) to NCAR/UCAR. During this time, NCAR also collaborated with Wyoming to prepare and submit the formal project proposal to NSF. This proposal package includes a Project Summary, the NWSC Science Justification document, and a Project Execution Plan. Submittal of these documents in September 2009 was a key milestone within the formal project review and approval timeline that has been established by NSF and agreed to by NCAR. NCAR Core funds primarily provided funding for the NWSC Project Office (NPO) during FY2009. In late FY2009, NSF awarded $2.5 million of NSF American Recovery

and Reinvestment Act (ARRA) funds to meet the remaining balance of FY2009 NPO expenses and to cover NPO expenses through FY2010 and part of FY2011.

The first major project milestone in FY2010 will be conducting the NWSC Preliminary Design Review (PDR) from 19-21 October 2009 in Arlington, Virginia. During this critical review, a panel of community experts seated by NSF will review the submitted project proposal materials and interview project team personnel to assess whether the project is sufficiently well developed to proceed to the final design phase. Assuming a positive outcome from the PDR, NCAR will launch the final design effort (consisting of the iterative preparation of 75%, 95%, and 100% construction documents) in late October or early November 2009. Completion of facility design (i.e., delivery and acceptance of 100% construction documents) is scheduled for February/March 2010. The project Final Design Review (FDR) will be conducted following completion of 95% construction documents. Pending a satisfactory FDR, NSF will grant formal approval for the project, and construction will begin following successful completion of the required National Environmental Policy Act (NEPA) study. NCAR hopes to begin construction in March or April 2010. The remainder of FY2010 will see significant progress being made on NWSC construction at the selected site in the North Range Business Park west of Cheyenne, Wyoming.

The first strategic imperative in CISL's Strategic Plan is the computing imperative for providing 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." NWSC design work during FY2009 was funded by the University of Wyoming. The majority of FY2009 NPO costs were met using NCAR Core funds. The remaining balance of NPO costs were met using ARRA funds awarded to NCAR by NSF.

Director's Message

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Computing Frontier: Center Virtualization

The virtualization of services and capabilities is a powerful trend serving the conduct and advancement of Earth System science. CISL has been in a leadership role in advancing such capabilities for a number of years now, and we invest heavily in pushing the envelope of this critical area. In production service at NCAR since 2000, the Earth System Grid provides an excellent example as it now serves a virtual community of over 17,000 international users with data products for climate change science.

These web banners collected from CISL's center virtualization efforts indicate the scope of this work that has been ongoing for the past decade. Details about each of these projects are provided in this section. Well-designed center virtualization adapts high-performance resources to the needs of specialized research communities anywhere on the internet.

To support CISL's computing frontier in center virtualization, we develop science gateways and other Grid-based technologies for virtual organizations. Higher wide-area network bandwidth, more powerful computers, and specialized software are creating a Grid that promises to provide simplified access to distributed HPC resources. Such a strategy offers several potential benefits. First, by teaming its computational resources with other powerful computing assets on the Grid, geographically dispersed partners can scale up processing cycles to meet increasingly large scientific challenges. Second, complementary expertise and resources can be combined across centers to tackle the complex and interdisciplinary challenges in computational science that are difficult or impossible for one center to tackle in isolation. This includes many computational geosciences problems, such as climate and earthquake modeling, for example.

Pushing the envelope of Science Gateways, eScience, and the general support of web-based virtual scientific communities, CISL is aggressively pursuing a model of delivering services to an international community through Center Virtualization.

The portfolio of projects and initiatives described in this section span climate simulation, regional climate changes, polar science, solar science, solar-terrestrial science, digital preservation, and international efforts to develop metadata standards for a range of problems. This work is supported in part by NSF Core funding, with a broad spectrum of other funding supplied by the sources noted in the following reports.

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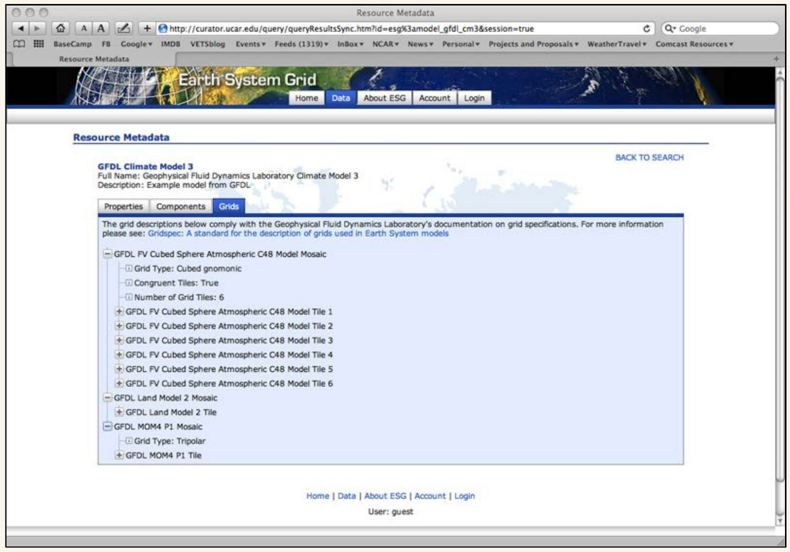
Toward an Earth System Knowledge Environment

The development of an Earth System Knowledge Environment (ESKE) is a cornerstone of the strategic plans for both NCAR and CISL. The goal is to continually develop new cyberinfrastructure that may be integrated into powerful, collaborative problem-solving environments that accelerate the community's ability to engage in research and scientific discovery and construct complex workflows. Our efforts span modeling frameworks, critical scientific data archives, federated data and knowledge systems, digital preservation, collaboration, and analysis and visualization environments.

In many cases our 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 Earth System Modeling Framework (ESMF), the World Climate Research Program (WCRP), the National Digital Information and Infrastructure Preservation Program (NDIIPP), and the THORPEX Interactive Grand Global Ensemble (TIGGE).



This is a snapshot of an innovative advancement in the integration of detailed model metadata and data management and access systems. It represents an aggressive effort to develop an ontology that can be used to describe the deep details associated with a given climate model simulation, including its computational grid (shown here), forcings, computational environment, and other scientific and technical properties. Scientists will be able to search and query across these details. This work reflects a sizable international collaboration of the Earth System Curator project, the Earth System Grid Center for Enabling Technologies, the Science Gateway Framework, and the EU METAFOR effort. Collaborations such as this are increasingly important relative to the success of the upcoming WCRP CMIP and IPCC AR5 initiatives.

Our strategy is to cultivate opportunities to advance the state of the art through R&D grants complemented by core funding, transition the most promising and effective results into production capabilities that we support and distribute, and integrate across capabilities to amplify our investments. This integration theme requires strategy and co-development across major initiatives such as the ones described in this annual report, and substantial activity is already underway. For example, the TIGGE effort reflects collaboration and joint development between our Research Data Archive (RDA) activity and the Community Data Portal (CDP).

In FY2009 we began work on integrating NCL as a back-end visualization and analysis engine for the Earth System Grid (ESG) data portal. We also made major progress in integrating VAPOR and NCL capabilities, focusing primarily on advancing the tools for the WRF community. One of the best examples of cross-project integrative work is in developing advanced metadata and query tools for the upcoming WCRP CMIP and IPCC efforts. A long-term collaboration involving the Earth System Curator (ESC) project, the Earth System Grid (ESG), the Cyberinfrastructure Strategic Initiative (CSI), and the EU-based METAFOR effort has led to prototype capabilities that allow researchers to query climate model data based on the fine details of model configuration and characteristics (see figure).

These efforts support a broad range of NCAR's strategic goals and priorities. They 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 directly address CISL's computing frontier for center virtualization by developing science gateways and other Grid-based technologies. This innovative work is made possible by NSF Core funding, with other support as indicated by the individual reports in this section.

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NCAR is sponsored by the National Science Foundation.

The Cyberinfrastructure Strategic Initiative

The NCAR Cyberinfrastructure Strategic Initiative (CSI) currently supports a collection of strategic and opportunity-development activities, along with core foundational thrusts including the development of the Science Gateway Framework (SGF) and the Community Data Portal (CDP). Our overarching goals are to build the cyberinfrastructure, integrate and extend the Information Technology, develop the critical relationships and projects with scientific and educational projects, and foster the development of human resources and culture to further advance our Earth System Knowledge Environment (ESKE).

In FY2009 we continued to support the Community Data Portal and provided support and updates for the various projects with data published in this environment. Most of our effort was focused on developing the next-generation Science Gateway Framework, which will underpin all of our efforts in FY2010. This portion of our activity is described in the Software Cyberinfrastructure section of this report. Along with the CDP, we continued to support the VSTO environment, TIGGE, IPCC, the GIS Strategic Initiative, the Whole Atmosphere Community Climate Model (WACCM), the NCAR Google Earth opportunity fund initiative, CADIS, WMO WIS efforts, Chronopolis, and many more.

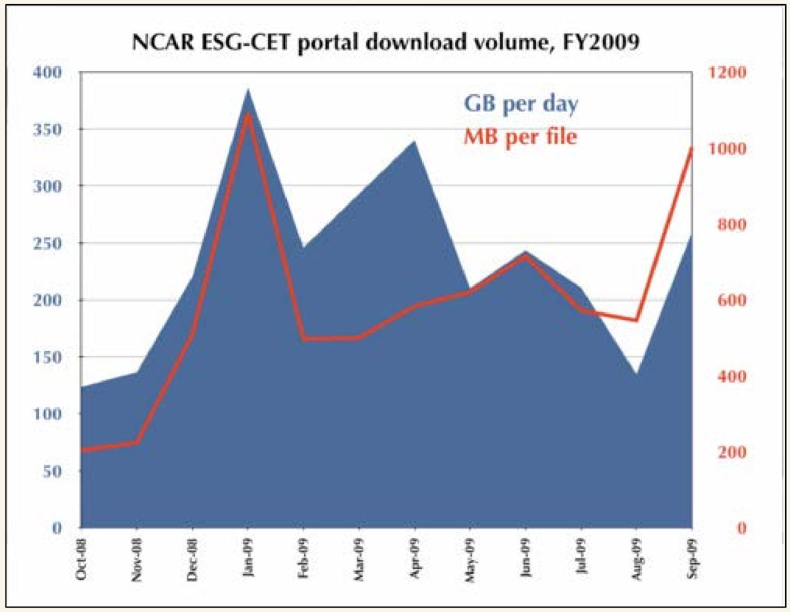
We continued to invest heavily in opportunity development during FY2009, and we secured supplemental funding for CADIS as well as Chronopolis. We engaged in proposal development for the Virtual Operations Center (VOC), along with TeraGrid initiatives including the new XD announcement of opportunity. We secured funding to advance ESG infrastructure from NOAA's new Global Interoperability Program (GIP), and also secured support to develop CCSM Science Gateway capabilities via TeraGrid PY5 and PY6 science gateways conduits. Initial activities to carry our CADIS work forward via the new NSF OPERA initiative were begun as well. The CSI continued to support our engagement with the WMO, primarily in the areas of advancing the WMO Information System (WIS) effort in the areas of federation, metadata specification, and validation. These efforts advance CISL's computing frontier for center virtualization by developing science gateways and other Grid-based technologies to support and enhance the development of virtual organizations.

These efforts also advance 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. This work also fulfills CISL's strategic action item to refactor existing Earth System Grid and Community Data Portal infrastructure into a Science Gateway Framework. This project is supported through NCAR Strategic Initiative funding and NSF Core funding, complemented by specific project support as described throughout this report.

Director's Message

The Earth System Grid Center for Enabling Technologies

The Earth System Grid Center for Enabling Technologies (ESG-CET) is a five-year project funded by the U.S. Department of Energy (DOE) SciDAC-2 program to develop and deploy an international virtual facility for climate and related impacts research. A follow-on to our earlier ESG project, the effort has grown into a large-scale collaboration among NCAR (SCD, CGD, and HAO), Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), Lawrence Livermore National Laboratory Program for Climate Model Diagnosis and Interpretation (LLNL/PCMDI), NOAA's Pacific Marine Environmental Laboratory (NOAA/PMEL), the University of Southern California Information Sciences Institute (USC/ISI), Lawrence Berkeley National Laboratory (LBNL), and Los Alamos National Laboratory (LANL). In addition to these formal, funded collaborations, ESG-CET is now aggressively collaborating with the Earth System Curator (ESC) project, the EU METAFOR effort, the British Atmospheric Data Center (BADC), and the Max Planck Institute for Meterorology in Germany.



This chart depicts the volume of data served by NCAR's ESG-CET portal and information about the size of the individual transactions. This reflects the consumption of climate change simulation data by an international community, and NCAR's portal delivered over 85 terabytes in FY2009. The ESG-CET federation has a registered user base of over 17,000 people.

The ESG federation currently provides a production service for most of the joint NSF/DOE climate change simulations conducted over the last seven years as well as the IPCC Fourth Assessment Report data holdings. Access is provided through a combination of web portal access as well as desktop applications that mediate large-scale transfers to the user. The ESG federation currently has approximately 17,000 registered users worldwide, manages over 230 TB of data in archives distributed around the nation, and has delivered over 800 TB of data to its constituents. Over the past two years, more than 500 scientific journal articles have been published from analyses of data delivered by the ESG. ESG thus plays an important role in advancing NCAR's strategic plan and supporting cross-agency and international climate change science. It's an important component in our strategic thrust for center virtualization and data management and access.

During FY2009 we have continued to operate our production systems and grow our data offerings as new climate data products have become available. Our primary focus has been the continued development of ESG-CET requirements as a primary driver for ESKE SGF efforts. This supports the general distribution of climate model data and the upcoming WCRP CMIP5 and IPCC AR5 requirements. We continued development of the gateway framework, continued to refine our RDF-based framework for semantically based search and discovery of scientific data, developed single sign-on capabilities based on OpenID, worked extensively with the Earth System Curator effort to integrate detailed model metadata into the interfaces, developed a distributed authorization service, and developed services that allow ESG data nodes to publish data into the gateway.

In FY2010 we will transition the existing operational ESG systems onto the new ESKE SGF infrastructure, migrating about 18,000 users to the new system. ESG Gateways and DataNodes will be deployed internationally to form a global federated system in support of climate change research and international assessment efforts. Much of FY2010 will be spent dealing with the transition to the new system, addressing performance requirements in the context of a distributed petascale data challenge, and emphasizing usability of the system. In FY2010 total data delivered by ESG will easily pass the petabyte mark.

These efforts 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. Specifically, this project fulfills CISL's strategic action item to refactor existing Earth System Grid and Community Data Portal infrastructure into a Science Gateway Framework. Primary support for this project comes from DOE's Scientific Discovery Through Advanced Computing program contract DE-FC02-06ER25772 with additional support from NSF via NCAR's Cyberinfrastructure Strategic Initiative and NSF Core funding.

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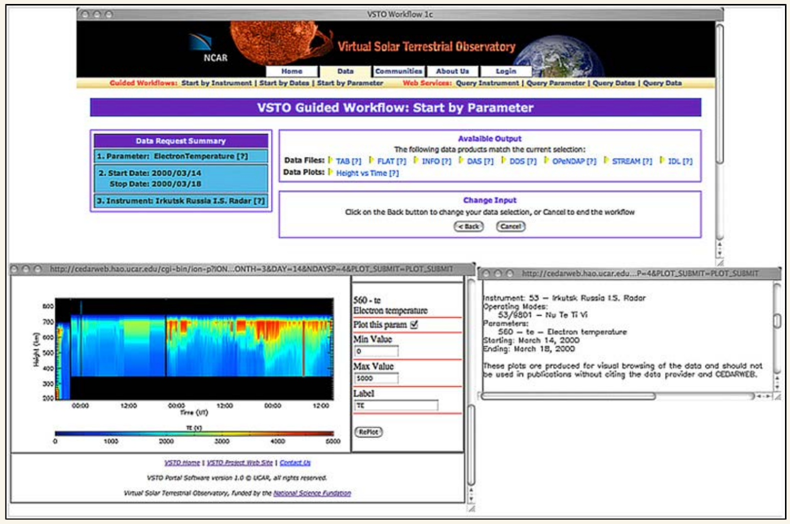
The Virtual Solar Terrestrial Observatory

The Virtual Solar Terrestrial Observatory (VSTO) is an NSF-funded collaboration of NCAR's High Altitude Observatory (HAO), NCAR's CISL, and Rensselaer Polytechnic Institute (RPI). The goal of the project is to research and develop a next-generation knowledge environment that will allow seamless integration and data access in the areas of solar, solar-terrestrial and space physics (SSTSP). By providing a higher-level semantic layer on top of the current array of data formats, services, and repositories, the project is aimed at facilitating and empowering data providers, scientists, researchers and educators across all these domains. The goal of the three-year project was to deliver a fully functional prototype allowing virtual access to selected services comprising observational and model data, different data formats, and different data archives.



This image depicts the VSTO portal's search and query interface along with a resulting visualization. Using a semantic-based approach, VSTO allows its users to request what they want without having to understand the underlying complexity inherent in highly heterogenous data. This example demonstrates the emerging value and importance of enabling science using semantic approaches and scientific ontologies.

Semantic data integration is increasingly important across all of our areas of science and technology, especially as we strive to provide capabilities that bridge domains and disciplines. VSTO thus occupies an important strategic position in NCAR and CISL's cyberinfrastructure R&D portfolio. The same technologies, design patterns, and interfaces that are being developed for VSTO have substantial promise for other scientific disciplines such as climate, weather, and forecast, and further on to the biogeosciences, geochemistry, and water/carbon cycles. VSTO addresses multiple goals of building an Earth System Knowledge Environment and dealing with complex, heterogeneous scientific data.

The NSF special support for VSTO is complete, and in FY2009 we continued to run the system for the community. During FY2009 we maintained the system, developed a strategy for carrying it into the future, and looked for opportunities to leverage the key ideas in other areas of scientific endeavor.

This work supports CISL's science frontier for center virtualization through operating and evaluating Grid environments. Ongoing VSTO operations are supported by NSF Core funding and the NCAR Cyberinfrastructure Strategic Initiative (CSI).

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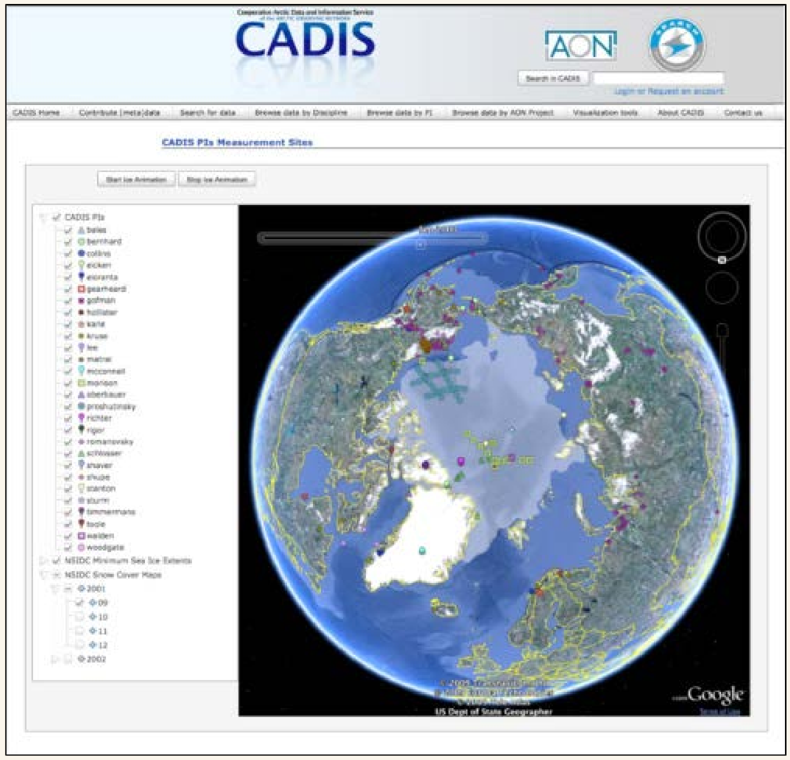
The Cooperative Arctic Data and Information Service

Arctic science in the U.S. lacks a single coordinated force setting a data management direction. To address the challenges of data management for Arctic-wide observing systems, this needs to change for several reasons: to meet scientists' growing expectations for sharing and working with data across diverse disciplines and in the broad Pan-Arctic geographic domain, to encourage the international exchange of data, and to reduce overlap and wasted effort spent developing data management solutions for small numbers of users.



This figure shows a "virtual globe" interface where the icons represent the locations of CADIS PI measurement sites superimposed on a time series of images that show September minimum ice extents. This image demonstrates the CADIS system's capability for visually presenting overlays of data that may highlight correlations between heterogeneous datasets, or show pan-arctic views of variables derived from multiple researchers' measurements, or provide a geographic browser that can take the CADIS site user to data associated with icons or images. This innovative integration of scientific data management capabilities with Google Earth™ supports a primary CADIS goal of an integrated and collaborative view and usage of arctic data.

The Arctic Observing Network (AON) is supported by the NSF and consists of more than 30 land, atmosphere, and ocean observation programs, some with new observing capabilities. This International Polar Year (IPY) initiative will succeed in supporting the science envisioned by its planners only if it functions as a system and not as a collection of independent observation programs. AON planners are working to create a data management system through which scientists can find all data relevant to a location or process: all data have browse imagery and complete documentation, time series or fields can be plotted online, and all metadata are in a relational database so that multiple data sets and sources can be queried.

CADIS is a joint effort of the University Corporation for Atmospheric Research (UCAR), the National Snow and Ice Data Center (NSIDC), and the National Center for Atmospheric Research (NCAR), all in Boulder, Colorado. Working with NCAR's Earth Observing Laboratory, NSIDC, and Unidata partners, CISL's contributions to CADIS include the application, integration, and enhancement of Community Data Portal (CDP) and Science Gateway Framework (SGF) infrastructure to support the needs of the Arctic research community.

During FY2009 we continued to operate the prototype CADIS system that allows PIs to publish their data sets along with detailed metadata into the CDP environment. In parallel with this, we continued development of the SGF and developed interfaces customized and optimized for the Arctic research community and CADIS constituents. We also advanced our capabilities in search and browse functions, in metadata federation using the Open Archive Initiative Protocol for Metadata Harvesting (OAI-PMH), and engaged in some innovative work in integrating Google Earth™ capabilities with CADIS data management systems (see figure).

Early in FY2010 we will release a public preview of the new SGF-based CADIS system, and shortly after that we will engage stakeholders at the annual AON PI meeting in early December. Community feedback will be used to improve our usability and to make plans for the next generation of data management capabilities for the polar science community.

These efforts 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. Specifically, this project fulfills CISL's strategic action item to establish metadata standards for diverse collections of data and models. CADIS is supported via a combination of NSF special support and NSF Core funding.

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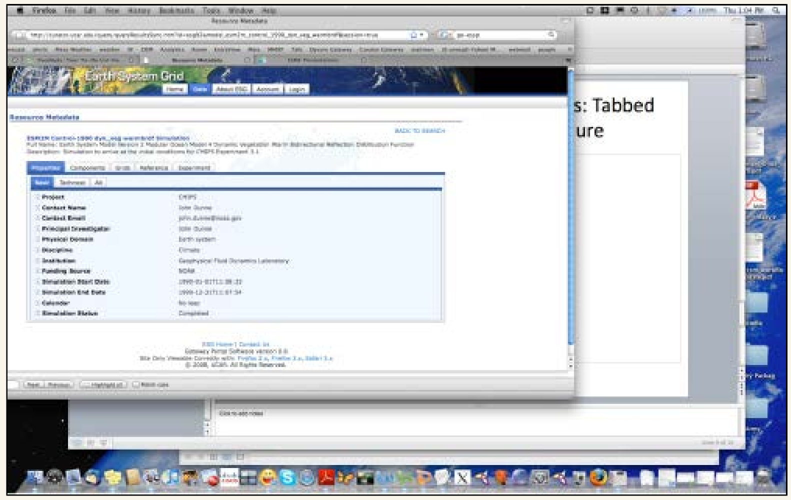
The Earth System Curator



This screenshot shows a "trackback" page developed by the Earth System Curator team that was implemented within the Earth System Grid science gateway. It links a thorough metadata description of a climate simulation to its output datasets. These details have never before been readily available to scientists and others interested in climate records. They enable climate scientists to locate, understand, and compare model results, and they provide information to the broader community about how and why climate runs were performed. Trackback pages will be deployed for all the simulations performed for the upcoming Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report, and the metadata they display archived together with these critically important datasets.

The Curator project is part of an international collaboration that is creating infrastructure for developing, documenting, and running complex, multi-component climate models, and analyzing and disseminating their output. Curator's role in this collaboration has centered on standardizing, collecting, displaying, and archiving model and simulation metadata. Climate simulation datasets are valuable records used in assessing the extent of climate change and its impacts. The Curator team is working with its collaborators to ensure that these simulations are appropriately documented. This documentation serves a core community of climate scientists as well as the many other communities (hydrology, ecosystems, epidemiology, etc.) interested in climate information. The Curator project has collaborated with three major efforts: the Earth System Grid (ESG), which is the data distribution portal used for the Intergovernmental Panel for Climate Change (IPCC) assessments; the Earth System Modeling Framework (ESMF), a coupling framework in broad use at NASA, NOAA, and the Department of Defense; and METAFOR (Common Metadata for Climate Modeling Digital Repositories), an EU-wide project focused on developing a common information model for climate models. METAFOR's recent activities have focused on creating a model metadata questionnaire to be filled out by participants in the Fifth Climate Model Intercomparison Project (CMIP5). CMIP5 is a foundational element of the Fifth IPCC Assessment Report (AR5).

In FY2009, working with ESG and METAFOR, Curator developed metadata-related infrastructure for IPCC AR5 that vastly improves upon that used in the previous assessment, AR4. Minimal metadata was available online for AR4 simulations. For AR5, the ESG gateway will include Curator-developed "trackback" pages that link datasets to descriptions of the simulations and experiments that generated them. The structure of each model is shown in terms of its constituent components. For each component, the trackback page lists basic scientific and technical properties, grids used, inputs and outputs, and coupling parameters.

The Curator team is also developing software that enables metadata generated by the CMIP5 questionnaire to be ingested into the ESG gateway, thus linking European and U.S. efforts to support AR5. In addition to the capabilities added for AR5, the infrastructure developed by Curator and its partners will be available to other intercomparison projects and campaigns. The Curator team also worked on model metadata collection and generation. Generation of exhaustive model metadata is a daunting problem – few modelers are willing to manually prepare files describing multi-component codes. This process can be simplified by having a modeling framework – which holds information about the grids and structure of the code it is used in – write out the metadata in a standard format.

The Curator project collaborated with the ESMF team to do just this, with the ESMF team adding features to its software that enabled the framework to write out standard packets of field and component metadata in XML. Software was developed by Georgia Institute of Technology graduate student Rocky Dunlap –a SIParCS intern – to ingest this XML into the ESG portal and transform it into a searchable, browsable display. The Curator project supports IPCC, an international imperative, and has supported the development of international collaborations at NCAR. Its funding has broadened to include several agencies as the importance of the project has been recognized.

In November 2009, the Curator team will move to the NOAA Earth System Research Laboratory (ESRL) and the Cooperative Institute for Research in Environmental Science (CIRES). Collaborations with NCAR, including the Visualization and Enabling Technologies Section in CISL, are expected to continue.

In FY2010 Curator will continue to develop capabilities to support CMIP5 and will begin exploring the introduction of more social elements – workspace and governance modules – into science gateways.

The Earth System Curator plays a vital role in advancing 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. This work also fulfills CISL's strategic action item to integrate ESMF with other NCAR infrastructure by providing the capability for modelers to link information about a set of experiments with detailed model information. It also supports the CISL computing frontier of center virtualization. The Earth System Curator is funded by NSF special support, NASA, and NOAA.

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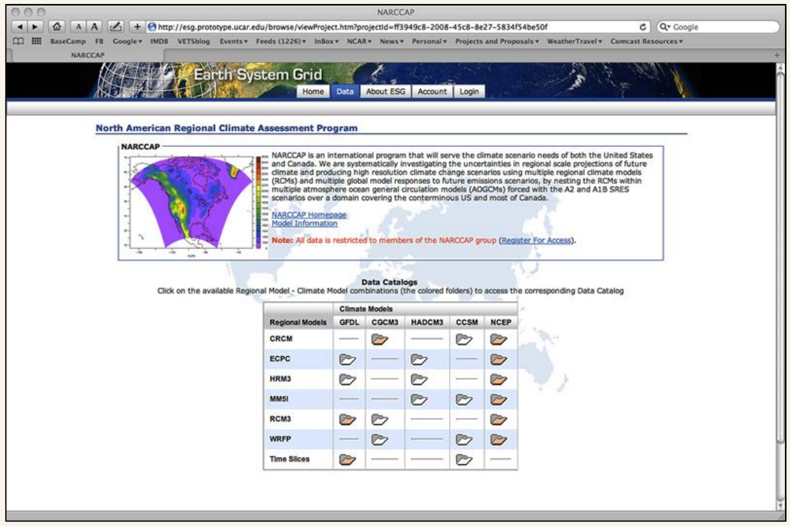
The North American Regional Climate Change Assessment Program

NARCCAP is an international program that will serve the climate scenario needs of both the United States and Canada. We are systematically investigating the uncertainties in regional-scale projections of future climate and producing high-resolution climate change scenarios using multiple regional climate models (RCMs) and multiple global model responses to future emissions scenarios. This is done by nesting the RCMs within multiple atmosphere-ocean general circulation models (AOGCMs) over a domain covering the conterminous U.S. and most of Canada. The plan also includes a validation aspect through nesting the participating RCMs within reanalyses.



This image depicts a web-based interface for accessing the data produced by a multi-model regional climate modeling study. NARCCAP leverages the Science Gateway Framework (SGF) and the Earth System Grid (ESG) infrastructure to provide community access to data. The ability to deliver seamless access to such multi-model studies is increasingly important in climate and weather research.

CISL's contribution to this project is primarily in providing data management cyberinfrastructure and community access for NARCCAP-produced datasets. This aspect of the work is a collaborative effort with NCAR/SERE, Lawrence Livermore National Lab (LLNL), and Iowa State University. NARCCAP heavily leverages existing Earth System Grid (ESG) infrastructure as well as established data management practices developed for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4).

During FY2009 we continued to run the NARCCAP Operational Data Management Plan. This includes the production processes of validating datasets, shipping storage arrays, receiving data, quality-controlling it, and publishing online and archival versions of data for the general NARCCAP community.

In FY2010 we will transition the existing NARCCAP data environment into the new Science Gateway Framework (SGF) environment. This will result in new capabilities for the regional climate modeling community, including much more flexible subsetting, enhanced queries by means of semantic infrastrucuture, and web-based visualization capabilities. We will also continue to publish data collections from various regional climate modeling experiments that are currently underway. Current plans call for us to complete the core NARCCAP work in FY2010, but we will continue to run the data services portion as long as the data resources are of value to the community.

This work supports CISL's science frontier for center virtualization through developing, testing, and evaluating Grid environments. It also advances CISL's science frontier for understanding large and heterogeneous data sets through establishing metadata standards for diverse collections of data and models. Funding for this project is provided by NSF special support, DOE, NOAA, and OURANOS.

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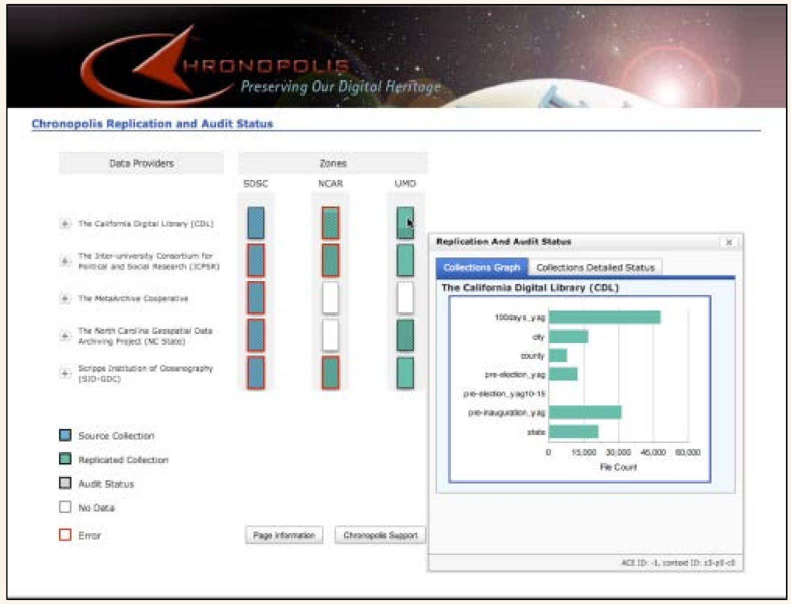
Chronopolis: Federated digital preservation across space and time

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 – science, engineering, humanities, and more. This new effort encompasses studying viable models and effective systems that facilitate establishing standard reference datasets, preserving collections that evolve over time, and establishing preservation resources "of last resort" for digital assets that might become lost. Digital collections that must persist for 100 or more years are one important focus of this activity. It is also worth noting the special synthesis of relationships and capabilities required to approach this problem: scientists, librarians, curators, computer scientists, and long-term distributed cyberinfrastructure.



This image of the Chronopolis Operational Status Page shows the integrated real time state of the Chronopolis system. Chronopolis software consists of a suite of replication, control, and validation packages running at the NCAR, SDSC, and UMD sites. This page allows the distributed system to be assessed at a glance and provides tools to drill into the information as required.

The problem spans the gamut of academic scientific disciplines, historical collections, and digital library content. Though broadly useful, new capabilities developed in Chronopolis are expected to be powerful services that we can potentially offer to the Earth System sciences community through, for example, NCAR's Community Data Portal (CDP). This activity supports CISL's computing frontier for center virtualization by advancing grid-based data preservation technologies.

In FY2009 the Chronopolis digital preservation systems were brought to full operational status and optimizations were undertaken relative to storage and wide-area data transfer performance. Chronopolis hardware was received from SDSC and installed, the Chronopolis software suite was installed, and the interconnections between storage zones were established. A simulated disaster recovery test was undertaken and successfully completed using the TeraGrid as the data transmission medium. The network performance was tested and tuned to give 5 Gbps performance between NCAR and SDSC on the TeraGrid. A status page was designed and implemented to provide an integrated view of Chronopolis software components across the geographically separated archive sites. This page provides access to key high-level information of interest to Chronopolis users that is stored separately in Chronopolis software packages, leveraging Web 2.0 technologies to gather and display this information from across Chronopolis zones and applications. Currently Chronopolis has four Library partners who have collectively contributed about 25 TB to the archive.

In FY2010 Chronopolis will move toward being a more robust operational system, adding TRAC certification, life cycle management, business models, and governance structures that will be needed to complement the technical development. Technical development will continue in the infrastructural and usability realms. As the iRODS technology becomes available, it will join and possibly supplant SRB as a replication mechanism. User interfaces and infrastructure to allow data providers to more automatically place data into the archive and request data from the archive will be adapted and developed. New data providers will be sought to bring a larger variety of data to Chronopolis. An alliance with the MetaArchive organization is being explored and promises to increase the technical robustness of Chronopolis by bringing technical heterogeneity to techniques used to store and retrieve data.

CISL is engaging in Chronopolis as an important strategic thrust, supporting it through a combination of NSF Core funding, NCAR's Cyberinfrastructure Strategic Initiative (CSI), and focused funding from the National Library of Congress.

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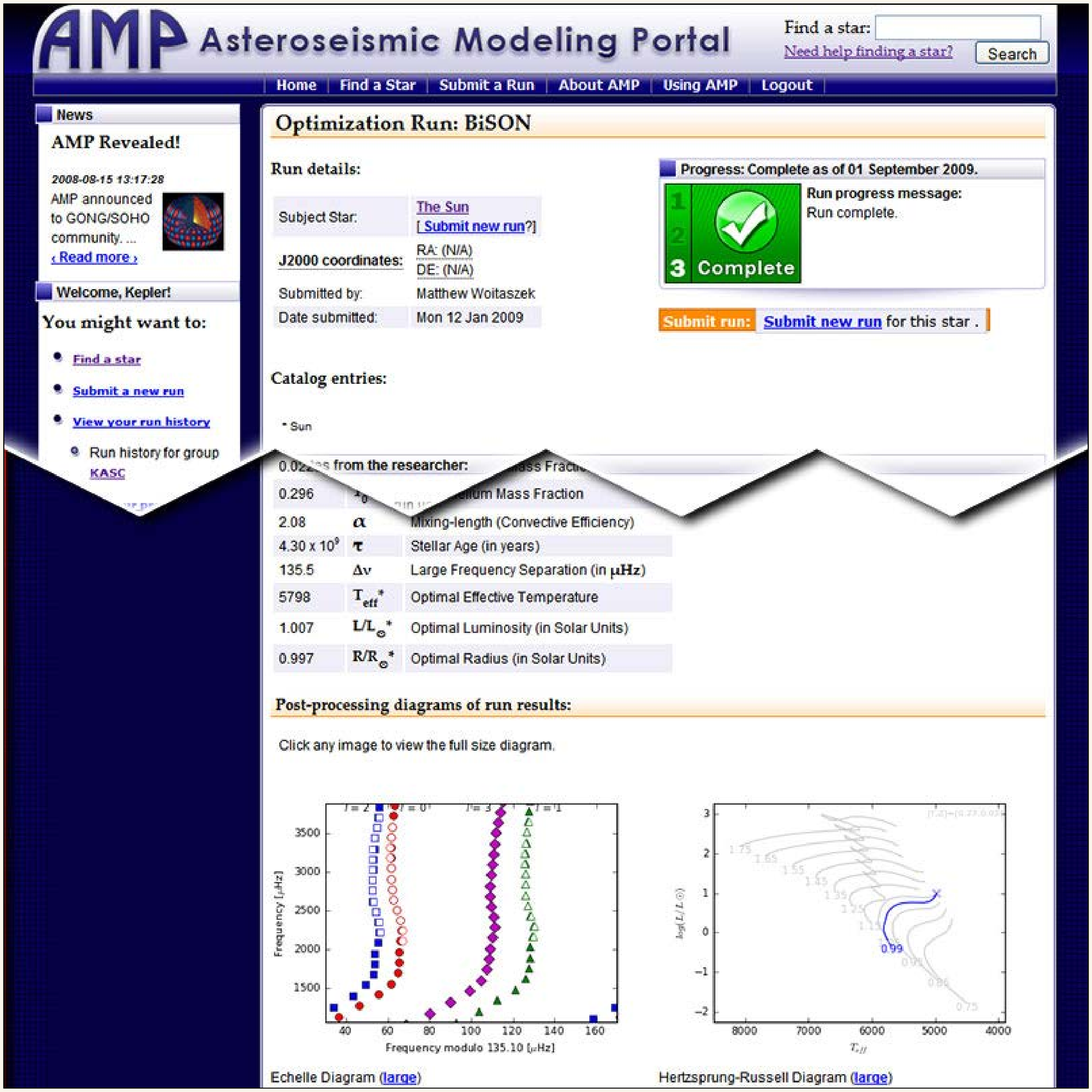
Computationally intensive science gateway development



This screenshot of the Asteroseismic Modeling Portal (AMP) shows the results of a test run for the Sun used to validate the operation of the computational model and AMP's grid-based workflow processing engine. AMP provides a web-based interface for astronomers to run and view simulations that derive the properties of Sun-like stars from observations of their pulsation frequencies. AMP's web-based user interface automates the execution of the asteroseismology software pipeline, allowing astronomers to easily execute the model on the NCAR Frost and NICS Kraken supercomputers.

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 the required data from online and archival storage systems, running preprocessing software to prepare data for the model, executing the simulation model itself, gathering and postprocessing output data, and 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 scientists are often required to perform many mechanical tasks just to coordinate the work on the computers.

Science gateways, also called "portals," 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. In a typical gateway, scientists can choose to upload original input data or select from popular community datasets, configure the experimental run parameters, run the job, and view raw or processed results. All of this can be done in an intuitive web-based environment without knowledge of the specific configuration on each computer that was used to run the simulation. By reducing the amount of platform-specific computer expertise required to execute models, gateways allow scientists to focus on science, increasing the efficiency of scientific inquiry for mature computational models.

In FY2009, CISL's Computer Science Section (CSS) continued work on two science gateways. The first gateway, Grid-BGC, was originally developed from FY2003 to FY2006 with funding from NASA. As several years have passed since its development, CSS has committed to maintain the gateway's base functionality, allowing the principal investigator and close collaborators to continue to use the gateway to run an updated version of the Daymet surface observation interpolation engine. CSS has also modernized the Grid-BGC gateway's computational support infrastructure using its TeraGrid science gateway-managed hosting environment.

NCAR also developed and deployed the Asteroseismic Modeling Portal (AMP), an asteroseismology model with a web-based interface provided to a broad international community of researchers to simplify model execution, data sharing, and analysis of asteroseismic data. AMP has been designed since its inception as a TeraGrid science gateway, and it is currently capable of running simulations on the NCAR Frost and NICS Kraken TeraGrid resources. About 30 astronomers from the Kepler Asteroseismic Science Consortium have obtained AMP accounts so they can use the gateway as soon as Kepler data becomes available.

The Grid-BGC and AMP science gateways play an important role in supporting the CISL computing frontier of center virtualization. In particular, these gateways leverage the combination of NCAR's local and multi-agency Grid-enabled cyberinfrastructure to support geoscience research. In FY2010, NCAR plans to continue supporting the Grid-BGC and AMP gateways while investigating additional applications and technologies useful for this type of collaborative research and development. The development and maintenance of the Grid-BGC and AMP science gateways 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.

Computing Imperative: Hardware Cyberinfrastructure

NCAR provides robust, reliable, secure high performance computing (HPC) resources as part of its mission to provide an end-to-end research environment for more than 1,300 users in a wide variety of disciplines related to the atmospheric sciences. The NCAR facility fulfills the CISL computing imperative to provision computing, storage, data analysis, visualization, networking, and archival systems customized to support the atmospheric and related sciences. CISL provides services that include:

- High performance production computing
- Data storage and archival
- Data analysis and visualization
- Network connectivity
- Cultivation of the research data archive
- Data distribution

The IBM Power 575 cluster Bluefire remained the primary High Performance Computing (HPC) workhorse for production computing at NCAR during FY2009. Some minor additions to and reconfiguration of the hardware, along with a major software and firmware upgrade in early May, provided a boost in the system's computational capacity and sustained performance. Bluefire is being used to improve climate and weather simulations, study solar processes, gain a deeper understanding of turbulence, and run and improve oceanic and atmospheric circulation models.

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:

- TeraGrid integration
- Earth System Knowledge Environment
- Experimental computing systems

During FY2009 NCAR took delivery of new data archival equipment to enhance the NCAR Mass Storage System (MSS) and to deploy a High Performance Storage System (HPSS) test bed. CISL also determined that future archival storage at NCAR will be based on HPSS and that the MSS system will be retired, so MSS data must be ingested into HPSS.

CISL's main supercomputer, Bluefire, became 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 fall of 2008, several projects were provided the opportunity to study challenging problems by participating in the Accelerated Scientific Discovery Program (ASD) on Bluefire, where large amounts of capability computing resources were dedicated to a few projects.

NCAR's plans for the NCAR-Wyoming Supercomputing Center (NWSC) developed through FY2009 with preliminary and 65% designs being completed. At the end of the fiscal year, NCAR was preparing for the preliminary design review to be conducted at NSF. Planning commenced during the year for the processes that will lead to the acquisition of the HPC computing and storage equipment to be installed in the NWSC.

CISL is committed to deploying and maintaining an end-to-end computational environment, and during FY2010 CISL will enhance the data analysis and visualization environment by significantly increasing the amount of online disk storage available to scientists. In addition, CISL anticipates the approval to break ground on NWSC construction, and by fiscal year end, release procurements for the acquisition of HPC, disk and data archival equipment for initial placement at the NWSC.

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

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Cyberinfrastructure procurement, deployment, and operations

NCAR maintains a comprehensive computational environment to satisfy CISL's strategic imperative for hardware cyberinfrastructure by provisioning robust, reliable, secure high-performance computing resources to enable world-class analysis and simulation of the Earth-Sun System. These resources for the numerical simulation community offer the best combination of computational capability and capacity with scientific data services that can be used effectively. CISL fulfills these responsibilities and provides computational hardware and scientific data services including:

- High performance production computing
- Data analysis and visualization
- Data storage and archival
- Network connectivity
- Cultivation of the research data archive
- Data distribution

This view inside NCAR's Mesa Lab computing facility shows the initial installation of NCAR's first High Performance Storage System (HPSS, left). In the background is Bluefire, the primary system for production supercomputing at NCAR during FY2009. Julie Harris, the Computing Facility Technician in CISL's Infrastructure Support Group (ISG), works to maintain the high reliability of NCAR's supercomputing infrastructure. ISG sustains this reliability by skillfully maintaining existing systems, operating a comprehensive change control program, collaborating with Physical Plant staff on major infrastructure improvements, and thoroughly planning future infrastructure needs.

CISL also actively participates in projects designed to provide advanced services and tools to enable Earth System science for a diverse community of users. CISL also invests in developing Grid technology projects that allow NCAR's cyberinfrastructure and the science it supports to be better integrated with other centers, scientists, and research programs throughout the country and around the world:

- TeraGrid integration
- Experimental computing systems
- Earth System Knowledge Environment

During the first quarter of FY2009, nine projects were afforded the opportunity to study challenging problems by participating in the Accelerated Scientific Discovery (ASD) program on Bluefire, where large amounts of capability computing resources were dedicated to a few users. In addition, two NCAR Capability Computing (NCC) and other on-demand computational campaigns were supported on Bluefire.

CISL is committed to deploying and maintaining an end-to-end computational environment, and during FY2009 enhanced the data analysis and visualization environment by significantly increasing the amount of online disk storage available to scientists.

In FY2009, CISL continued to measure the performance of selected applications on new platforms, both at NCAR and at other computer centers. To maintain a high level of performance on the NCAR system, CISL also routinely measured vendor system performance on a representative workload selected with the input of NCAR scientists.

During FY2010, CISL plans to perform additional supercomputer and storage hardware enhancements as power, space, and cooling limits allow. In the coming year, CISL will phase out its Mass Storage System software and replace it with a High Performance Storage System. With this software change, NCAR's archival system will become compatible with that used at a large number of HPC centers and will not require purchase of new hardware. A portion of funding received by NCAR under the American Recovery and Reinvestment Act of 2009 will be applied in FY2010 to further enhance data storage for the Research Data Archive (RDA) and for analysis and scientific visualization.

Planning will also begin for obtaining a Track-2-scale supercomputer with a peak performance in excess of 1 petaflops by 2012, to be housed in the NCAR-Wyoming Supercomputing Center to be located in Cheyenne, Wyoming. A detailed workload analysis performed by CISL concluded that a system comparable in size to an NSF Track-2 system (such computers are installed at the

Texas Advanced Computing Center and the National Institute for Computational Science) is needed merely to develop and test Earth System models capable of exploiting other, even larger computing complexes around the country.

Enhancement of Grid cyberinfrastructure at NCAR will continue in FY2010 to provide user access to substantial resources and collaborations needed to perform the most challenging research. CISL will continue to operate as a TeraGrid Resource Provider through FY2010, then continue until directed otherwise by the NSF. Investments will then be determined by CISL's role in the TeraGrid follow-on program, TeraGrid eXtreme Digital.

A key to making these cyberinfrastructure elements successful is to facilitate easy access to CISL systems by authorized researchers. For example, remote visualization or GridFTP sessions require ports to be opened through our security perimeter, particularly for trusted centers. During FY2010 CISL will develop and implement a plan that provides openness for collaborative purposes balanced with appropriate security. CISL will continue to track ease-of-access issues via user problem reports and user experiences expressed as responses to periodic surveys. User feedback via the TeraGrid system will also continue to be solicited.

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

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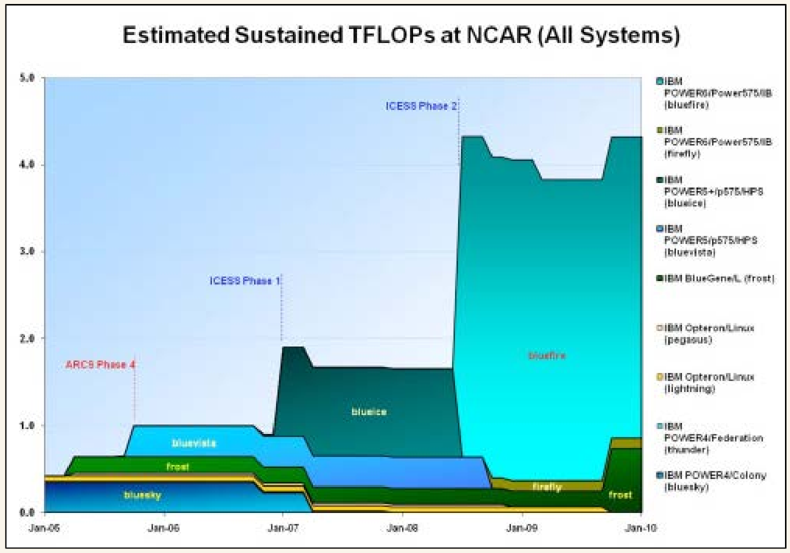
Production supercomputing status

As part of its computing imperative for hardware cyberinfrastructure, CISL provisions robust, reliable, secure high-performance computing resources to provide an end-to-end research environment for more than 1,300 users in a wide variety of disciplines related to the atmospheric sciences. Resources are balanced for the needs of the numerical simulation community to provide the best combination of computational capability and capacity with scientific data services that can be used effectively. This comprehensive computational hardware environment enables world-class analysis and simulation of the Earth-Sun System.



Estimated sustained computing capacity (in teraflops) available to the NCAR community over the past five years. CISL strives to provide substantial periodic computational capacity increases to meet the scientific research demands of the community.

Within the realm of production supercomputing, CISL's goals are to provide equitable access to reliable computing resources with minimal user wait times, while maximizing resource utilization. These goals are achieved by maintaining and monitoring a proper balance of resource allocation, prioritized job scheduling, a well-tuned queue structure, and single-job resource limits. Where possible, CISL works to increase the computational capacity available to the community on a regular basis.

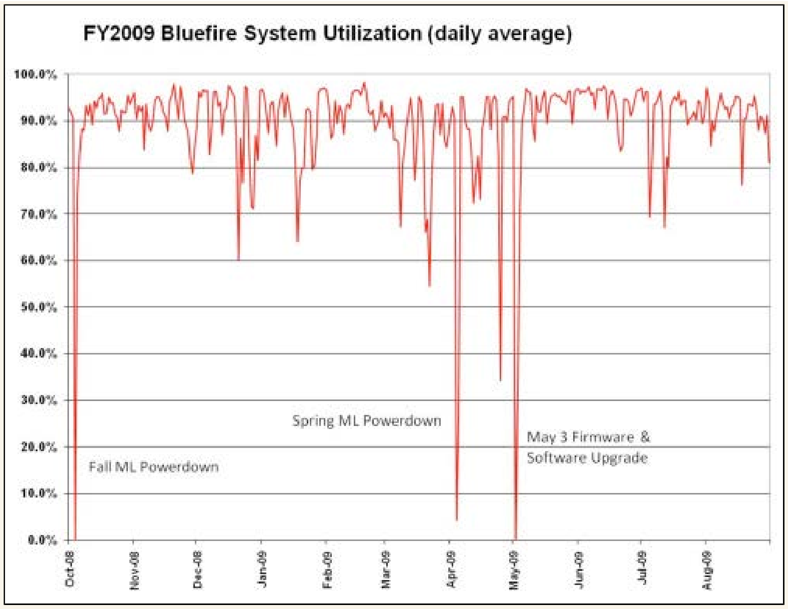
Further, CISL provides the organizational focus, capabilities, and skill-sets required to support important field and computational campaigns – including those driven by unfolding natural disasters – with on-demand resources. Bluefire supports the CISL-developed on-demand capability computing model that enables the entire cluster or portions of it to support dedicated or shared special computing campaigns, such as the Accelerated Scientific Discovery campaign or this year's High Resolution Hurricane Simulation Special Computing Campaign.

Supercomputer status

The most recent major enhancement of the production computing capacity was deployment of the IBM Power 575 system Bluefire in July 2008. During FY2009, CISL upgraded both the hardware and software on Bluefire and its Power575 test cluster (Firefly). CISL received funds from the NSF's Office of Polar Programs to redeploy the Antarctic Mesoscale Prediction System (AMPS) from an aging Linux cluster (Pegasus) to Bluefire and Firefly. New hardware was added to these systems, and the twice-daily AMPS forecasts began running on the Power575 systems in November 2008. A major software upgrade to Bluefire was conducted in May 2009; it significantly improved system stability and performance, particularly InfiniBand interconnect fabric and MPI communications performance. Additionally, two Bluefire nodes previously reserved for system activity were converted to batch computation nodes.

In early September 2009, CISL's TeraGrid supercomputer (Frost) was upgraded by adding three more frames, bringing the system to 8,192 PowerPC processors running at 700 MHz yielding a peak speed of 22.9 teraflops.

Enhancements to the Computation Analysis Visualization Enabled Storage (CAVES) peripheral resources, which complement and supplement the high-end computing environment, were applied to appropriately match the growth in compute capacity. These significantly increased the amount of



Average user utilization of Bluefire during FY2009. Keeping scientific production at a high level meets NCAR's goal of providing reliable and robust computational services to the community.

online, readily accessible data storage for analysis and visualization to meet the demands of the community.

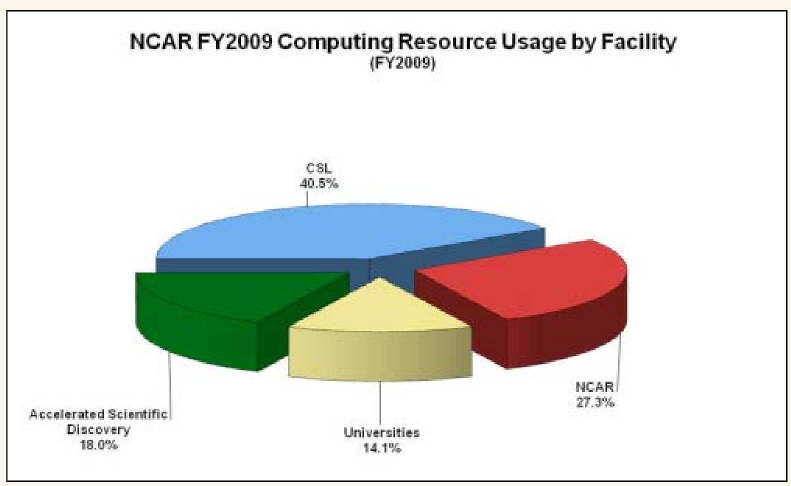
While the power constraints within the NCAR computing facility during FY2009 have required CISL to operate within a limited envelope of electrical capacity, these incremental enhancements have allowed CISL to meet most of the continuing needs and requirements of the scientific community for computationally expensive endeavors.

A portion of funding received by NCAR under the American Recovery and Reinvestment Act of 2009 will be applied in FY2010 to further enhance data storage for the Research Data Archive (RDA) and for analysis and scientific visualization.

Plans for FY2010 include infrastructure for building and furnishing a multi-petaflops computing facility. The new facility will require acquisition of several important components simultaneously, including a new Track 2 supercomputer, an HPC storage cluster, an integrated visualization system, as well as new archival and wide-area shared filesystems.

Production deployment of Bluefire supercomputer

CISL operated, upgraded, and maintained its IBM Power 575 hydro-cluster system (Bluefire) through FY2009, providing 77 TFLOPS of peak production supercomputing resources to the Climate Simulation Laboratory (CSL), the NCAR and University communities, and to the Accelerated Scientific Discovery (ASD) and NCAR Capability Computing (NCC) projects. Bluefire exhibited 94.8% availability and 90.0% system-wide user utilization for FY2009. CISL decommissioned a predecessor system, Bluevista, on the final day of FY2008, and continued operating the IBM e1350 Linux cluster (Lightning) through FY2009.



This chart shows relative use of the Bluefire supercomputer by Climate Simulation Laboratory projects, NCAR users, University Community users, and Accelerated Scientific Discovery projects during FY2009.

During the first three months of FY2009, CISL provided a substantial portion of Bluefire (3.7 million CPU hours) to ASD projects. For FY2009, ASD used approximately 18% of Bluefire's resources, NCC approximately 6%, and the remaining 76% for CSL and NCAR/University Community production supercomputing.

In addition, various needs for special computational campaigns and on-demand computing were satisfied by either dedicating resources or using high-priority queues and advanced reservation features of the Bluefire job scheduler. For example, during FY2009 CISL supported special "near-real-time" computational campaigns, such as WRF Hurricane forecasts, while maintaining high levels of system utilization and throughput for all other users. The average queue wait time for regular queue jobs was 36 minutes.

Impact on science

Scientists at NCAR and across the country used Bluefire to accelerate research into climate change, including future patterns of

precipitation and drought around the world, changes to agriculture and growing seasons, and the complex influence of global warming on hurricanes. Researchers also used it to improve weather forecasting models so society can better anticipate where and when dangerous storms may develop or hurricanes may strike. The system also allowed scientists to study in unprecedented detail the relationship between solar processes and weather on Earth, gain a deeper understanding of turbulence, and develop and refine models that simulate many of the processes responsible for elements of the Earth climate system.

During FY2010, demand will increase for resources to generate the climate simulations for the next Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), which conducts detailed studies under the auspices of the United Nations. An upgrade of computing resources is being considered that will enable IPCC simulations and facilitate the transition to the NCAR-Wyoming Supercomputing Center, while remaining conservative in power and cooling.

Funding sources

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

Postal Address: P.O. Box 3000, Boulder, CO 80307-3000 • Shipping Address: 1850 Table Mesa Drive, Boulder, CO 80305 • Contact

Director's Message

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Research Catalog

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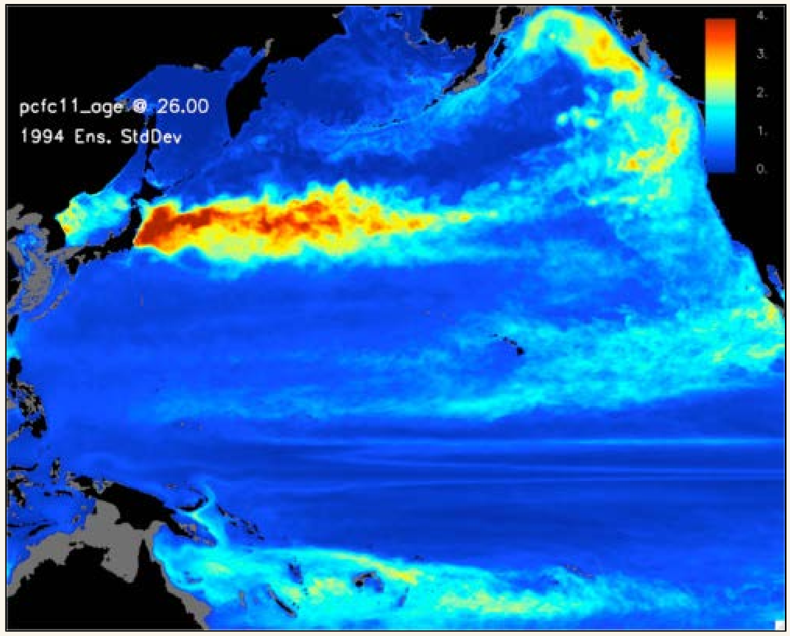
Very large computational experiments: FY2009 Accelerated Scientific Discovery on Bluefire



Estimated from five ensemble members, this visualization of the Pacific Ocean shows the standard deviation of non-seasonal variability of CFC11 on the 26.0 potential density surface during 1994. As expected, there is strong variability in the Kuroshio extension, a highly energetic and time-varying current system. The CFC11 variability is almost as strong in the northeastern Pacific and on the southeast flank of the subtropical gyre where there is rather weak mesoscale variability in the currents (relative to the western boundary currents). In these regions, very strong gradients in CFC are established by the contrast between ventilated and unventilated waters. It takes only modest stirring across these CFC fronts to generate strong variability. Also somewhat unexpected is the rather weak variability in CFC11 in the recirculation gyre to the south of the Kuroshio. This is a region of very strong eddy energy, but the CFCs have become so homogenized by eddy stirring that there are very weak large-scale gradients within the recirculating region, and hence only weak mesoscale variability in CFC. The simulation was performed on Bluefire in FY2009 using computational resources from the Accelerated Scientific Discovery (ASD) program. (Figure courtesy of Frank Bryan, NCAR, also see project summary entitled "Eddy Induced Tracer Variability" below.)

In FY2009 CISL offered university and NCAR researchers the opportunity to apply for computational resources under the Accelerated Scientific Discovery (ASD) program. This program provides very large allocations to a few projects by filling Bluefire's queues during the time between when the system first became available to users and before it would be fully allocated. Bluefire's very large capacity plus the capability of its fast processors combined to create a unique opportunity for the research community. The special allocations from the ASD program immediately maximized the utilization of the system and allowed well-prepared researchers to exploit its full capacity by running very large jobs without the normal competition for system resources that exists on a fully subscribed supercomputer.

With the concurrence of NCAR management, the CISL HPC Advisory Panel (CHAP), and the NSF Program Manager for UCAR, CISL advertised the availability of 3M GAUs between 1 September 2008 and 30 November 2008 to the university and NCAR communities. The minimum award size was 300K GAUs.

All of the projects except one used 100% (or more) of their allocation by 8 December 2008. The project that did not use all of its allocation used 300K GAUs to complete all planned experiments. Projects that finished early had the option to request more resources if it would not impact the other ASD projects. By the end of the ASD program, the eight projects used a total of 4M GAUs.

This program to maximize the supercomputer's usefulness while offering researchers a unique opportunity to quickly complete high-end simulations supports CISL's computing imperative for hardware cyberinfrastructure. CISL's ASD initiative was supported by NSF Core funding. The university researchers participating in the ASD were also supported by the National Science Foundation through individual NSF awards to the PIs.

FY2009 accomplishments

In FY2008 CISL began planning to maximize early use of Bluefire in a program similar to the FY2007 Breakthrough Science initiative on Blueice. Many university high performance computing centers provide early user time to "friendly users" to shake down a new computer. In recent years, CISL's strategy has been to make this early time available on a competitive basis to a few university and NCAR researchers. It is very difficult to provide large amounts of resources for a few projects when a computer is fully allocated, so the ideal time is immediately prior to parceling out all the new capacity when a computer first enters production.

The university and NCAR user communities again proposed significant research projects that could only be done using long-running simulations. The projects were reviewed and awarded resources approximately four months prior to the start of the ASD initiative.

- Proposals were solicited from university researchers with NSF awards in the atmospheric and related sciences who had

experience using a large allocation. Joint university/NCAR projects were also encouraged. These proposals were reviewed by CHAP in June 2008. Three projects received allocations of between 360K and 500K each for a total of 1.25M GAUs.

- The NSF contacted researchers with NSF awards in the upper atmosphere and recommended two projects to receive a total of 960K GAUs.
- Two NCAR projects were selected by the NCAR Executive Committee to receive allocations of 500K GAUs each, and one project was selected to make early use of Bluefire shortly after it came online because of their ability to run during Bluefire's "shakedown period" with any remaining computations to be done during September – November at a lower priority than the other ASD projects.

The time period of 1 September 2008 through 30 November 2008 was selected to ensure that Bluefire would be ready for a heavy load of production work on a day-to-day basis and that the selected projects would have a few months to tailor the codes to Bluefire and ensure that they were running efficiently. A deadline of 8 August 2008 was set to provide a benchmark to CISL showing efficient utilization. Each project was assigned a consultant from CISL's Consulting Services Group to help them tune their code for maximum efficiency on the new system. Any project not meeting this deadline would lose 80% of their allocation. This proved to be a sufficient incentive as all of the project teams met the 8 August deadline. Their deadline to start production was 5 September, and all ASD projects started on time with efficient codes. These deadlines and the proven experience of the project teams allowed the proposed work to be completed successfully in the short time available.

CISL used high-priority queues for the ASD projects, then restricted access to the ASD nodes to ensure that non-ASD projects could continue to make research progress and consume their normal allocations. On 1 December 2008 the allocations to the university, NCAR and CSL projects were raised to new, higher levels. On 8 December the ASD program ended on Bluefire, but as noted below, the big job of data analysis and visualization was just beginning.

As part of the ASD, CISL reached out to ASD PIs to offer computing resources and support for data analysis and visualization. Over 50 TB of CAVES disk space was allocated among seven ASD groups. Though the computational (HPC) component of ASD ended in December, many of the participants are still performing data analysis at the end of FY2009 (over half of the groups requested and received extensions to their CAVES storage allocations, which otherwise expired in May). As a condition of receiving support, all of the ASD participants willingly agreed to provide imagery (visualizations) from their data that highlights their work as part of the ASD project. Seven of the eight groups have provided imagery to date.

The ASD projects were able to make significant research advances in a short time period with this guaranteed access to 40% of Bluefire. Highlights from the ASD project accomplishment reports are given below.

ASD project highlights

The following three project summaries provide insight into the scientific advances made possible by ASD's three months of dedicated computing time.

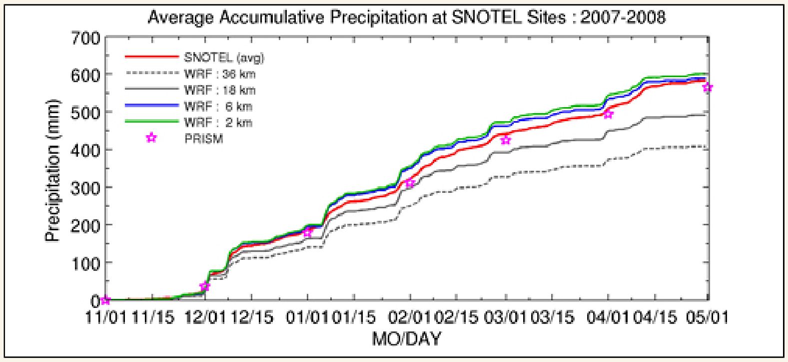
"Assessing Winter Precipitation, Snowpack and Runoff Processes from Colorado's Headwater Basins using a Very High Resolution Fully Coupled Atmospheric-Hydrologic Model"

Researchers: Roy Rasmussen, Changhai Liu, Kyoko Ikeda, David Gochis, David Yates, Kathy Miller, Fei Chen, Mike Barlage, Mukul Tewari, Ethan Guttman, Greg Thompson, Jimy Dudhia, Rit Carbone, and Mitch Moncrieff (NCAR), Vanda Grubisic (University of Vienna), Yang Liang (University of Texas), Kristi Arsenault and Paul Houser (George Mason University).

GAUs allocated: 500,000. GAUs used: 500,000.

The Advanced Research WRF (ARW) model was used to conduct high-resolution regional climate simulations of cold-season snowfall, snowpack, evapotranspiration, and runoff in the Colorado Headwaters region. Simulations included:

1. Five 6-month, 2-km-resolution simulations of present-day climate using the North American Regional Reanalysis (NARR) data, covering two cold seasons (i.e., year 2004–2005, and year 2005–2006) of normal (i.e., approximately multi-year mean) precipitation and snowpack, one cold season (i.e., year 2007–2008) of anomalously high snowfall and snowpack, one cold season (i.e., year 2002–2003) of anomalously low snowfall and snowpack, and the 2008 warm season
2. A few coarse-resolution simulations of the 2007–2008 cold season with grid spacings of 6km, 18km, and 36 km



Time history of accumulative precipitation between 1 November 2007 and 1 May 2008 comparing average precipitation simulated with the WRF model at 2, 6, 18, and 36 km grid resolutions and measured at 112 SNOTEL sites throughout the Colorado Headwaters domain and simulated with the model. Average of values at four grid points nearest to the individual SNOTEL sites were taken from the simulation outputs. Precipitation from the PRISM database is also overlaid. The figure indicates that precipitation simulated at a

grid resolution of 2 and 6 km agrees well with the measurements at SNOTEL sites. Precipitation is significantly underestimated at coarser resolutions (15% at 18 km, 30% at 36 km). The main reason for the better agreement with the observations with finer resolutions is the improved simulation of topography which better resolves vertical motions.

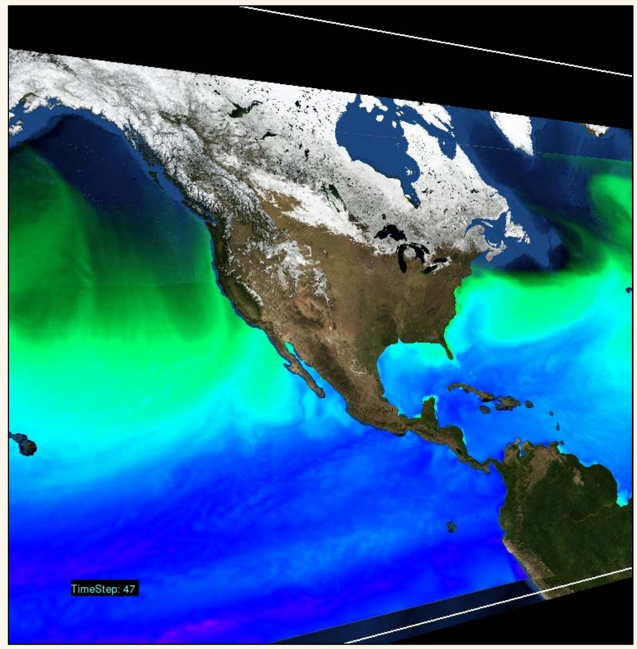
3. One 6-month, 2-km-resolution simulation of snowfall and snowpack in response to a pseudo climate warming, in which the initial and boundary conditions were derived from the combination of the 3-hourly NARR data with the climate perturbations representing the differences between the present (i.e., 10-year averages from 1995–2005) climate and the future (i.e., 10-year averages from 2045–2055) climate projected by CCSM
4. Two future climate simulations at grid spacings of 6 km and 18 km for the 2052–2053 cold season using the 6-hourly CCSM output for the IPCC SRES A1B scenario

The diagnostic analysis of the simulations is still in progress, but results so far have demonstrated unprecedented success in realistically reproducing the wintertime precipitation over complex terrain. Responses of snowfall and snowpack to an idealized warming climate suggest increased snowfall. The simulated strong dependence of snowfall and snowpack on grid resolutions illustrates the importance and usefulness of high-resolution models in improving the future climate projections by global climate models. These results have been presented in quite a few conferences, and have drawn much attention and many responses. It is anticipated that multiple papers for professional journals will be written based on these simulations and some ongoing simulations.

"Effect of Global Warming on U.S. Regional Climate"

Researchers: Greg Holland, Cindy Bruyere, James Done, Jim Hurrell, Joe Tribbia, Peter Webster, and Asuka Suzuki-Parker (NCAR), Ruby Leung (Pacific Northwest Laboratory).

GAUs allocated: 500,000. GAUs used: 550,000 plus cycles available during Bluefire's shakedown.



This image and animation show results from a study of water resource management in the Intermountain West of North America: atmospheric rivers of moisture flow up from the tropical Pacific and affect the U.S. West Coast. These rich moisture sources contribute to powerful winter storms that often produce damaging winds and flash floods. (Click image to view 81 MB animation in .mov format.)

Using "friendly user" time on Bluefire during its initial shakedown in addition to an ASD allocation, two sets of climate change experiments over North America were performed to study water resource management in the Intermountain West and Tropical Cyclone (TC) variations in tropical North Atlantic. Researchers focused on the period 1995–2055, as there are strong immediate needs for social decision making for adaptations to regional climate change. However it is computationally expensive to run a 50-year simulation at adequate resolution to resolve mesoscale phenomena. Hence "time-slice" experiments of three 10-year periods were performed: 1995–2005, 2020–2030, and 2045–2055.The NRCM was run at 36 km horizontal resolution. To increase statistical confidence, three ensembles were run for the each of the future time slices. During this experiment the output from CCSM3 for IPCC-AR4 was directly used to force NRCM, referred to as NARC I (North American Regional Climate I).

Shortly after Bluefire was installed, the NRCM team occupied nearly a quarter of Bluefire's computational capacity to run up to five simulations in parallel, producing more than 350 TB of data. The original plan was to use NARC I to explicitly predict TC variability in the North Atlantic. However it was discovered that NARC I had a severe bias in the large-scale flow that caused anomalously large vertical wind shear. The magnitude of this anomalous shear was so high that it did not allow any TCs to form in the tropical North Atlantic. Instead TCs formed in the high latitudes of the North Atlantic, and the East Pacific TCs were pushed westward compared to observations. Further analysis revealed that this bias in the large-scale flow is also present in the CCSM. In CCSM and most ocean-coupled GCMs, SST exhibits El Niño-like anomalies over the tropical East Pacific and North Atlantic oceans. El Niño conditions are known to increase vertical wind shear and hence suppress TC formation in the North Atlantic. The bias in the CCSM was fed directly into the NRCM, and it was unable to correct for the bias even with its large domain and high resolution.

Based on the outcome of NARC I, the team designed a methodology to remove the systematic bias in CCSM using NCEP/NCAR reanalysis data. Using the adjusted data to drive NRCM is called NARC II. Preliminary analysis of the current climate (1995–2005) simulation shows that the vertical wind shear bias is significantly reduced, allowing TCs to form throughout the tropical North Atlantic. NARC II thus far produces a huge improvement over NARC I. More comprehensive analysis of the NARC II experiment is scheduled for FY2010.

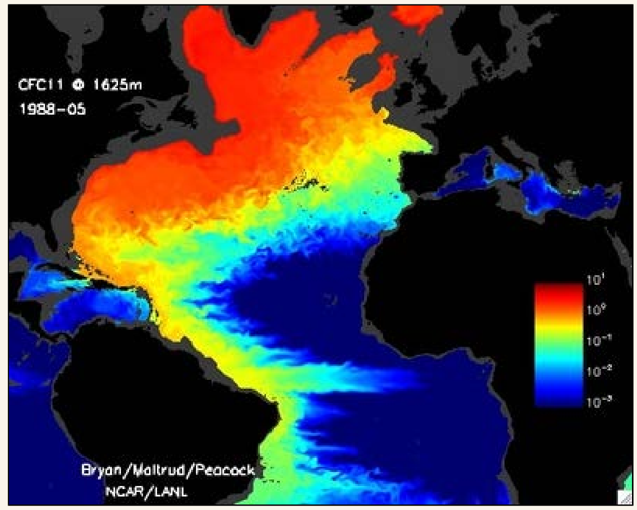
"Eddy Induced Tracer Variability"

Researchers: Frank Bryan and Synte Peacock (NCAR), Sabine Mecking and Luanne Thompson (University of Washington), Julie McClean (Scripps Institute of Oceanography).

GAUs allocated: 489,000. GAUs used: 621,000.

We accomplished our objective of completing the first-ever, global eddy resolving ensemble simulation of transient tracers. We simulated the evolution of the anthropogenic tracer CFC11 for the period of the World Ocean Circulation Experiment (1985–2000). Five realizations of the tracer were simulated, and the results of the experiment are currently being reduced into a set of statistics of CFC variability. This information will aid in interpreting observations of passive tracers from this era and in establishing metrics for evaluation of climate model experiments. In particular, the statistics will provide an estimate of the noise level expected in observations arising from stirring by mesoscale eddies. This noise level must be considered as a source of uncertainty either when repeat observations are being compared for climate signal detection, or in deciding "how close" a model must come to the observations to be considered "good enough."

An example measure of the variability of CFC11 from the experimental results for the Pacific Ocean is shown in the figure at the top of this page. The image and animation at right shows CFC11 variability in the Atlantic Ocean. In addition to our primary goal of simulating CFC11, we also advanced an ensemble of five idealized tracers referred to as "boundary impulse response functions." These provide a compact diagnostic of the model transport, and an additional metric for comparison against observations and other simulations.



This image and animation show a time evolution of CFC11 concentrations at 1,625-meter depth in the Atlantic at a monthly sampling interval. (Click image to view 21 MB animation in .mpg format.)

Three manuscripts are being prepared based on the results of these simulations. Three presentations at international and national meetings have highlighted these experiments:

- Tracer transport in eddy-resolving global ocean simulations. CLIVAR WGOMD Workshop on Ocean Mesoscale Eddies. Exeter, United Kingdom, 27 April 2009.
- The global ocean transit time distribution computed with an eddy-rich general circulation model. AGU Fall Meeting, San Francisco, 16 December 2008.
- An ensemble of CFC-11 tracer distributions from a global eddying ocean circulation model. AGU Fall Meeting, San Francisco, 16 December 2008.

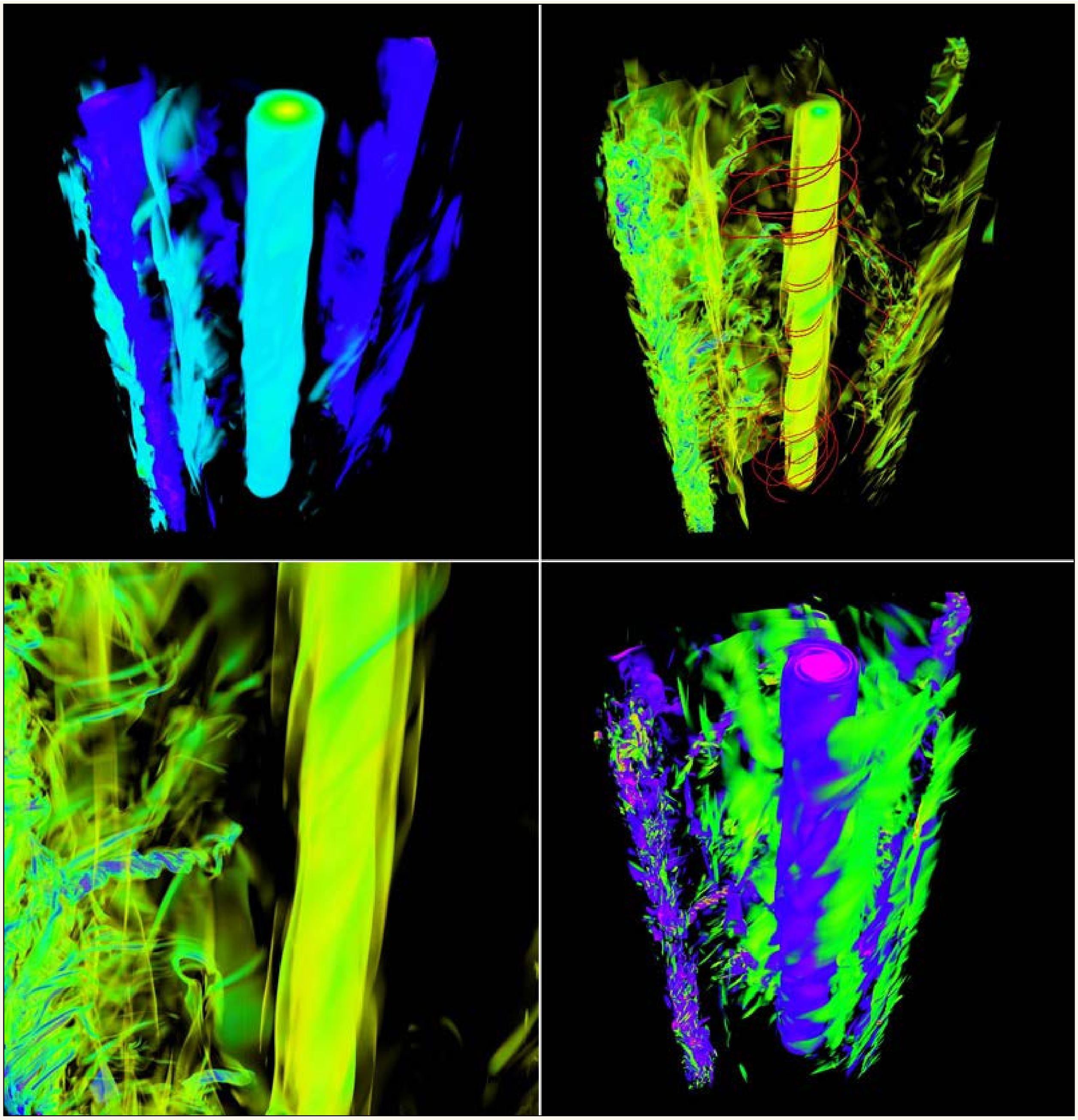
Animations of experimental results were also shown by Dr. Rana Fine of the University of Miami in her Sverdrup lecture at the Fall AGU meeting in December 2008.

"Rotation and helicity in turbulent flows"

Researchers: Pablo Mininni (NCAR and University of Buenos Aires), Annick Pouquet and Duane Rosenberg (NCAR).

GAUs allocated: 700,000. GAUs used: 884,000.

Invariance properties of a physical system govern its behavior: energy conservation in turbulence drives a wide distribution of energy among modes, as observed in geophysics, astrophysics, and engineering. In hydrodynamic turbulence, the role of helicity (which measures departures from mirror symmetry) remains unclear since it does not alter this distribution. However, the interplay of rotation and helicity leads to significant differences. Using numerical simulations we show the occurrence of long-lived laminar cyclonic vortices together with turbulent vortices, reminiscent of recent tornado observations. Furthermore, the small scales are completely self-similar with no deviations from Gaussianity. This result points to the discovery of a small parameter in rotating helical turbulence.



Produced using VAPOR, this visualization shows a small region at late times in a 1,536^3 simulation of helical rotating turbulence: upper left is the z component of velocity, upper right is the vorticity intensity with velocity field lines in red, lower left is a close-up of the vorticity field, and lower right is helicity (alignment of velocity and vorticity; green is negative and blue-magenta is positive). The Reynolds number for the simulation is ~5600 and the Rossby number is ~0.06. Note the co-location of laminar structures with smooth paths and a tangle of vortex filaments with more complex paths. These structures coexist at very disparate scales. (Figure courtesy of Pablo Mininni, NCAR.)

More information about this research appears in Turbulence science: Numerical algorithms and code development and its links to the CISL Research Catalog.

"Examining the role of small-scale processes on the global system in the corona, the magnetosphere, and the ionosphere"

Researchers: Aaron Ridley and Ward Manchester (University of Michigan).

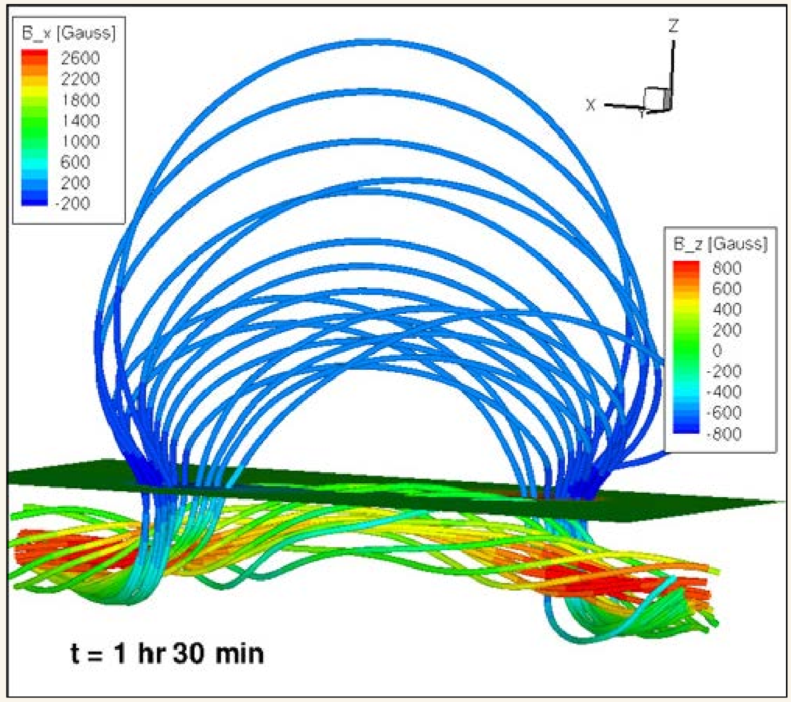
GAUs allocated: 625,000. GAUs used: 300,000.

Coronal mass ejections (CMEs) are energetic expulsions of plasma from the solar corona that are driven by the release of magnetic energy typically in the range of 10^{32-33} ergs. The majority of CMEs originate from the eruption of pre-existing large-scale helmet streamers. Less common fast CMEs typically come from smaller, more concentrated locations of magnetic flux referred to as active regions. In this case, the CMEs often occur shortly after the flux has emerged at the photosphere, but can also happen even as the active region is decaying. While CMEs occur in a wide range of circumstances, common features suggest that the coronal magnetic fields that spawn CMEs and large flares are coupled to the solar interior. In the case of homologous CMEs, more than two dozen eruptions may occur from the same active region, often separated by only a few hours. Such repetitive behavior suggests that the magnetic field can be continuously recharged over a relatively short period of time. A

connection of CMEs to the solar interior dynamo is suggested by the role CMEs play in restructuring the global coronal magnetic field during the solar cycle by expelling magnetic flux and helicity.

The outstanding question of our research is to determine how magnetic fields emerge from the corona to form structures that erupt into CMEs: what are the initiation mechanisms? Since the coronal field cannot be directly observed in detail, it is essential to infer its structure using theory. We used the Bluefire computing system to perform large-scale three-dimensional magnetohydrodynamic (MHD) simulations of flux emergence from the convection zone into the corona. We employ the parallel, adaptive-mesh MHD code BATS-R-US, which allows us to resolve the necessary length scale of photospheric pressure scale height (140 km) in a computational domain that extends beyond 20,000 km.

The simulation begins with the magnetic flux rope 5,000 km below the photosphere. The central part of the flux rope is made buoyant and allowed to rise through the stratified atmosphere. After the flux rope rises through the photosphere, the upper extremity of the rope erupts into the corona while the main body (including the center line) remains below the photosphere. The results are shown in the figure at right, which gives a color representation of the magnetic field lines. The main body of the flux rope remains below the photosphere which is colored to show the vertical field strength. The upper part of the flux rope erupts as a result of shear flows driven by the Lorentz force. The shear flows are the result of deformation of the magnetic field in the stratified atmosphere, causing the electric current to be oblique to the magnetic field and producing the Lorentz force that drives the horizontal shear flow.



Erupting magnetic flux rope shown with field lines colored to show axial field strength (Bx) at time t = 1 hour and 30 minutes. The photosphere is shown as the z=0 plane colored to show the vertical field strength (Bz). The flux system separates by reconnection to form a new flux rope that erupts into the corona. (Figure courtesy of Ward Manchester, University of Michigan.)

This research helps us understand how magnetic flux emerges to form active regions, and how those fields spontaneously erupt in CMEs and flares. The primary result demonstrates sufficient understanding of CMEs eliminating the need to artificially energize coronal magnetic fields to model these events. Two points of this research stand out: (1) flux emergence to produce active regions with self-organized shear flows, and (2) energetic coupling the convection zone and corona during flux emergence that leads to magnetic eruptions; these offer an explanation for CMEs, filament eruptions, and flares. This work makes large strides forward not only in understanding the basic physical processes that cause solar eruptions, but also by including that understanding in realistic numerical simulations and making a direct connection to reality by predicting observations in detail.

"Simulating the effects of convective storms and associated weather hazard due to anthropogenically enhanced global radiative forcing"

Researchers: Jeff Trapp, Mike Baldwin, Noah Diffenbaugh, and Eric Robinson (Purdue University).

GAUs allocated: 399,000. GAUs used: 406,000.

This ASD project is motivated by the need to more fully evaluate the potential response of convective precipitating storms (CPSs) to anthropogenic global warming. In our approach, we dynamically downscaled global model integrations using the Weather Research and Forecasting (WRF) model. The Advanced Research core of the WRF model (ARW) was run using a horizontal gridpoint spacing of 4.25 km over a domain encompassing much of the continental United States. Based on our previous research and some exploratory experiments, our procedure was to integrate the model over one day, reinitialize the model, and then integrate/reinitialize over each subsequent day during warm season months of 1991 2000. In one set of experiments, global reanalysis data (from the NCEP NCAR Reanalysis Project; NNRP) were used for the initial and boundary conditions, and in another set of experiments, data from a historical run of the NCAR CAM3 were used.

The analysis efforts thus far have focused on CPS hazards, in particular, heavy rainfall and convective storm rotation. We mined the WRF output to determine how frequently each of these hazards occurs, then compared these analyses to climatological distributions derived from relevant observations. Thus far we have considered mainly the NNRP driven WRF experiments.

Analyses show that the monthly geographical progression of heavy rainfall occurrence compare remarkably well to the Brooks and Stensrud (2000) analyses of hourly rain gauge data (the Hourly Precipitation Dataset), both in terms of the spatial distributions and the average frequency. At this point, we can conclude that, given so called "perfect boundary conditions," our

dynamical downscaling approach has reproduced the climatological distribution of heavy rainfall events in the United States with a high degree of fidelity.

Convective storm rotation was evaluated using updraft helicity (Kain et al., 2008). Analyses of the monthly geographical progression of updraft rotation frequency are consistent at least with the known northward migration of severe convective weather during these months. We are still working on equitable ways to compare the model derived fields to observations, but we are encouraged that at least the broad regions of highest spatial density of updraft rotation occurrence correspond with the regions of moderate-to-high tornado probability.

In the coming months, we will apply analysis techniques to the CAM3 driven WRF experiments. We are also in the process of identifying individual events that can be analyzed further.

References:
Brooks, H.E. and D.J. Stensrud, 2000: Climatology of heavy rain events in the United States from hourly precipitation observations. *Mon. Wea. Rev.,* **128**, 1194 1201.
Kain, J.S. et al., 2008: Some practical considerations regarding horizontal resolution in the first generation of operational convection allowing NWP. *Wea. Forecasting,* **23**, 931 952.

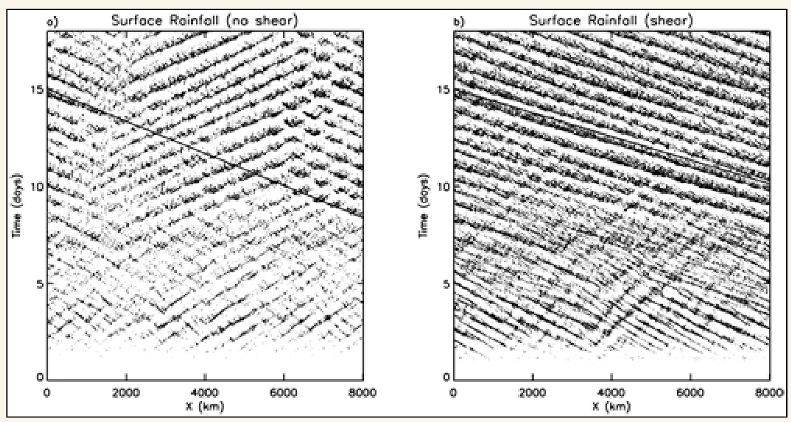
"Mechanisms of Convection-Wave Interactions"

Researchers: Stefan Tulich (CIRES, University of Colorado) and George Kiladis (NOAA, Earth System Research Laboratory).

GAUs allocated: 360,000. GAUs used: 400,000.

This project seeks to improve our mechanistic understanding of convection-wave interactions in the Tropics, with an emphasis on zonally propagating, inertia-gravity waved disturbances with periods <2.5 days. Such disturbances are of interest owing to their strong ties to the diurnal cycle and potential for predictability out to several days in advance. Furthermore, space-time spectra of high-resolution satellite data show a dramatic westward bias in the propagation direction of these high-frequency wave modes, begging explanation and perhaps holding critical clues about wave-convection modulation mechanisms.

A suite of carefully designed nested cloud-resolving model experiments on an equatorial beta-plane was performed on Bluefire using the Weather-Research Forecast (WRF) model. In the absence of vertical shear of the background zonal wind, results showed the spontaneous development of convectively coupled gravity waves with horizontal wavelengths of ~1,000 km and propagation speeds of ~14 m/s but with no preferred direction of propagation (left panel of the figure). On the other hand, imposing moderate easterly shear of the zonal flow at low levels (5 m/s over 2 km) led to a strong westward bias in propagation (right panel of the figure), similar to observations.



Hovmöller diagrams of the surface rainfall in cloud-resolving WRF simulations of radiative-convective equilbrium on an equatorial beta-plane extending 8,000 km in the horizontal. In the left panel (no shear), the zonal-mean zonal winds were relaxed to zero on a 6-hour time scale, while winds in the sheared experiment (right panel) were relaxed to -5 m/s above 2 km, decaying linearly to zero at the surface.

Results of this project have so far been presented at two scientific meetings of the American Meteorological Society, and will soon be published in a scientific journal article.

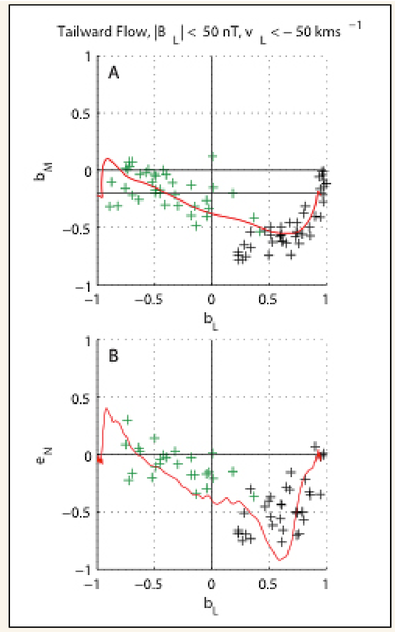
"Collisionless Magnetic Reconnection in the Earth's Magnetosphere"

Researchers: Michael Shay, Paul Cassak, and Kittipat Malakit (University of Delaware).

GAUs allocated: 336,000. GAUs used: 345,000.

Under NCAR's Accelerated Scientific Discovery allocation, kinetic particle-in-cell simulations were used to study the kinetic properties of asymmetric magnetic reconnection. These simulations do not have the limitations of fluid models, such as lack of mixing of plasma along field lines and unrealistic electron physics. The simulations were quite large, typically 4,096 by 2,048 grid cells on 512 to 2,048 tasks. A variety of simulations were performed with varying upstream conditions. All of the simulations used a mass ratio of $m_i / m_e = 25$. The strong up-down asymmetry of the reconnection is clearly present due to the differing inflow conditions. The presence of the extremely strong electrostatic electric field E_y is particularly interesting.

The basic theoretical predictions for the reconnection rate were tested, and the agreement is quite good. We have begun to carefully study the structure of the electron diffusion region, and one of the first signatures we examined is the location of the electron diffusion region relative to the ion diffusion region. This is quite difficult to do



Comparison of satellite data with simulations. Satellite data are shown as "+" signs and virtual satellite passes through the simulations are shown with the red lines

owing to the relatively large noise level in kinetic PIC simulations. We have averaged over large numbers of time steps (over a short interval) to reduce the noise. One of the basic features expected is that the electron stagnation point will not be co-located with the ion stagnation point. As expected, the electron stagnation point is much closer to the x-line than the ion stagnation point. There are some unexpected results, however. The substructure of the diffusion region is much more complicated than expected, with extremely large normal electric fields, frozen-in out-of-plane ion flow, and significant modifications of the expected Hall magnetic fields. This work is described in "Kinetic Structure of the Asymmetric Diffusion Region" by Malakit, K., M.A. Shay, and P.A. Cassak, in preparation.

Reconnection is normally thought of as occurring between two magnetic field lines that are antiparallel. However, in many cases the field lines are not antiparallel, but have some magnetic shear less than 180°. Although the antiparallel case of kinetic large-scale reconnection has been studied at length, basic studies of its structure for smaller magnetic shear have yet to be performed. Through the ASD work, we simulated large-scale kinetic reconnection with magnetic shears from 180° to 90°. In terms of 2½D simulations (where no variation is allowed in one direction, but flows and field are allowed in that direction), the non-antiparallel case can be represented as reconnection in the presence of a uniform "guide" field in the direction where variation is not allowed.

The figure shows scatter plots with data from a virtual satellite (red line). The upper plot shows two components of magnetic field b_L and b_M. The scatter of electric field e_N relative to b_L is shown on the bottom plot. The agreement is quite good. This work is described in "Asymmetry of the Diffusion Region Hall Electric and Magnetic Fields During Guide Field Reconnection: Observations and Comparison with Simulations" by Eastwood, J.P., M.A. Shay, T.D. Phan, and M. Oieroset, submitted to *Journal of Geophysical Research*, 2009.

Other FY2009 accomplishments under Very large computational experiments

ASD publicity energizes university community and increases number and size of requests

The ASD program generated significant excitement and enthusiasm among CISL's university community of users because the ASD program announcement was sent to existing PIs and users as well as people the NSF identified as recent awardees in the upper atmosphere. It appears that a number of university groups made plans to request more resources with the availability of Bluefire. The October 2008 CHAP meeting saw a doubling of the number of university requests and a three-fold increase in the amount of time requested. This meant that university requests for computational resources were 140% of available resources at the first panel meeting following Bluefire's general availability. Contributing to the large of amount of resources being requested, five of the requests were resubmissions of non-selected ASD proposals that had received positive reviews. These projects requested from 300K to 550K GAUs each.

NCAR continues program to provide large allocations to a few projects

The resources available to NCAR researchers continue to be limited, even with the installation of Bluefire. This results in fragmentation of resources down to sections, then groups and individuals, limiting NCAR scientists' ability to make research advances that require large amounts of computing resources. In December 2008, NCAR expanded the resources for very large computational experiments performed by NCAR researchers through the NCAR Capability Computing (NCC) pool of resources. NCC resources now total 200K GAUs per month and are typically given to one project at a time for two or more months. Two projects were supported through NCC resources in FY2009 after the ASD program ended in December 2008.

Code efficiency emphasized for large university allocations

Based on the Consulting Services Group's work with ASD projects, CISL implemented a new code efficiency program for university projects that receive large CHAP allocations. Fifteen CHAP projects received more than 150,000 Bluefire processor hours in fall 2008 and were asked to provide a benchmark of their production code showing good utilization of Bluefire. The projects were given a modest allocation for testing to set up their production codes and run benchmarks. CISL consulting staff were assigned to each of the projects and analyzed the benchmarks for code efficiency. After the projects submitted a satisfactory benchmark, the full allocation recommended by the CHAP was provided.

The university community has been very responsive to the efficiency requirement. All 15 projects responded with appropriate benchmarks, and if necessary, worked with CISL staff to improve their code's performance.

New minimum allocation for CSL projects in FY2009

During 2007 the NSF-appointed Climate Simulation Laboratory (CSL) Allocation Panel suggested that some CSL proposals were requesting too few processor hours. After discussions between the NSF (the lead agency for the CSL) and CISL, a new minimum

request size of 900K GAUs over 18 months was established. This also became the minimum allocation size, and it resulted in a reduction of the number of CSL projects being supported from 13 to 7. The NSF Program Manager approved this change, noting that it is in line with the goals of the CSL. CSL was established in 1995 to provide resources for the very largest computational experiments in the area of climate change research.

FY2010 plans: Code efficiency for projects receiving very large allocations

CISL plans to continue requiring university projects that receive very large allocations to show adequate code efficiency. The strategy of withholding the full allocation pending a satisfactory benchmark performance has proven very effective in encouraging university researchers to improve the efficiency of their applications. This method has also been used for NCAR projects receiving very large allocations, such as the NCC projects described above.

Computational resources for university researchers receiving CHAP allocations are sponsored by the NSF.

FY2010 plans for the Climate Simulation Laboratory

The next round of CSL allocations will take place during Q4 FY2010. They will be effective on 1 December 2010. The computational resources for the CSL in FY2010 will be about the same as in FY2009, since Bluefire will remain as NCAR's main computational platform. CISL staff will continue working with CSL projects to improve code efficiency.

The Climate Simulation Laboratory (CSL) is a multiagency computing facility dedicated to climate modeling in support of the U.S. Global Change Research Program. The CSL is administered by the National Science Foundation and hosted by NCAR.

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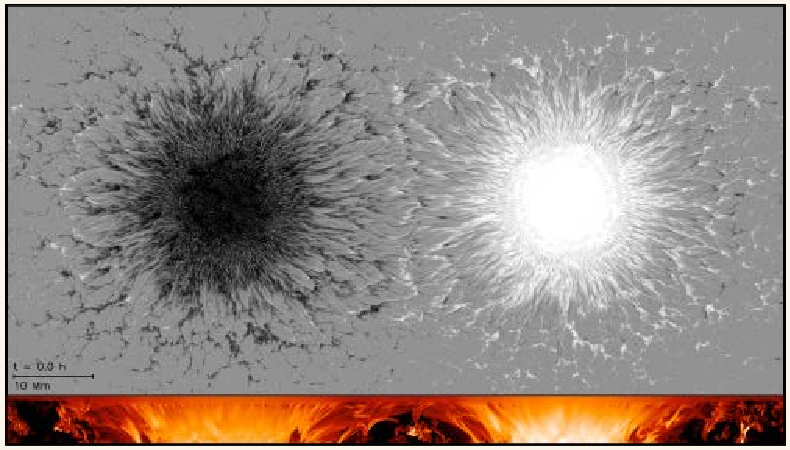
Special computational campaigns

In last year's annual report, CISL reported on the beginning of the Accelerated Scientific Discovery (ASD) computational campaigns' use of the IBM POWER6 system, Bluefire. Nine ASD projects used Bluefire over four months spanning the FY2008-FY2009 transition, accumulating over 3.7 million CPU hours. Also in FY2009, NCAR Capability Computing (NCC) and two other real-time projects used approximately 1.3 million CPU hours. Additionally, development and early control runs for the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5) used 1.47 million CPU hours.



This figure shows bipolar magnetic structure diverging from sunspots from simulations enabled by the Advanced Scientific Discovery (ASD) project on Bluefire. The upper panel shows the vertical magnetic field in the solar photosphere while the lower panel shows the corresponding subsurface magnetic field strength on a vertical plane through the center of the spot pair. The computation includes 1.8 billion grid points and required about 250,000 CPU hours. This allowed scientists to simulate about 2 hours of temporal evolution, which is sufficient to understand the magneto-convective origin of sunspot fine structure. Performing computer simulations of entire sunspots is challenging. Sunspots have a typical size of several 10,000 km and show structure down to the smallest observable scales on the order of a few 100 km, requiring large computing domains to simulate, which has only become feasible recently. Detailed modeling of the origin, dynamical evolution, and decay of sunspots is essential for our understanding of the solar magnetic cycle and the impact of solar magnetic activity on the Earth System through solar flares and coronal mass ejections. Radiative energy loss to outer space associated with them gives rise to variations of the solar heating of the Earth, leading to variations of the Earth's climate that are yet to be understood. Courtesy of Matthias Rempel, NCAR-ESSL-HAO.

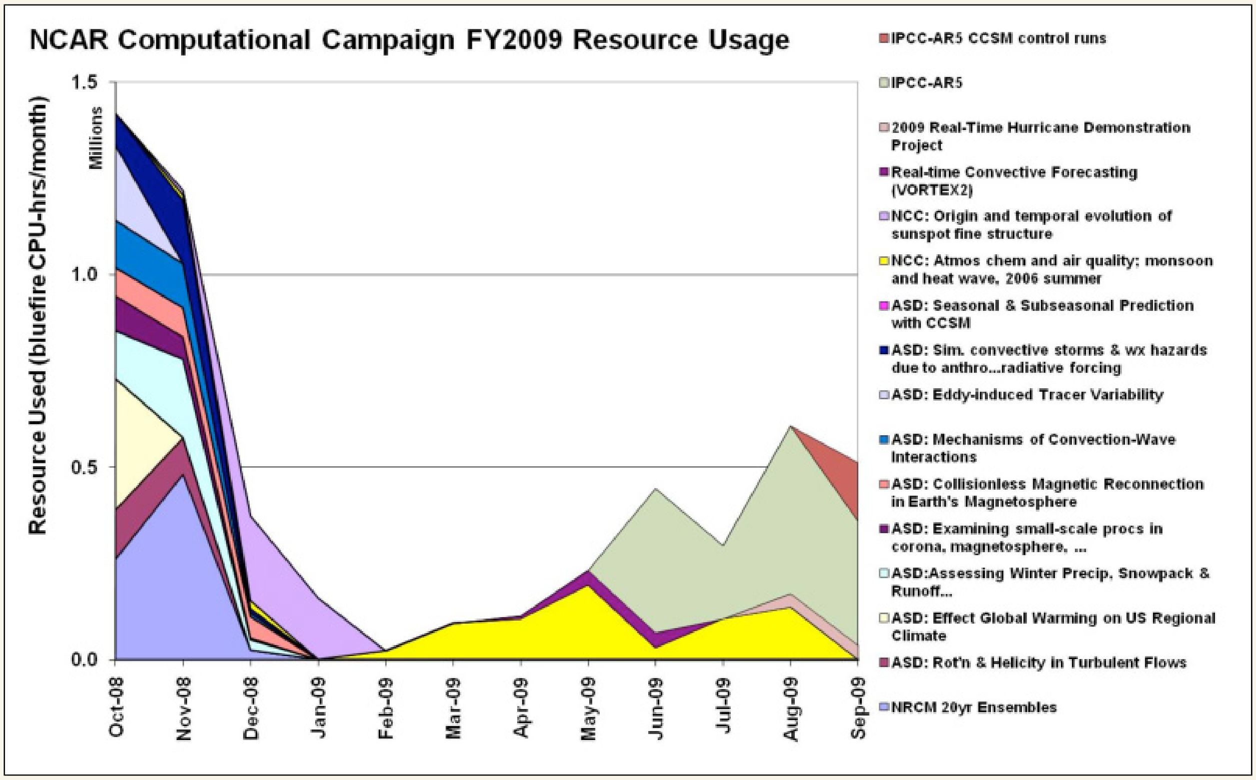
While the NCAR production supercomputing environment provides capacity computing to NCAR, university, and CSL scientists, the special campaign mechanism supports ongoing and special computational projects and campaigns and on-demand capability computing.

The following table lists the special computational campaigns supported by CISL during FY2009. In FY2009, CISL continued running the Nested Regional Climate Model (NRCM) and ASD that commenced during FY2008, and CISL began supporting two NCC projects (modeling of the summer 2006 air quality and atmospheric chemistry during monsoon and heat wave events, and fine-scale modeling of the origin and evolution of sunspots). Additionally, early IPCC AR5 development and control runs were commenced on Bluefire near the end of FY2009.

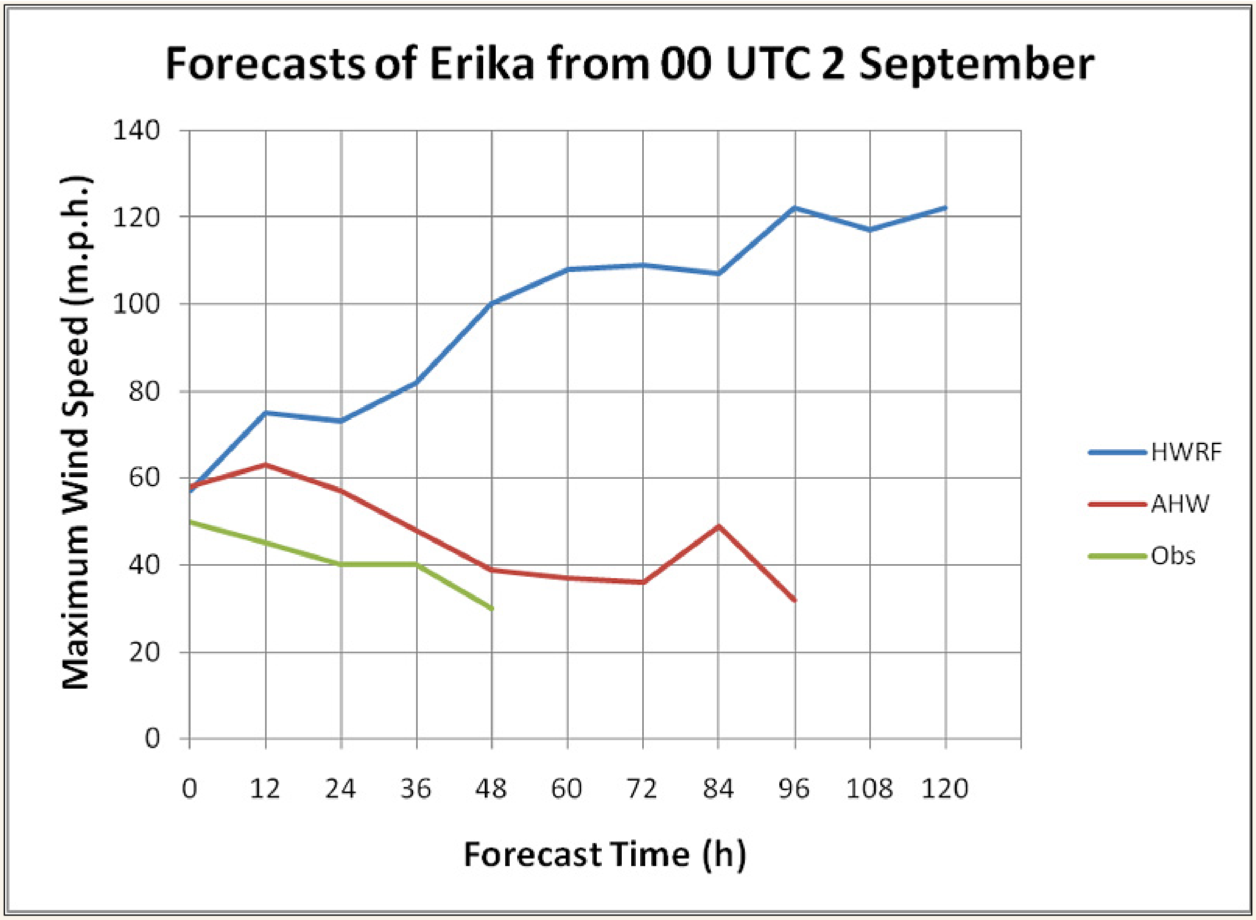
FY2009 Special Project	Principal Investigator	Begin	End
NRCM 20-year Ensembles	Greg Holland, et al.	1-Jul-08	2-Dec-08
ASD: Rotation and helicity in turbulent flows	Pablo Mininni, et al.	1-Jul-08	11-Nov-08
ASD: Effect of Global Warming on U.S. Regional Climate	Greg Holland, et al.	1-Jul-08	23-Nov-08
ASD: Assessing Winter Precipitation, Snowpack and Runoff Processes from Colorado's Headwater Basins using a Very High Resolution Fully Coupled Atmospheric-Hydrologic Model	Roy Rasmussen, et al.	1-Jul-08	2-Dec-08
ASD: Examining the role of small-scale processes on the global system in the corona, the magnetosphere and the ionosphere	Aaron Ridley	1-Jul-08	2-Dec-08
ASD: Collisionless Magnetic Reconnection in the Earth's Magnetosphere	Michael Shay	1-Jul-08	2-Dec-08
ASD: Mechanisms of Convection-Wave Interactions	Stefan Tulich and George Kiladis	1-Jul-08	2-Dec-08
ASD: Eddy-Induced Tracer Variability	Sabine Mecking, et al.	1-Jul-08	30-Nov-08
ASD: Simulating the effects of convective storms and associated weather hazards due to anthropogenically enhanced global radiative forcing	Robert J. Trapp, et al.	1-Jul-08	2-Dec-08
ASD: Seasonal and Subseasonal Prediction with CCSM	Kathy Pegion, et al.	1-Jul-08	15-Nov-08
NCC: Atmospheric chemistry and air quality; monsoon and heat wave, 2006 summer	Mary Barth, et al.	10-Oct-08	31-Aug-09
NCC: Origin and temporal evolution of sunspot fine structure	Matthias Rempel,	29-Oct-08	26-Jan-09

	Michael Knölker		
Real-time Convective Forecasting (VORTEX2)	Morris Weisman, Wei Wang	20-Apr-09	30-Jun-09
2009 Real-Time Hurricane Demonstration Project	Chris Davis	1-Aug-09	-
IPCC-AR5	multiple	1-Jun-09	-
IPCC-AR5 CCSM control runs	Jon Wolfe	10-Aug-09	-

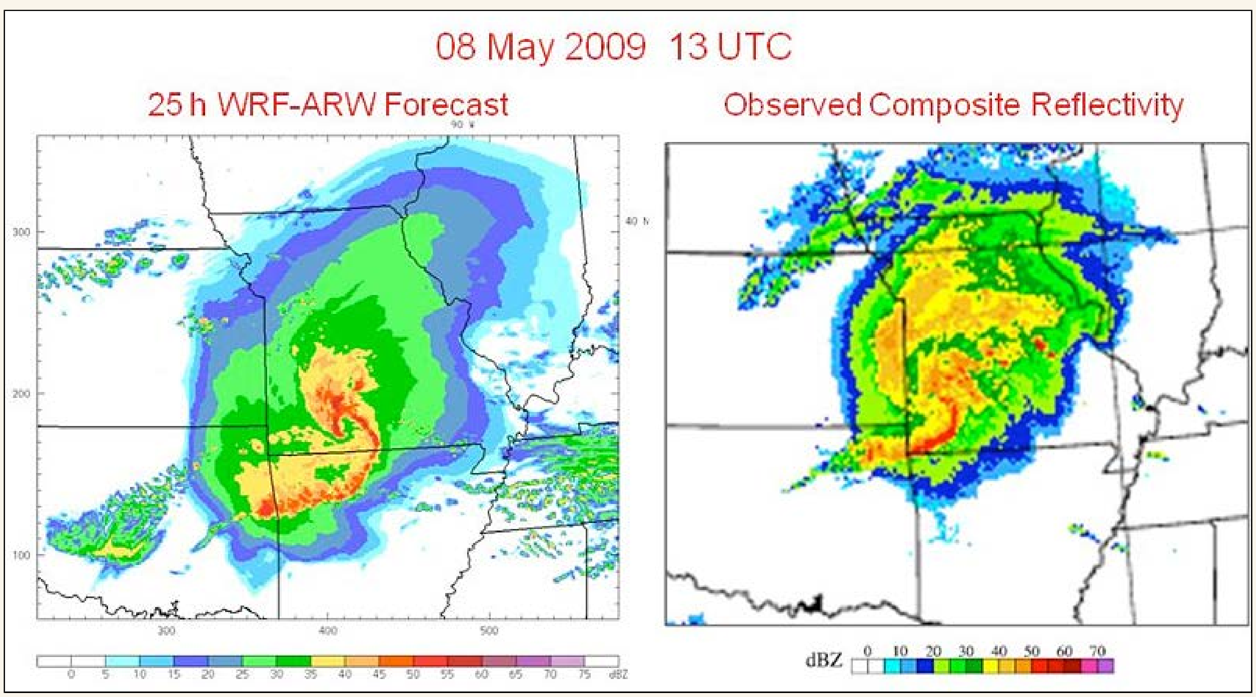
The special computing campaigns and provision of on-demand and real-time computing support CISL's computing imperative for hardware cyberinfrastructure by provisioning computing, storage, data analysis, visualization, networking, and archival systems customized to support the atmospheric and related sciences. 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.



This chart shows the monthly usage of Bluefire for special computational campaigns (continuation of the Accelerated Scientific Discovery projects, NCAR Capability Computing projects, real-time projects, and early IPCC AR5 runs) during FY2009. CISL's provision of a significant portion of the Bluefire system to special campaigns has accelerated scientific discovery through numerical simulation.



Results from the 2009 Real-time Hurricane Demonstration Project run on Bluefire. Tropical cyclones in 2009 were strongly influenced by vertical variations of environmental wind that caused the storms to tilt and displaced the thunderstorms that are essential for hurricane development. Most 2009 hurricanes tended to weaken, and this was well predicted by the Advanced Hurricane-research Weather Research and Forecasting (WRF) model (AHW) but not by most operational models. This figure shows a time series of maximum sustained surface wind in numerous forecasts of tropical storm Erika which weakened rapidly in nature, and AHW was the only model to systematically predict its evolution. The blue line shows the predictions of the operational Hurricane WRF (HWRF) model which is based on NCEP's nonhydrostatic mesoscale model; red shows NCAR's AHW model predictions, and green shows observed wind speeds. Used for real-time tropical cyclone forecasts of Atlantic storms during the 2009 season, AHW applies advanced data assimilation, improvements in surface flux parameterization, and coupling to a simple ocean model to produce the first real-time system to simulate tropical cyclones with an innermost grid spacing of near 1 km. Courtesy of Chris Davis, NCAR-ESSL-MMM.



This figure shows a visualization from a realtime explicit convective forecast run on Bluefire to test the latest improvements in the WRF-ARW modeling system. In collaboration with NOAA/ESRL (Earth System Research Laboratory) and to support the VORTEX-2 field campaign and National Severe Storms Lab (NSSL) and Storm Prediction Center (SPC) 2009 Spring Program, the WRF-ARW simulation (left) of a severe-wind-producing convective system observed on 8 May 2009 (right) closely simulated this unusually intense and long-lived warm-core mesoscale vortex that was responsible for producing an extensive swath of damaging surface winds. Displaying some similarities to incipient tropical

cyclones, this event was forecast successfully in real time 25 hours in advance. The output from this forecast will allow for unprecedented diagnoses of the processes responsible for the development of such an intense mesoscale vortex over land. Courtesy of Morris Weisman, NCAR-ESSL-MMM.

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Support for supercomputer users

CISL provides multiple levels of user support through its ExtraView HelpDesk application (on screen). Frontline customer support is provided by Computer Production Group staff (Lewis Johnson, seated, is a Computer Support Specialist). Si Liu (standing, a Software Engineer in the Consulting Services Group) is one of five consultants who provide in-depth assistance with complex cases. This tiered customer support allows CISL to maximize its resources and tailor its services to the specific needs of its supercomputing users.

NCAR has a strategic commitment to provide robust, accessible, and innovative information services and tools to our customers. CISL provides end-to-end services for its supercomputing users using the full capability of the laboratory staff. Consulting service includes frontline assistance as well as in-depth expertise. Contacts are tracked using an ExtraView HelpDesk trouble ticket system.

In FY2009, frontline support resolved 1,607 tickets in the time interval from September 2008 through August 2009. In the same interval, advanced support resolved an additional 856 contacts, for a total of 2,463. The average number of log entries per ticket was 4.84, with communication highest with users on complex cases. Average response time for frontline support for ticket resolution was about 0.61 days (down from 1.3 days last year), while a longer average response time of about 5.1 days (up from 4.2 days last year) was required for more complex issues. The average number of staff who worked on tickets was 1.38, demonstrating cross-team cooperation in resolving issues.

CISL Consultant Siddhartha Ghosh (right) worked with Edmund Chang (SUNY Stony Brook) to improve performance of a Community Atmosphere Model (CAM) ensemble using the Data Assimilation Research Testbed (DART) on Bluefire. Ensemble models of this sort are challenging to run efficiently, partly because it is difficult to schedule multiple instances on the IBM job scheduler. Several scenarios were run to address this problem, including staggering the scheduling of CAM instances. They determined that running the code on one node was the most efficient use of resources. Chang noted, "It appears that running with one node instead of two nodes is more efficient. With one node, the saving becomes about 23% over what I was using. The way that I am doing it now is already much more efficient than the way DART-CAM was originally set up. The original set up used three large-memory nodes, and an average job took about 1,700 seconds to complete. We have cut it down to one regular-memory node, using 2,934 seconds to complete, so this represents a total saving of 42% over the original DART setup."

A benefit of tiered customer support has been to free CISL staff to supply customized, one-on-one service for special campaigns such as the Accelerated Scientific Discovery program (July through December 2008 including planning and postprocessing), which provided opportunities for capability computing projects requiring hundreds of thousands of processor hours on the IBM POWER6 platform, Bluefire. We provided documentation and training on the new features of the system as the system was released to general users. Other special projects included performance benchmarking and optimization of large projects approved by the CISL High Performance Computing Advisory Panel (CHAP) and the Climate Simulation Laboratory (CSL).

In FY2010, we anticipate further growth in this type of scientific support, as well as continuing support for NCAR "flagship" models such as the Community Climate System model (CCSM) and the Weather Research and Forecasting model (WRF). We also expect to increase support for TeraGrid-allocated projects, with the recent quadrupling in capacity of Frost, an IBM BlueGene/L system.

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

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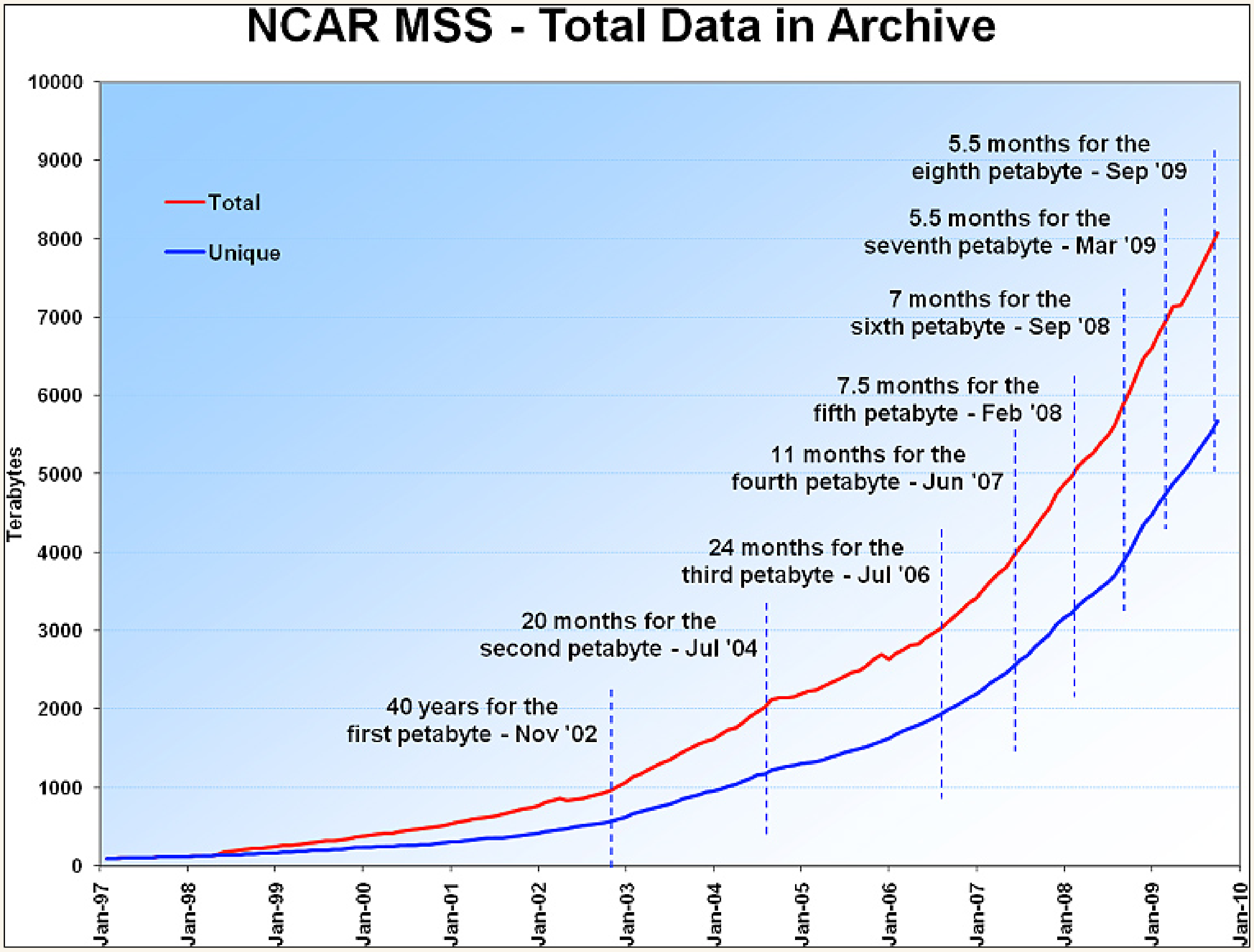
Mass Storage System (MSS) improvement: AMSTAR



This chart of the past 12 years of NCAR MSS growth shows unique and total (includes duplicate copies) bytes. This exponential growth of the NCAR MSS is expected to continue with the annual growth rate exceeding 5 petabytes by 2012.

The MSS must scale up to meet an ever-growing demand for secure, reliable data storage and high-performance access. This requires the constant evaluation and periodic deployment of the latest, highest-performance, and most cost-effective hardware and software technologies available.

The completion of the CISL Integrated Computing Environment for Scientific Simulation (ICESS) Phase 2 deployment in the summer of 2008 more than quadrupled NCAR's peak computing capacity. With the ICESS supercomputing upgrade combined with the planned growth of CISL's Data Support Section's scientific data holdings and the upcoming Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), CISL is planning for an unprecedented increase in the capacity of the MSS through FY2012. Additionally, the Sun/StorageTek Powderhorn tape library robotics currently in production are nearing end-of-life. Sun has set an end-of-service date of December 2010; this allows only 15 months to deploy replacement tape technology, then migrate about 8 petabytes of data to the new system.

To meet these challenges, CISL initiated a Request For Proposal (RFP) at the beginning of FY2008 named "Augmentation of the Mass Storage Tape Archive Resources" (AMSTAR). Released in late November 2007, AMSTAR is a four-year subcontract awarded to replace the MSS StorageTek Powderhorn tape libraries (silos), 9940x tape drives, and media with new robotic tape libraries, tape drives, and media that will increase MSS data storage capacity to more than 30 PB and position the archive for future technology upgrades that will enable the management of 100s of PB of data. AMSTAR contract negotiations were completed at the end of August 2008. The contract will meet NCAR's projected needs until the expected move to the NCAR-Wyoming Supercomputer Center in 2012.

Production deployment of the AMSTAR technology was completed in December 2008 after which time all new data started being

written to AMSTAR. At the end of FY2009, approximately 3.5 PB of the 8 total PB were stored on the AMSTAR media. The start of the data migration (data ooze) to the new tape technology began in August 2009 after an optimized ooze process was implemented. The ooze is expected to finish in the spring of 2010, well ahead of the December 2010 deadline. Additionally, a decision was made in FY2009 to replace the NCAR MSS with the IBM High Performance Storage System (HPSS) software. A transition plan was developed at the end of FY2009 with a target completion date of January 2011.

The older Powderhorn tape libraries and 9904x drives and media will be decommissioned after the data ooze completes in FY2010. The NCAR HPSS server and disk cache capacity will be increased to support the NCAR MSS workload in preparation for the transition. The AMSTAR equipment is fully compatible with HPSS and will be reused by HPSS once the NCAR MSS is decommissioned. HPSS will be modified to read the NCAR-MSS-formatted AMSTAR tape media, eliminating the need for any data migration between the two systems.

This work supports CISL's computing imperative to provision hardware cyberinfrastructure for the atmospheric and related sciences. The NCAR MSS is managed by CISL under the UCAR/NSF Cooperative Agreement and is supported by NSF Core funds including CSL funding.

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High Performance Storage System (HPSS)

The National Science Foundation TeraGrid uses high-performance networks to integrate supercomputers, data archives, and data analysis facilities around the country. Its coordinated work environment enables 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. The IBM High Performance Storage System (HPSS) has been deployed by a number of the TeraGrid Resource Providers. The deployment of HPSS at NCAR will enable a homogeneous storage solution for the TeraGrid, allow potential data archive connectivity directly with Wide Area Network (WAN) filesystems on the TeraGrid, and provide a data management system administration learning opportunity in a security environment external to the UCAR security perimeter.

NCAR's HPSS robotic tape library was acquired in the AMSTAR contract. The library was initially sized to support 1.5 PB of data, and it can be expanded to 10 PB at the current media density. Multiple libraries can be physically connected to provide 100s of petabytes of seamless archival storage.

In FY2009 CISL deployed this HPSS to be directly accessible from outside the UCAR security perimeter and provide higher-performance lower-latency access to archive data than what is currently available with the NCAR MSS. The deployment included a 30 TB disk cache and a 1.5-PB-capable tape library, six tape drives, and 1 PB of media acquired from the Augmentation of the Mass Storage Tape Archive Resources (AMSTAR) procurement. The initial software installation of HPSS was upgraded during FY2009 to an enhanced version of HPSS providing optional Hierarchical Storage Management (HSM) integration with the IBM General Parallel File System (GPFS). GPFS is currently deployed as a WAN filesystem resource on the TeraGrid. 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 will be executed in FY2010. The multi-phase plan includes HPSS direct access to the existing NCAR MSS tape archive data once the NCAR MSS is decommissioned, thus eliminating the need to copy data.

NCAR's MSS-to-HPSS transition will continue through FY2010. The existing NCAR MSS tape archive equipment will be reused by HPSS. However, HPSS server capacity will be enhanced to prepare for supporting the NCAR MSS workload by January 2011. A custom HPSS accounting solution will be developed to provide archive data transfer and storage accounting data that are compatible with CISL's existing General Accounting Unit (GAU) system. Commonly used TeraGrid/open source and vendor-supported HPSS user interfaces will be available with deployment consulting support and documentation for HPSS client machine system administrators. A LAN-GPFS test bed will be deployed in FY2010 that includes HSM functionality with HPSS. CISL will conduct a proof-of-concept test of the WAN-GPFS/HPSS HSM capabilities with NCSA as part of NCAR's participation in the TeraGrid Data Archival and Replication Working Group and will establish a Lustre-WAN test bed in response to the TeraGrid Data Architecture recommendations. Additionally, other filesystem HSM capabilities with HPSS will be investigated as they arise.

This effort supports CISL's computing imperative for hardware cyberinfrastructure by deploying an operational HPSS test bed and evaluating the feasibility of transitioning to the HPSS tape archive system as an alternative to the existing MSS system. The NCAR HPSS is managed by CISL under the UCAR/NSF Cooperative Agreement and is supported by NSF Core funds.

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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 FY2009:

- UCAR network infrastructure recabling
- Network monitoring
- Multicast support activities
- UPS, grounding, wireless networking, Voice over IP
- CISL LAN and SAN projects
- Security redesign projects

NETS pursued these MAN projects in FY2009:

- Boulder Point-Of-Presence (BPOP)
- Boulder Research and Administration Network (BRAN)
- Boulder Valley School District fiber partnership
- Remote-working and home-access

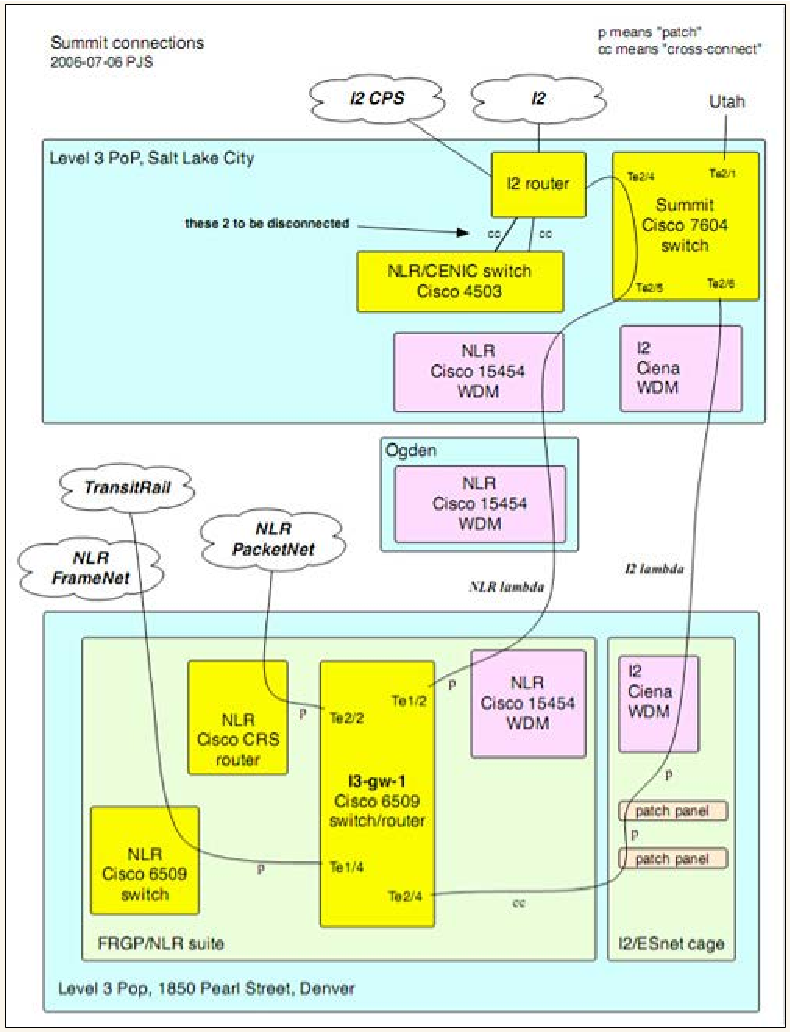
NETS pursued these WAN projects in FY2009:

- Front Range GigaPOP (FRGP)
- UCAR Point of Presence (UPoP)
- National LambdaRail (NLR)
- Internet2
- Bi-State Optical Network (BiSON)
- TeraGrid
- SUMMIT: The Mountain West Advanced Networking Cooperative
- Western Region Network (WRN)
- NOAA Research Network (NRN)

In FY2010, NETS will continue to provide support and enhancements for these essential networking services. NETS activities are supported through UCAR Communications Pool indirect funds.

The following reports on the SUMMIT network, the Western Region Network (WRN), and the NETS directory project provide more information about some NETS accomplishments in FY2009.

SUMMIT: The Mountain West Advanced Networking Cooperative

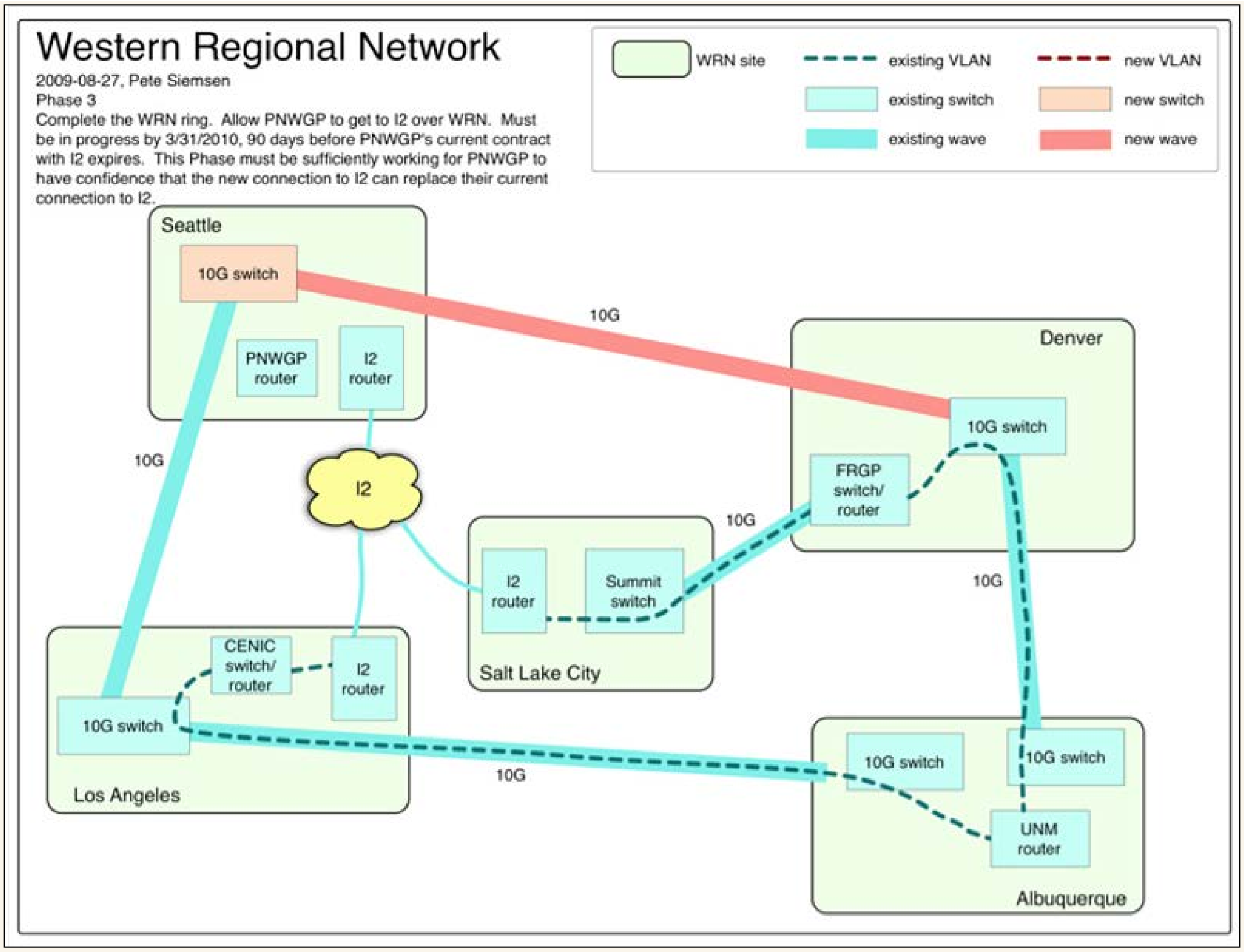


This diagram shows NCAR's SUMMIT network installation. The SUMMIT network enables the FRGP and UEN to share NLR, I2, TransitRail (TR), and intra-regional traffic. These research networks are critical to scientific access and data transport. Sharing this infrastructure allows UCAR to have access to more and higher-speed networks at lower cost.

SUMMIT is a collaboration of the Front Range Gigapop (FRGP), a project of the University Corporation for Atmospheric Research (UCAR) and the University of Utah, on behalf of the Utah Education Network (UEN) to establish and maintain state-of-the-art advanced networking connectivity to universities, long-standing and emerging state education networks, and other affiliated research, development, clinical, and educational organizations in the Intermountain states of Colorado, Idaho, Utah, and Wyoming.

SUMMIT is designed to be a flexible and nimble cooperative with lightweight but engaged governance. SUMMIT's initial purpose is to aggregate the region's Internet2 connectivity through Salt Lake City and NLR through Denver. However, SUMMIT may also support commodity Internet aggregation, connections to other research and education networks (fednets), regional peering, experimentation in distributed IT services, and other network-based and related services.

Western Region Network (WRN)

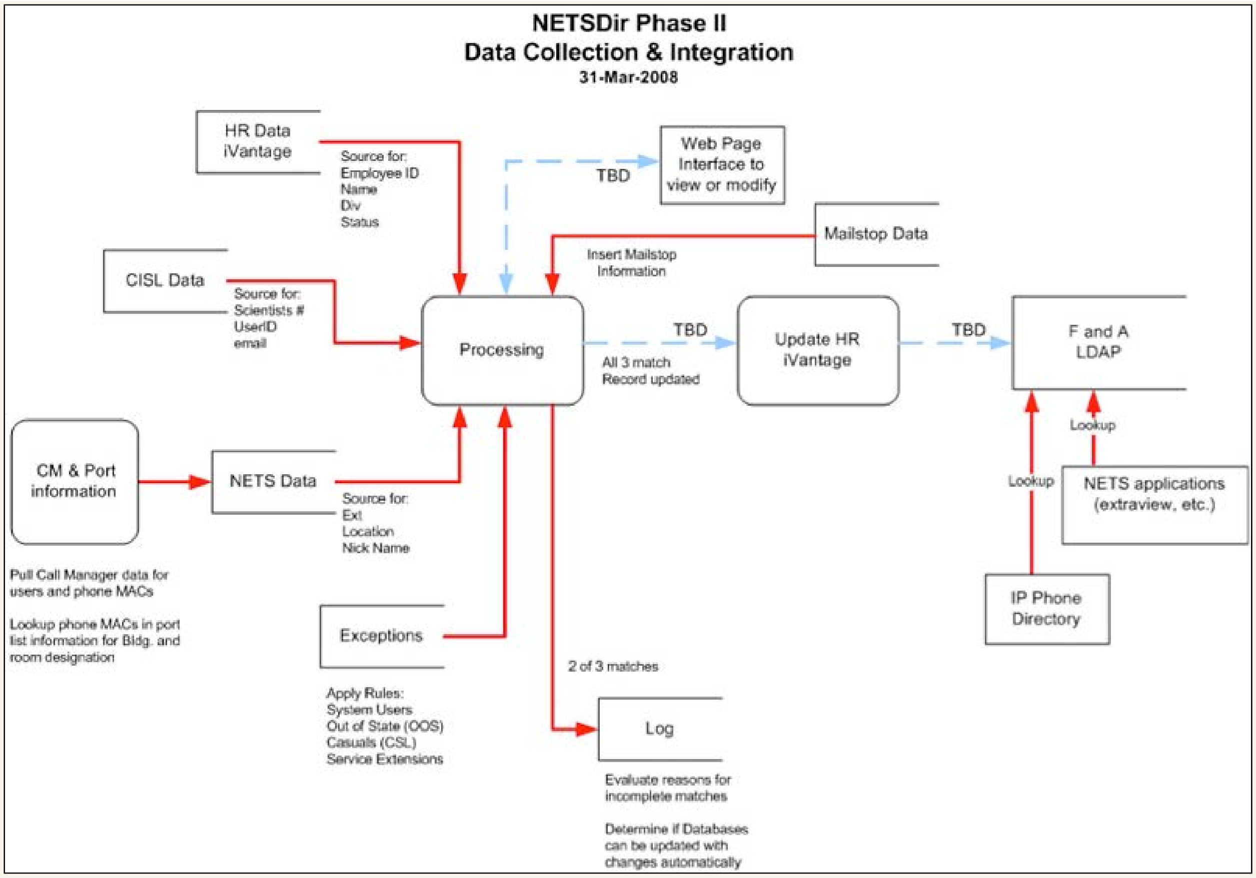


This shows the proposed WRN network at its final phase. The WRN network enables the FRGP to super-aggregate WAN connections in order to purchase larger bandwidth at significantly lower costs. WRN also builds a significant geographical consortium, which will allow increased influence over vendors and R&E network providers. By participating in WRN, UCAR will have access to more and higher-speed networks at lower cost.

The 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 Arizona, California, Colorado, Idaho, Nevada, New Mexico, Utah, Washington, and Wyoming. WRN plans to establish, maintain, and sustain networking interconnections and share services among the members. Each member operates advanced networks for, and on behalf of, themselves, their members, and other affiliates.

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.

NETS directory project



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.

The goal of this project is to provide accurate, up-to-date directory information. In addition to bringing together disparate elements not previously in any single location, NETS also hopes to reduce or eliminate the current manual, often redundant, steps involved in the manipulation of directory information. NETS emphasized secure solutions and work to keep directory data in formats that can easily be exported and shared with other systems both now and in the future.

This effort will address issues specific to NETS at this time and not larger, organization-wide issues (though pieces of this effort may be adopted for that purpose later). One initial project assumption was that NETS will provide UCAR's authoritative source for room number and telephone extension.

NETS requires specific aspects of staff information to perform its daily tasks to support the telephone, network, and other systems. This information consists of: first name, last name, division or program or laboratory, username (to match UCAS login, email address, or other system login ID), telephone extension, and network device/phone location. To reduce the amount of manually entered data and increase the accuracy of people information generated by NETS, NETS obtained people information from existing systems including the Voice over Internet Protocol (VoIP) telephone systems.

The NETS directory relies on four main sources of people information: HR name/division data, CISL email alias/account names, telephone (Call Manager) extension numbers, and port list device (telephone/MAC) room locations.

This project developed an automatic method to marry all the sources of staff information into one location and remove 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 IPT team.

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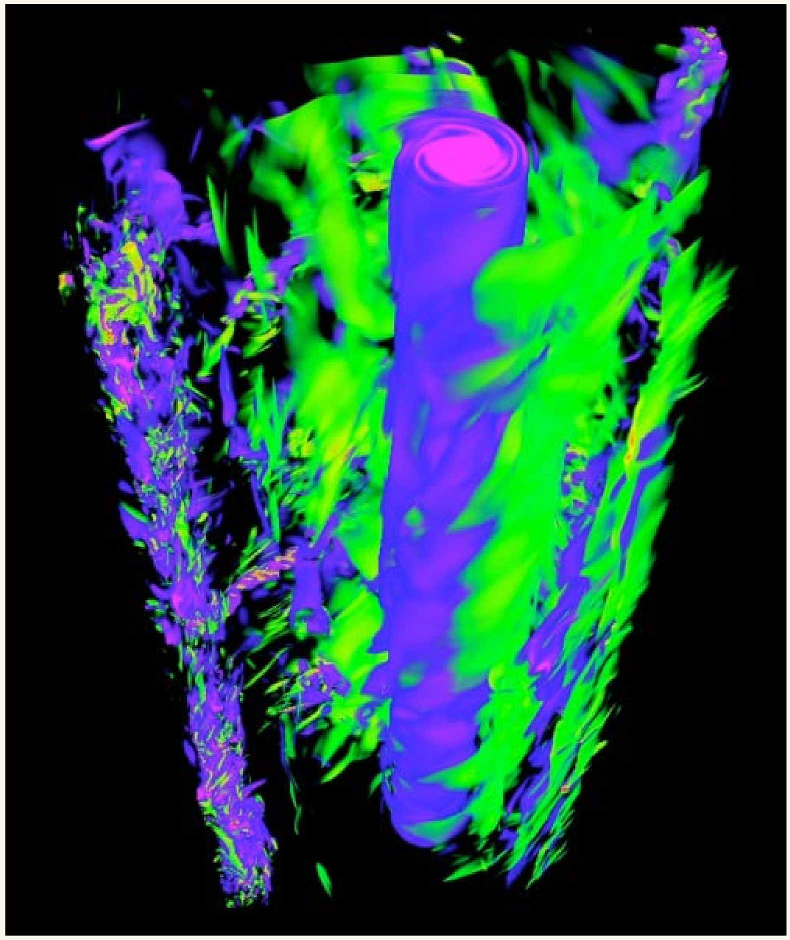
1.3.9 Data analysis and visualization environment

The Data Analysis and Visualization Lab enhances scientific workflow 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.



Generated using VAPOR, this image illustrates the rotation and helicity in turbulent flows. This project was part of CISL's Accelerated Scientific Discovery (ASD) initiative. To support ASD's computational efforts, CISL's Data Analysis Services Group (DASG) provided award recipients with data analysis and post-processing computing resources and over 30 TB of disk storage, along with advanced user support for scientific visualization.

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

The evolution of this facility from a collection of dedicated standalone resources into a tightly coupled unified computing environment has been a multi-year process. In FY2009 we completed the installation of a centralized high-performance storage cluster to provide high-bandwidth data access shared between NCAR's supercomputer, data analysis cluster, and visualization cluster, significantly streamlining the scientific workflow. This included the installation of a 10 Gbps high-speed data network and an augmentation of storage capacity allowing us to allocate large data spaces for data analysis and visualization projects.

In FY2010 we will continue to augment the computational, visualization, and storage offerings and integrate new high-bandwidth data transfer services, enhancing our ability to bring computational data from other sites to NCAR for post-processing, analysis, and visualization.

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.

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Cybersecurity

UCAR manages and maintains a large and diverse set of compute, data, data storage, 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 by the UCAR organization and 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 represents an enterprise to the community and adheres to NSF security best practices and recommendations.

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, reports, and posts an incident analysis if one occurs.

It is vital to the organization that we protect systems, data, and intellectual property at the highest level possible that keeps usability and security in balance.

During FY2009, these factors were vital to the continued security of IT systems at UCAR:

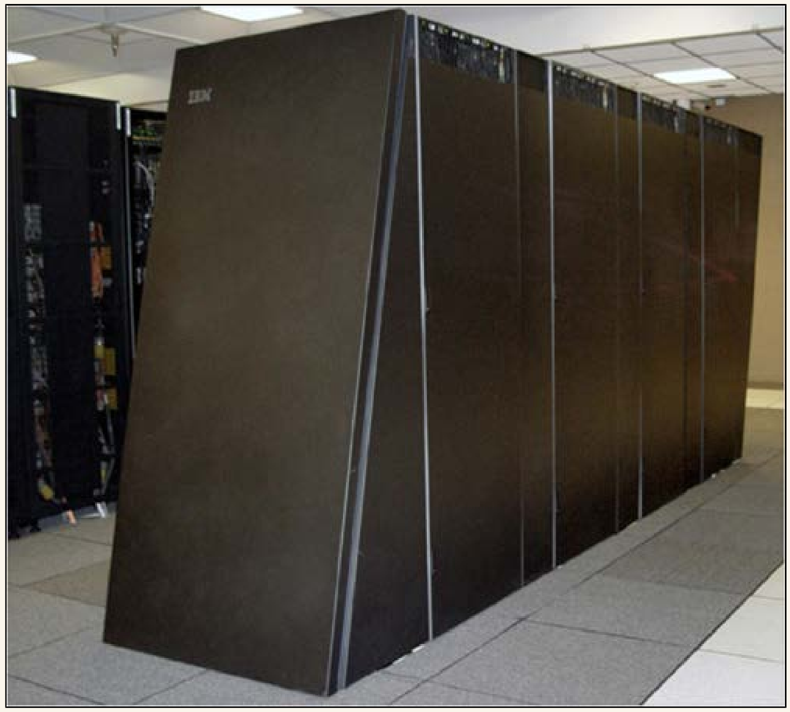
- Coordinated consistent security policies and procedures across UCAR by the Computer Security Advisory Committee (CSAC), with the goal of achieving the appropriate balance between reasonable protection and pursuit of the scientific mission of the institution
- Staff participation in the community-wide, NSF-sponsored Cybersecurity Summit 2009 held in September 2009
- Maintaining UCAR-wide token authentication which uses one-time password (OTP) tokens
- Placed increased importance on computer and network security when acquiring and configuring new equipment (computers, storage, network routers, etc.)
- Redesigned the in-house security training for system administrators throughout UCAR
- Produced a UCAR/NCAR Cybersecurity Strategic Plan for 2009-2012
- Completed implementation of OTP technology across UCAR including the new gateway to Bluefire
- Enhanced our aggressive network and host monitoring tools to support increased traffic loads and provide redundancy by taking advantage of our other campuses

To maintain a meaningful security posture and to fulfill CISL's near-term security objectives, the following plans for FY2010 are in place:

- Act in a leadership role at the NSF-sponsored Cybersecurity Summit 2010
- Engage in collaborative efforts with peer and TeraGrid centers to share cybersecurity information, best practices, and incident notification
- Optimize our central logging system to incorporate all of UCAR
- Develop a federated authentication system for TeraGrid users
- Implement Kerberos authentication for all UCAR/NCAR users requiring the use of passwords for internal resources

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

TeraGrid supercomputing operations



The recently expanded IBM Blue Gene/L supercomputer at NCAR, named Frost, is designed for high performance and low power consumption. With 8,192 processors in a single system, Frost provides a platform for CISL, NCAR, and TeraGrid collaborators to perform research and development that explores ways to use computers with large numbers of processors for geosciences research. In addition to serving NCAR's traditional charter as a resource provider for the atmospheric and related sciences, Frost serves researchers across a broad range of disciplines as a TeraGrid resource.

NCAR joined TeraGrid as a resource provider in June 2006. TeraGrid, sponsored by the National Science Foundation, uses high-performance networks and grid software to integrate supercomputers, data repositories, and special-purpose data analysis and visualization facilities through the United States. As a TeraGrid resource provider, NCAR makes a portion of its computational resources available to researchers that request cyberinfrastructure support from NSF through TeraGrid and participates in TeraGrid's quarterly allocation process.

NCAR operates a four-rack IBM Blue Gene/L supercomputer named Frost and its associated storage and visualization equipment as a TeraGrid resource. The original Frost supercomputer, consisting of a single-rack IBM Blue Gene/L system with 2,048 processors, was procured in 2005 in collaboration with the University of Colorado at Boulder and the University of Colorado at Denver. In 2008, Frost was enhanced with additional 10-Gbps networking infrastructure and an additional 110 TB of disk storage capacity. In 2009, Frost was expanded with three Blue Gene/L racks acquired from the San Diego Supercomputer Center; the resulting four-rack system consists of 8,192 processors and 22.8 TFLOPS peak performance. As a TeraGrid resource, Frost supports the TeraGrid Coordinated Software and Services (CTSS) stack, a collection of software installed across TeraGrid resources to present a consistent user experience across diverse systems. Frost is managed by the CISL Technology Development Division's Research Systems Evaluation Team (ReSET) commensurate with its original charter to serve as an experimental research system while also providing the availability and reliability required to serve as a production TeraGrid resource. Frost is shared between NCAR users, collaborative university users, and TeraGrid users, with roughly one-fourth of the system's available processing capacity allocated to the TeraGrid community.

As a resource supporting NCAR, university, and TeraGrid researchers, Frost must fulfill its research and development (experimental) and operational (production) requirements simultaneously. As a production resource, Frost supports NCAR researchers and collaborators investigating and addressing the technical obstacles to achieving practical petascale computing in geoscience and mathematical applications. Frost is also used as one of the primary computational resources for the University of Colorado's "High Performance Scientific Computing" course, annually providing 20-30 graduate and undergraduate students with direct experience on NSF cyberinfrastructure. Moreover, Frost provides the ability for NCAR and its collaborators to utilize, evaluate, and refine Grid computing environments for collaborative research. Frost's TeraGrid-compliant integration of computational, storage, and data analysis systems provides experience with these technologies and encourages NCAR to deploy the software required to support the distributed workflows conducted by scientists spanning CISL, NCAR, NSF, and Department of Energy supercomputing environments. The opportunity to experiment with systems like the Blue Gene/L in environments such as TeraGrid is essential for NCAR to maintain its ability to provide capability and capacity supercomputing for an increasingly distributed community.

Throughout FY2010, NCAR will continue to operate Frost as an NCAR and TeraGrid computational resource. On March 31, 2011, TeraGrid will be superseded by the NSF's TeraGrid eXtreme Digital (XD) program, and possible roles for CISL in this program will be investigated in the intervening year.

This work supports CISL's computing imperative to provision hardware cyberinfrastructure for the atmospheric and related

sciences. 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 NSF Core funding. The enhancements to Frost's storage system were funded by NSF Core funds. Frost's FY2009 expansion was made possible by NSF Special funds.

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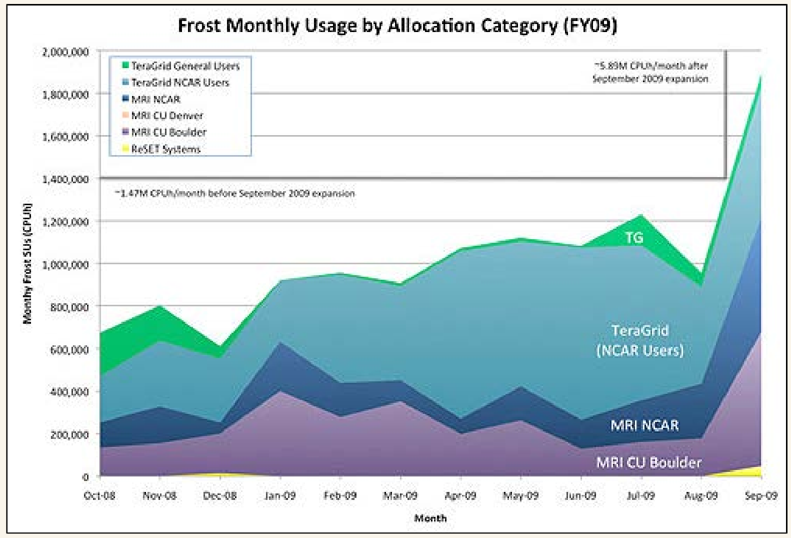
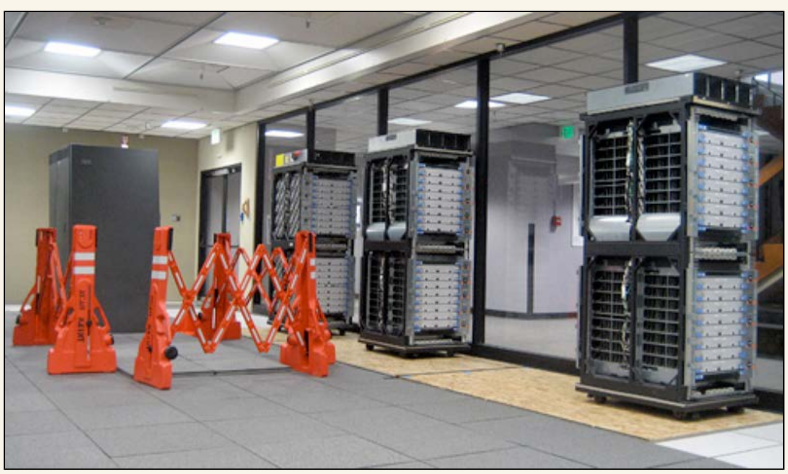
TeraGrid supercomputing status

NCAR's TeraGrid supercomputing environment consists of Frost, an IBM Blue Gene/L supercomputer with 8,192 processors, 110 TB of shared high-performance storage, and an associated visualization cluster (Twister). The Frost system, as well as its network and storage, are operated by CISL's Research Systems Evaluation Team (ReSET) as a production TeraGrid resource; the Twister visualization component is operated in conjunction with CISL's Data Analysis Services Group (DASG).



This graph shows Frost's monthly usage in CPU hours by its various user communities. Throughout 2009, Frost's utilization continued to increase and almost approached the system's capacity. In September, the system was expanded to four times its original size. In addition to the collaborators at NCAR and the University of Colorado that originally acquired the system through the NSF's MRI program, Frost is now increasingly used by researchers at NCAR and external institutions via TeraGrid infrastructure and allocations.

In early FY2009, NCAR planned to replace Frost with another supercomputing platform. The original one-rack Blue Gene/L system was purchased in 2003 under an NSF Major Research Infrastructure (MRI) grant and contained 2,048 processors. While analyzing competitive power-efficient computing technologies for the replacement system, NCAR had the opportunity to acquire three additional Blue Gene/L racks from the San Diego Supercomputer Center (SDSC) at minimal cost. Expanding the existing Blue Gene/L offered the most competitive solution in terms of power utilization and cost, providing 8,192 processors while using the existing front-end support systems and eliminating the inconvenience of user transition from one system to another.



In September 2009, three Blue Gene/L racks from the San Diego Supercomputer Center were connected to the existing single-rack Frost system (left rear) at NCAR. NCAR has accordingly increased the number of service units available for TeraGrid allocations by a factor of four to 16 M SU/year. NCAR intends to operate Frost and provide SUs to the TeraGrid until the end of the TeraGrid Extension.

Frost's user community consists of the collaborators at NCAR and the University of Colorado that acquired the original Blue Gene/L machine as well as an increasing number of TeraGrid users. About one-fourth of Frost's computational capacity is provided to the TeraGrid allocations committee for allocation to researchers seeking computational resources from the NSF.

Recently, NCAR scientists have also started to use Frost's TeraGrid capabilities to coordinate their collaborative research programs. Frost's TeraGrid-compliant computational platform easily integrates with resources at other TeraGrid resource providers. Thus, scientists performing simulations at other TeraGrid resource providers can coordinate their data analysis and visualization tasks using Frost. This is an example of how the integration of CISL resources with broader NSF cyberinfrastructure supports research in Earth System sciences.

As a production TeraGrid resource, Frost supports a user community spanning many organizations, so maintaining its uptime and availability are particularly important. Even though Frost has demonstrated a proportionately low hardware failure rate and robust management software suite since its delivery, ReSET continues to improve on the original system integration design and operational procedures to provide an increased quality of service to its user community.

In FY2009, the major causes of downtime were the scheduled half-day semi-annual machine room preventive maintenance periods, plus one week of downtime during the upgrade to four racks. In FY2010, ReSET plans to continue supporting Frost and its computational environment as a TeraGrid resource. As the system ages while still under heavy use, attention will be paid to updating and testing Frost's disaster recovery and data continuity plans. Specific areas of emphasis include leveraging NCAR's new HPSS archival storage system for system and user data backups and preparing spare resources for the few remaining single points of failure, allowing the system to be quickly returned to operation in the event of a hardware failure.

This work supports CISL's computing imperative to provision hardware cyberinfrastructure for the atmospheric and related sciences. 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.

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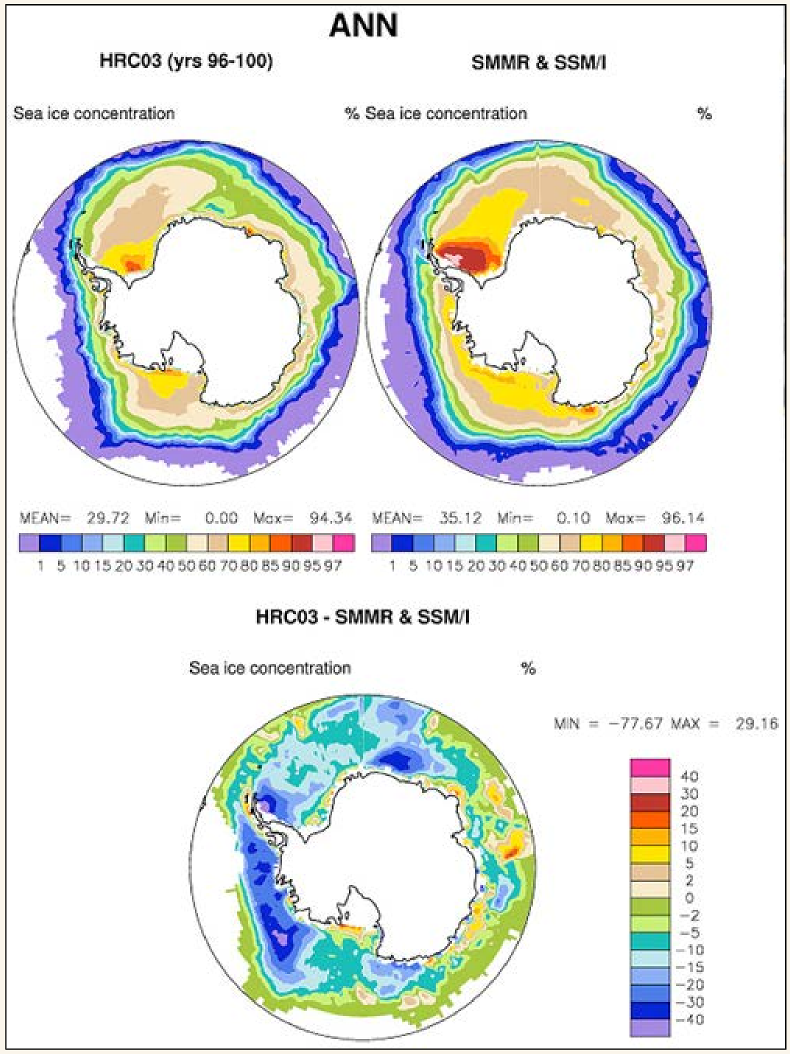
TeraGrid visualization server



This is a diagnostic image produced on Twister from an NSF-funded PetaApps project that studies the impact of high-resolution modeling on climate variability. The image compares modeled and observed concentrations of sea ice. Imagery such as this plays a critical role in the validation phase of this PetaApps effort.

As part of its involvement in the NSF TeraGrid (TG), CISL provisions computing resources to the TG community for simulation, and beginning in FY2009, analysis and visualization as well. In FY2009 CISL deployed its first TG data analysis and visualization (DAV) resource, Twister, an HP xw8600 workstation with 8 processing cores, 64 GB of memory, and hardware-accelerated graphics. The system shares disk storage with CISL's Frost HPC platform, enabling Frost users to analyze and visualize their data as soon as it is output from their simulations. Further, Twister provides a remote visualization service that permits users to access the machine's hardware graphics capabilities from virtually anywhere with a network connection.

Analysis and visualization is an integral component of the computational science workflow. By coupling a DAV resource with Frost, users are able to investigate model outputs without having to transfer their data to a separate resource.

Friendly user testing of Twister was completed in FY2009, and the system was announced as a production resource. To improve reliability and handle a greater user load, a second Twister node was procured. The new node is being readied for production and will be deployed in early FY2010. One of the largest user groups for Twister is an NSF-funded PetaApps project (NSF-0749206) exploring high-resolution climate simulations. In support of this effort, a GrADS data server was deployed in FY2009.

CISL will finish deploying the second Twister node early in FY2010. We will also substantially improve IO performance on the resource by migrating the shared file system from NFS to GPFS, and upgrading the storage system networking fabric from 1GigE to 10GigE technology.

This work supports CISL's computing imperative to provision hardware cyberinfrastructure for the atmospheric and related sciences. This work is supported by NSF Core funding.

Support for TeraGrid users

CISL continues to provide user services and support for the TeraGrid infrastructure on Frost, an IBM BlueGene/L system. We collaborated in planning, resource allocation, and accounting, and we extended our scientific computational tools to a broader scientific community.

During FY2009, we reviewed and handled 28 NCAR-related TeraGrid user tickets. CISL Consulting Services also provided dedicated consulting support for users with MRAC allocations. We assisted CISL personnel in notifying users of the availability of a new storage resource, the High Performance Storage System (HPSS). We participated in weekly Services-WG teleconferences and coordinated NCAR-related documentation on the TeraGrid portal, handling requests for documentation upgrades or corrections.

Late in FY2009, following an extended friendly-user period, CISL deployed a production TeraGrid Data Analysis and Visualization (DAV) Resource named Twister. User support for the new resource was provided in an ad-hoc manner by CISL's Data Analysis Services Group. Consulting Services also provided documentation for the new DAV resource in the Frost user guide. In FY2010, a formal user support mechanism, more consistent with CISL's broader TeraGrid support policies, will be established in conjunction with the deployment of the new NCAR resource.

With the increase in users who compute at multiple centers across the TeraGrid and other HPC centers, higher-speed data transfer capability is becoming more critical. During the past year, CISL has gained expertise in GridFTP, a TeraGrid tool that enables data transfers to be done in parallel. Early use has shown data transfer rates up to 80 times faster than previously. We have written documentation to help NCAR users familiarize themselves with this tool on our Frost and Bluefire systems, as well as instructions for installing it on user workstations.

In FY2010, we plan to continue working with CISL's High Performance Systems Section staff to help users transition smoothly from the NCAR Mass Storage System to HPSS. We will also continue porting, scaling, and validating NCAR flagship models such as CCSM4 and WRF on non-NCAR TeraGrid resources. We presented a poster, "Performance and Scaling of WRF and CCSM on Ranger, Hydra, and Bluefire," at the 2009 LCI Conference to share our previous work in this area.

CISL's contribution to the TeraGrid relates to multiple areas of the CISL Strategic Plan. CISL's computing imperative for facilities is to deploy and operate the physical and virtual computational facilities needed to support the science community, which involves integration with others to create virtual facilities. CISL's computing frontier in center virtualization involves developing Grid-based technologies to support and enhance the development of virtual organizations. Finally, CISL's computing imperative to provision hardware cyberinfrastructure includes operation as a TeraGrid Resource Provider at least through the end of the TeraGrid Extension. Consulting support for TeraGrid users is supported by NSF Core funds.

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Computing Imperative: Software Cyberinfrastructure

CISL develops and supports software infrastructure specific to the simulation, analysis, and forecasting needs of the atmospheric and related sciences. This software infrastructure includes modeling and data assimilation frameworks; software for accessing, comparing, and exploring data through science gateways; and data analysis and visualization software for climate, weather, and turbulence applications. CISL prioritizes opportunities to provide the stability and long-term support necessary for transitioning software research projects to supported infrastructure. The prioritization criteria include: the SI's importance to NCAR's mission, dependencies of other infrastructure on its continuation, and the SI's adherence to CISL's strategic principles.

Earth System science discipline-specific software cyberinfrastructure

Part of CISL's research in numerical methods and data assimilation has naturally led to several mature codes and environments that support community research. The Data Assimilation Research Testbed (DART) is an extensive software environment, running on many different platforms, that supports ensemble data assimilation for geophysical models. DART supports a wide variety of geophysical models including NCAR's weather and climate models for the atmosphere. Because of its modular design and the computational benefits of ensemble filter methods, DART can incorporate new models with far fewer software engineering resources than traditional assimilation methods.

In FY2009 DART has been extended to the POP ocean model, and the next release will support the assimilation of oceanographic observations. Another milestone is a MATLAB hands-on tutorial of DART for teaching data assimilation.

Plans for 2010 include a major new version that will improve performance on large numbers of processors and more accurate handling of observations at irregular times. With DART's emphasis on ocean/atmosphere data assimilation, support for DART's scientific applications will continue to expand.

TeraGrid software infrastructure at NCAR

In Project Year 4 (PY4) of the TeraGrid (roughly corresponding to FY2009) CISL performed two projects partially funded by the TeraGrid Grid Integration Group, but with substantial co-sponsorship from CISL's Core funding. The first project, building a test environment for ESMF, leverages the existing nightly build system of the ESMF, a leading community-developed software infrastructure focused on coupling high-performance, multi-component Earth System applications.

The second project relates to building a TeraGrid Astroseismic Modeling Portal (AMP) to better understand the Sun because it plays a critical role in improving our understanding the Earth's climate. Until recently, scientists have had only one example to study in detail – the Sun itself. In February 2009, NASA successfully launched the Kepler satellite, which has begun acquiring data on oscillations in hundreds of Sun-like stars. Interpreting these observations using state-of-the-art stellar models will be a significant challenge but will yield important information such as stellar diameters, which in turn can be used to determine the diameters of planets found by Kepler to within 3%. A team led jointly by the High Altitude Observatory (HAO) and CISL has designed and deployed AMP on the TeraGrid to lower the data analysis barriers. ASG will model stellar parameters using a proven but computationally expensive parallel genetic algorithm.

FY2009 accomplishments

TeraGrid Build Test Environment for ESMF: The TeraGrid Build and Test service was enhanced in FY2009 to run required nightly tests on multiple TeraGrid systems from a single submit platform. Test scripts have been installed on Cobalt, Lincoln, NSTG, and Lonestar. Further progress developing build and test services for ESMF on other TeraGrid resource has been stymied by technical problems with the website build:teragrid.org .

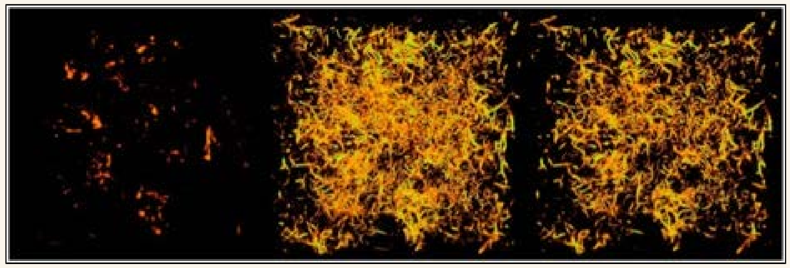
Asteroseismic Modeling Portal (AMP): AMP, a web-based interface provided to a broad international community of researchers to simplify model execution, data sharing, and analysis of asteroseismic data, was deployed for testing in early FY2009. NASA's launch of the Kepler satellite in March 2009 paved the way for a successful allocation request for 1.5 M CPU-hours in TeraGrid computing resources to support the AMP science gateway.

FY2010 plans

In FY2010 NCAR will use PY-4 GIG carryover funds to provide support for the AMP gateway until this support service can be transitioned to staff supported by NSF Core funds. Also in FY2010 (TeraGrid PY-5 plus part of the TeraGrid Extension period), NCAR's GIG funding will shift to three new projects:

- VAPOR support for TeraGrid objectives: Funding from the TeraGrid Data and Visualization area will be devoted to VAPOR software development. Specifically, NCAR will:

- Develop and support a public, parallel API for reading and writing Cartesian gridded data into VAPOR's current wavelet-based progressive data access (PDA) format. This API will enable in situ data encoding from a running simulation (or via a standalone parallel translator), and will permit extant scalable tools (e.g., ParaView and VisIt) to readily exploit progressive data access to substantially improve their own scalability.
- Develop a prototype next-generation PDA scheme based on our promising research results in wavelet coefficient prioritization. The new scheme offers far greater data reduction than the current multi-resolution approach at comparable fidelity, or improved fidelity at the same level of data reduction.



A volume rendering of the enstrophy field from a fully developed $1{,}024^3$ homogenous turbulence simulation, compressed by a factor 512:1. Shown from left to right are: compression with VAPOR's current, multiresolution scheme; the original, uncompressed data; and the field compressed with the proposed coefficient prioritization scheme to be developed and deployed in VAPOR with FY2010 TeraGrid GIG funding.

- Science gateway for the Earth System Sciences on the TeraGrid: In FY2010, NCAR will use TeraGrid Science Gateway funds throughout the year to build a prototype Earth System science gateway. This work will be done with Purdue University, which will receive an equal amount of funding. The activity will leverage existing gateway efforts, including the Earth System Grid (ESG), Earth System Curator (ESC), Earth System Modeling Framework (ESMF), the Community Climate System Model (CCSM) climate portal developed at Purdue, and NCAR's Science Gateway Framework (SGF) development effort. NCAR will work with Purdue to:
  - Extend the Earth System Grid-Curator (ESGC) science gateway so that Community Climate System Model runs can be initiated on the TeraGrid
  - Integrate data publishing and wide-area transport capabilities such that model run datasets and metadata may be published back into the ESG, from both the ESGC and Purdue's CCSM climate portal
  - Investigate and prototype an interface that allows ESG to federate with Purdue's climate model archives, such that Purdue holdings become visible and accessible as part of the ESG collections

  The end result of this work will be one or more gateways that provide access to integrated modeling, data management, search, browse, analysis, and visualization functionality for climate research, effectively harnessing TeraGrid resources and engaging new users.

- Geosciences SG support: After April 2010, additional TeraGrid funds will become available to provide grid technology support to the TeraGrid's Science Gateway Area Director for the geosciences. The details of these projects are currently undetermined.

Support

CISL's computing imperative for software cyberinfrastructure is primarily supported by NSF Core funding, with supplemental funding supplied by other sources as noted in this and the following reports.

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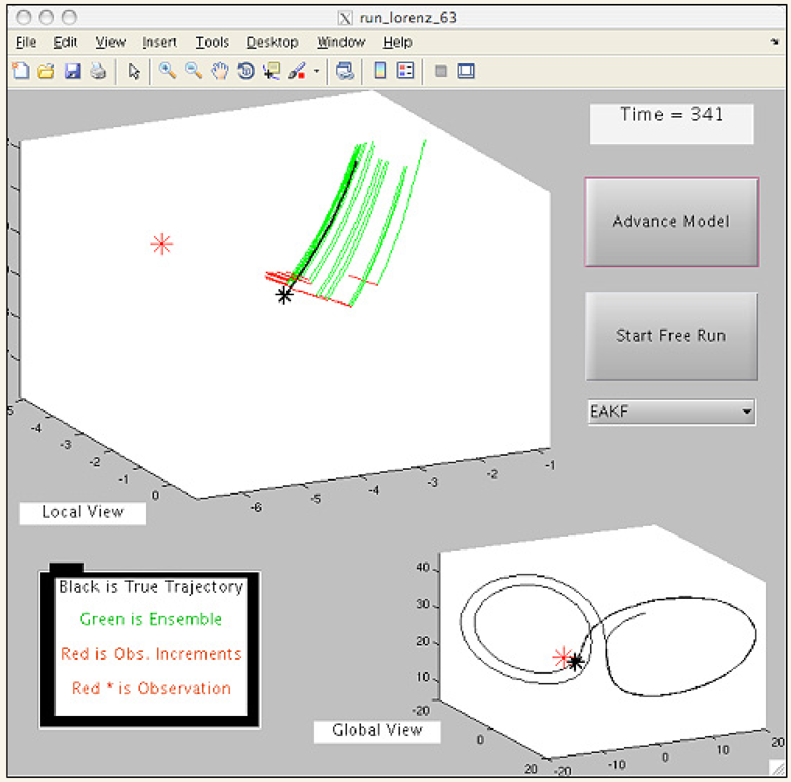
Data assimilation research

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 doing 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.



A Matlab graphical user interface (GUI) from the new DART interactive tutorial. The evolution of a set of 20 ensemble members (green in the central part of the panel) and the impact of an observation (red) in the middle of an extended assimilation are displayed. This GUI allows users to interactively explore an ensemble Kalman filter assimilation using the three-variable Lorenz 1963 model.

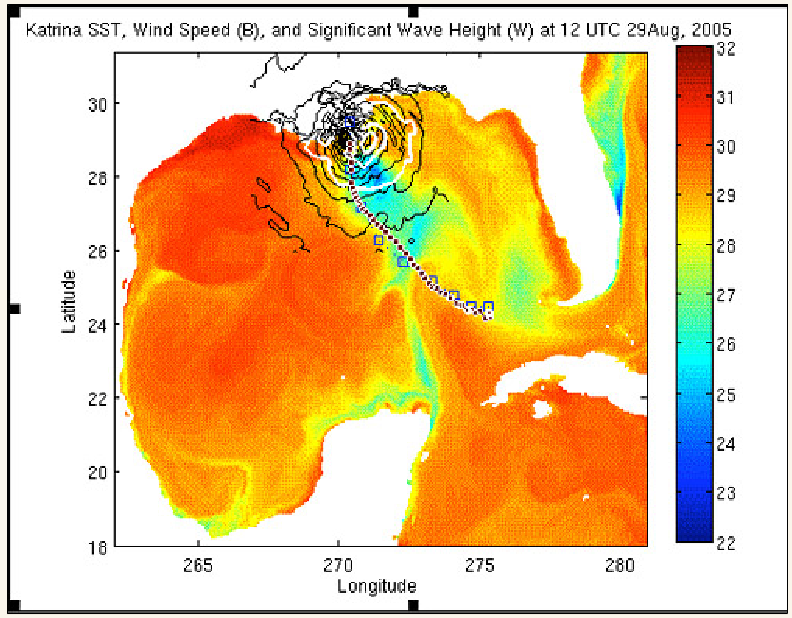
The DART software is continually upgraded and improved. During FY2009, DAReS has supported the incorporation of three new large geophysical models: the POP ocean model developed by the Los Alamos National Laboratory and NCAR/CGD, the WRF/CHEM regional chemistry model, and a version of the ECHAM global atmosphere model developed in Germany and used for climate prediction by a number of organizations. Tools to process and assimilate surface wind observations for QuikSCAT and temperature and moisture retrievals from AIRS were developed and tested. The tools for assimilating radar reflectivity and doppler velocity were significantly improved. Significant improvements to the DART tools that allow processing and diagnosis of observations were also completed. A new Matlab-based tutorial on the DART ensemble filtering algorithms was developed and presented at several workshops and universities. The new tutorial uses a series of interactive Matlab GUIs to introduce students to ensemble methods and DART. A comprehensive new web page documenting DART was developed and released in concert with the cover article for the September 2009 issue of the *Bulletin of the American Meteorological Society*.

A new major release of DART is planned for FY2010. Many of the planned enhancements are focused on improving the performance of DART on large processor counts for large models. Features to allow improved control of assimilation experiments will also be included. A major enhancement to the core algorithms will allow forward operators for observations to be interpolated to the time of the actual observation which should result in enhanced assimilation quality for most DART users.

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 and NASA Grant NNX08A23G.

Earth System Modeling Framework integration with models

The Earth System Modeling Framework (ESMF) was motivated by the growing complexity of developing Earth System models. These are constructed of separate software components representing physical domains and processes; for example, atmosphere, ocean, and sea ice. The components, which are often developed at separate sites, are coupled into integrated systems on supercomputers to create realistic simulations. To make this process easier, ESMF provides standard component interfaces and high-performance tools for common functions, such as grid interpolation. Now in its seventh year, the ESMF project has transitioned from NASA funding to multi-agency support. ESMF is the chosen infrastructure for the consortium of U.S. operational weather and space weather prediction centers (known as the National Unified Operational Prediction Capability, or NUOPC), the DoD Battlespace Environments Institute, the NASA Modeling Analysis and Prediction Program, and a host of smaller programs and projects.



This image shows a Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) 48-hour simulation of hurricane Katrina. The three-way coupling between COAMPS, the Navy Coastal Ocean Model (NCOM), and the Simulating WAves Nearshore (SWAN) model is achieved through ESMF. This simulation uses three atmospheric domains, two ocean domains, and one wave domain. The innermost atmospheric nest automatically translates along with the storm. COAMPS predicts a cold sea surface temperature anomaly (degrees C, color shaded area) to the right of the hurricane track in response to the passage of the hurricane's high wind speeds (m/s, black contours). The significant wave height (m, white contours) shows increased wave growth on the northern quadrant of the hurricane due to wind-wave-current coupling effects. The white squares denote the observed location of the eye at six-hourly intervals, and the dotted line denotes the model location of the eye at hourly intervals beginning at 1200 UTC 27 August. Image courtesy of Sue Chen, Naval Research Laboratory.

ESMF is a key element of a U.S. modeling strategy, expressed in National Resource Council and other reports, aimed at enabling federal centers and research institutions to leverage shared resources, to combine and exchange components from different centers, and to create a more inclusive and distributed approach to modeling.

During FY2009, the ESMF team built rapidly on central data structures that had been redesigned for greater flexibility during the previous two years. One of the highlights of a new public release, ESMF 4.0.0r, was a remapping utility that produces interpolation weights, in parallel or serial, 2D or 3D, for grids that can be represented by triangles or quadrilaterals (tetrahedra are not yet supported). The remapping utility supports bilinear or higher-order weights; a conservative approach is being developed for release next year. Other development focused on enabling ESMF applications to interact with models of regional processes. The ESMF team has been interacting closely with the data services community via the Earth System Curator project to create workflows that span modeling and data services.

Adoption of ESMF capabilities by NCAR models continued this year. ESMF higher-order interpolation weights were adopted by CCSM to reduce interpolation noise, and options for ESMF interfaces were included on all CCSM components for the next public release of the model, CCSM4. A WRF-LIS coupled system was developed for operational use at AFWA. Many other applications used ESMF coupling services and utilities.

In November 2009, the ESMF team will move to the NOAA Earth System Research Laboratory (ESRL) and the Cooperative Institute for Research in Environmental Science (CIRES). Collaborations with NCAR, including the CCSM, WRF, IMAGe, and the CISL Visualization and Enabling Technologies Section, are expected to continue. In FY2010 ESMF will extend capabilities related to grid support and remapping, and will introduce ease of use and interoperability improvements.

The ESMF project advances 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. This work also fulfills CISL's strategic action item to integrate ESMF with other NCAR infrastructure. ESMF is funded by NSF Core funds with support from the Department of Defense, NASA, and NOAA.

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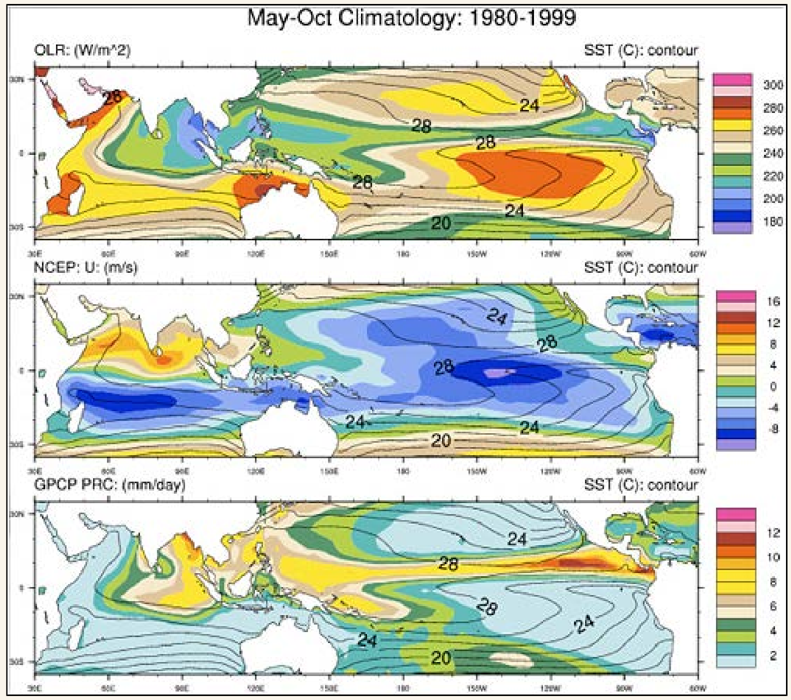
Community data analysis and visualization software



This image shows NCL output from diagnostics developed by the U.S. Climate Variability and Predictability Research Program (CLIVAR) to objectively evaluate the Madden-Julian Oscillation (MJO). This visualization illustrates a supplemental diagnostic known as the "mean state." These diagnostics hold promise for guiding future model testing and improvement as well as increased sub-seasonal forecast skill.

The NCAR Command Language (NCL) is a data analysis and visualization environment developed primarily at NCAR/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 systems to high performance computers. PyNIO and PyNGL are Python modules based on NCL's file input/output and visualization capabilities, thereby enabling NCL's software components to be exposed 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.

NCL, PyNIO, and PYNGL are used for data analysis and display in many graduate-level courses, for generating publication-quality visualizations in geoscientific 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 for their thesis 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. Since releasing NCL under a fully open source license in November 2007, the annual number of NCL downloads increased by 44% (20,652 downloads) in FY2009 over FY2008, the number of registered users increased by 46% (7,779 users), and the traffic on the main email list—with 958 subscribers—increased by 41%.

In FY2009 CISL released two versions of NCL that contained support for the highly requested "shapefile" data format, other geospatial formats, and the HDF5-EOS format. NCL capabilities were successfully blended with VAPOR to allow quantitative visualizations to be composited into a 3D scene, and this work contributed to the open-source geotiff library. A suite of NCL functions for analyzing WRF-ARW data was enhanced to include new specialized calculations, and these functions are now in heavy use by the WRF community. A number of NCL applications were developed for analyzing specialized datasets, including high-resolution precipitation data, satellite swath data, and GODAS data. A suite of highly used core analysis functions in NCL was overhauled to prevent unnecessary data copies, significantly decreasing memory requirements and improving speed. Full research into NCL's performance and memory issues was put on hold until after support for new data formats and required data types was added in late FY2009. Wider adoption of these tools continued to grow, and the NCL/Python team was invited to give introductory tutorials at the annual TeraGrid meeting in Washington DC, the annual CCMVal meeting in Toronto, a WRF workshop in Boulder, and a NetCDF conference in Boulder.

The top development priorities in FY2010 are to 1) further address memory and scalability issues, in particular, the handling of large (> 2 GB) arrays, 2) add transparent access to data in netCDF (V4) and HDF (V5) format, 3) upgrade an aging display model by allowing transparency and more fluid use of color tables to expand visualization capabilities, and 4) modernize PyNGL and PyNIO software to reflect changing Python trends. Other NCL/Python priorities are derived from collaboration with a number of core scientific groups and projects. These include preparation for CCSM-based IPCC-AR5 studies, development of new visualization and analysis capabilities for WRF, ICON, and other Earth System models and datasets, and integration of NCL with the Earth System Grid.

This work strengthens 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: NCL, PyNGL, and PyNIO. Our development and deployment of community tools and frameworks for geoscientific analysis and visualization are supported by NSF Core funding.

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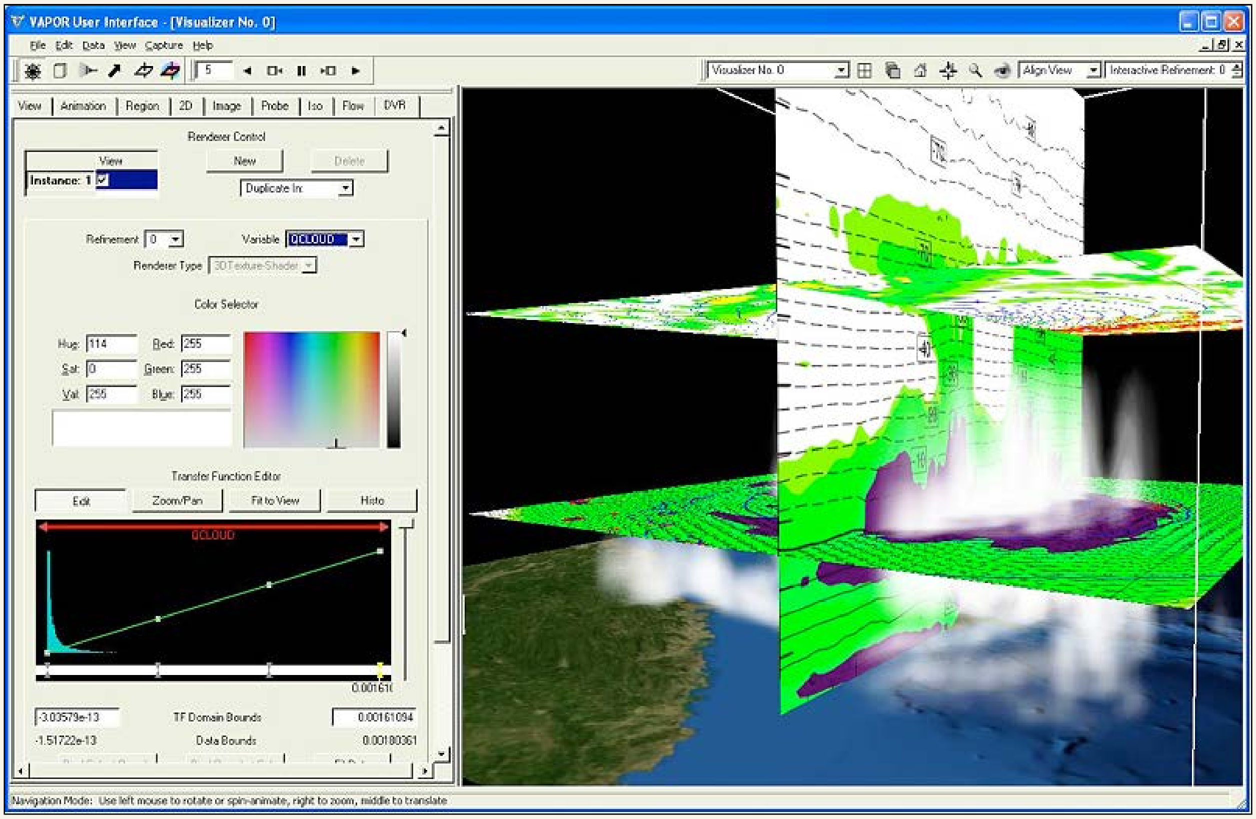
VAPOR visualization software for very large datasets



This image highlights the past year's efforts to couple the capabilities of CISL's VAPOR and NCL packages and provide support for geo-referenced data and imagery. The horizontal and vertical planes were generated by NCL, the satellite image was imported from a Web Mapping Service, and the volume rendering and integration of these separate data sources was performed by VAPOR. Incorporating geo-referenced information is critical to aiding VAPOR users who analyze geo-spatial data.

The Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers (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, Davis and the Ohio State University. VAPOR has transitioned from a research project to a production product. 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 System scientists from around the world. The steering committee sets development priorities, dictates software requirements, and serves as friendly users for testing and evaluating new software features. Unique to VAPOR are 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.

Two major new releases of VAPOR were completed during FY2009. Both releases had a strong emphasis on broadening VAPOR's appeal to the NSF science community by providing numerous new features aimed at supporting numerical weather simulation and other atmospheric science domains with geo-referenced data. The second release also made significant strides toward coupling the capabilities of VAPOR with NCL, CISL's 2D analysis package. The VAPOR team was also successful with two research proposals (NSF-09-06379 and TeraGrid GIG PY5) that will supply additional staff members for the project. The VAPOR user community continues to grow, and VAPOR was cited in over 20 scientific scholarly articles published in the past year.

In FY2010 CISL will continue efforts to expand VAPOR's capabilities to support a broader atmospheric sciences community, particularly numerical weather researchers. Efforts will also focus on satisfying contractual requirements of our research grants, such as incorporating VAPOR's progressive access data model into other visualization tools, developing a next-generation data model that offers more aggressive compression, and providing a parallel API that supports in situ output of VAPOR data from a

running simulation.

This work strengthens 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 develop VAPOR visualization capabilities for very large datasets. Further, this work advances CISL's strategic imperative to produce scientific excellence by preparing a foundation for petascale and exascale computing. This project is supported by NSF Core funds, NSF-09-06379, and a TeraGrid GIG PY5 award.

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Science Gateway Framework from ESG and CDP infrastructure

The NCAR Cyberinfrastructure Strategic Initiative (CSI) was originally proposed as a collection of strategic activities that spanned data and knowledge management, collaboration environments, and advancing our web presence. Having accomplished our goals and realizing production capabilities in the latter two, our primary focus is now on advancing data and knowledge environments and aggressively developing our opportunity space in this and related areas. The CSI effort currently funds a collection of strategic and opportunity-development activities, along with core foundational thrusts including the development of the ESKE Science Gateway Framework (SGF) and the Community Data Portal (CDP). Our overarching goals are to build the cyberinfrastructure, integrate and extend the Information Technology, develop the critical relationships and projects with scientific and educational projects, and foster the development of human resources and culture to further advance our Earth System Knowledge Environment (ESKE).

This image shows an alpha version of the new Earth System Grid Center for Enabling Technologies (ESG-CET) gateway, which is built on the Science Gateway Framework (SGF). Gateways such as this will provide access to comprehensive CCSM results, along with access to federated data holdings that span the WCRP CMIP enterprise, and constitute the data foundation for a portion of the upcoming IPCC AR5 effort. Federated scientific data systems such as this are essential to the advancement of global climate change science.

The Science Gateway Framework (SGF) is a major software development effort aimed at building shared cyberinfrastructure for supporting several important data and knowledge management initiatives. The primary drivers for this effort include the Earth System Grid, CADIS, and the Community Data Portal, and each of these presents common, as well as unique, requirements for community data management and access.

The new SGF will include support for virtual organizations via authorization groups and theme-based branding/skinning; federated identity based initially on the emerging OpenID standard along with federated authorization; search and browse functions based on Semantic Web technologies; access to MSS/HPSS holdings; metadata, ontology, and semantic support; federation/interoperability with ESG, THREDDS, WMO, GCMD, Google Earth, etc.; and support for a wide variety of digital object types. The result will be an Open Source software product that serves ESG-CET, WCRP-CMIP, IPCC-AR5, CADIS, WMO, and the CDP. Our first production release will occur in early CY2010, as CMIP/IPCC data products begin appearing. Addressing requirements arising from the upcoming CMIP/IPCC endeavor, we invested heavily this year in developing strategies for dealing with the important and complicated issue of dataset versioning and citable digital objects. We also continued to advance our capabilities in the area of metadata federation, drawing on earlier work with the Protocol for Metadata Harvesting developed by the Open Archives Initiative (OAI-PMH). Gateways built on the SGF will also be able to use OpenID federated identity management approaches, and we have demonstrated a cross-gateway single-sign-on capability. To reinforce the foundation for all of this, we have heavily invested in strengthening our software engineering process, including a continuous integration process, an integrated issue-tracking system, and movement toward an Agile software engineering paradigm.

In FY2010 we will deploy the SGF for ESG, CADIS, and CDP. CDP will include operational capabilities for CMIP5 and IPCC-AR5. New capabilities in the area of dataset versioning will be released and evaluated, and overall, we will spend much of the year evaluating community feedback and enhancing the software in response. Drawing on support from the TeraGrid-supported CCSM Science Gateway project along with the new NOAA Global Interoperability Program (GIP), we will continue to refine our capabilities for semantic query, the integration of modeling and data management, and support for collaborative group endeavors.

This work strengthens 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 supports 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 provides advances in CISL's science frontier for understanding large and heterogeneous data sets. This project is supported through NCAR Strategic Initiative funding and NSF Core funding, augmented by specific project support as described throughout this report.

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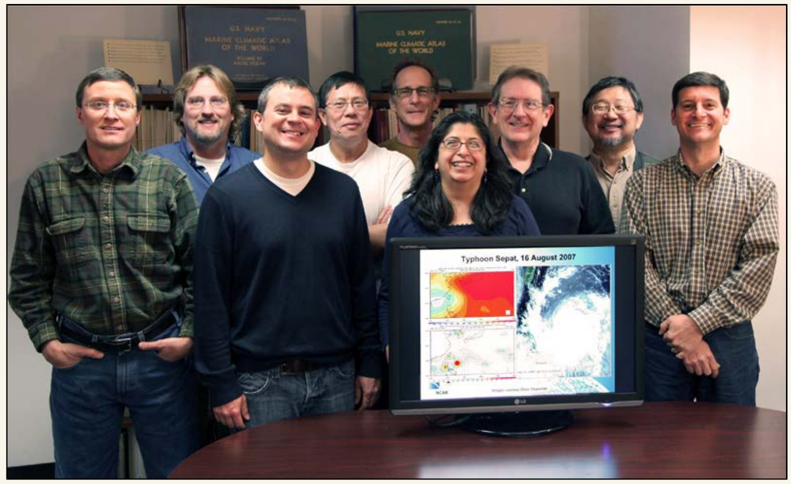
Computing Imperative: Data Curation

The important role of scientific data archives in supporting NCAR research is recognized as significant. Professional data curation and stewardship greatly amplifies the value of the data for science. These services assure good quality data with complete documentation, long-term preservation, easy access, and knowledgeable data experts to fulfill a variety of consulting and service functions.


CISL's Data Support Section staff actively manages the 246-TB, 580-dataset Research Data Archive (RDA) at NCAR. It has gained international prominence through dedicated development and stewardship. The RDA is known as a world data resource on the web that supports scientific studies in climate, weather, Earth System modeling, and increasingly other related geosciences.

CISL, including its predecessors, has a 40-year history dedicated to data curation that benefits users at NCAR, within the UCAR university community, and national and international research teams. Today these activities are realized as developments of the Research Data Archive (RDA) as a whole, and of one of its notable large subsidiary projects THORPEX Interactive Grand Global Ensemble (TIGGE).

Data curation is a computing imperative in CISL's Strategic Plan. The significance of NCAR's collection of research data for the worldwide community is evident in the usage and growth of this open resource. RDA maintenance and development within CISL is supported entirely by NSF Core funding.

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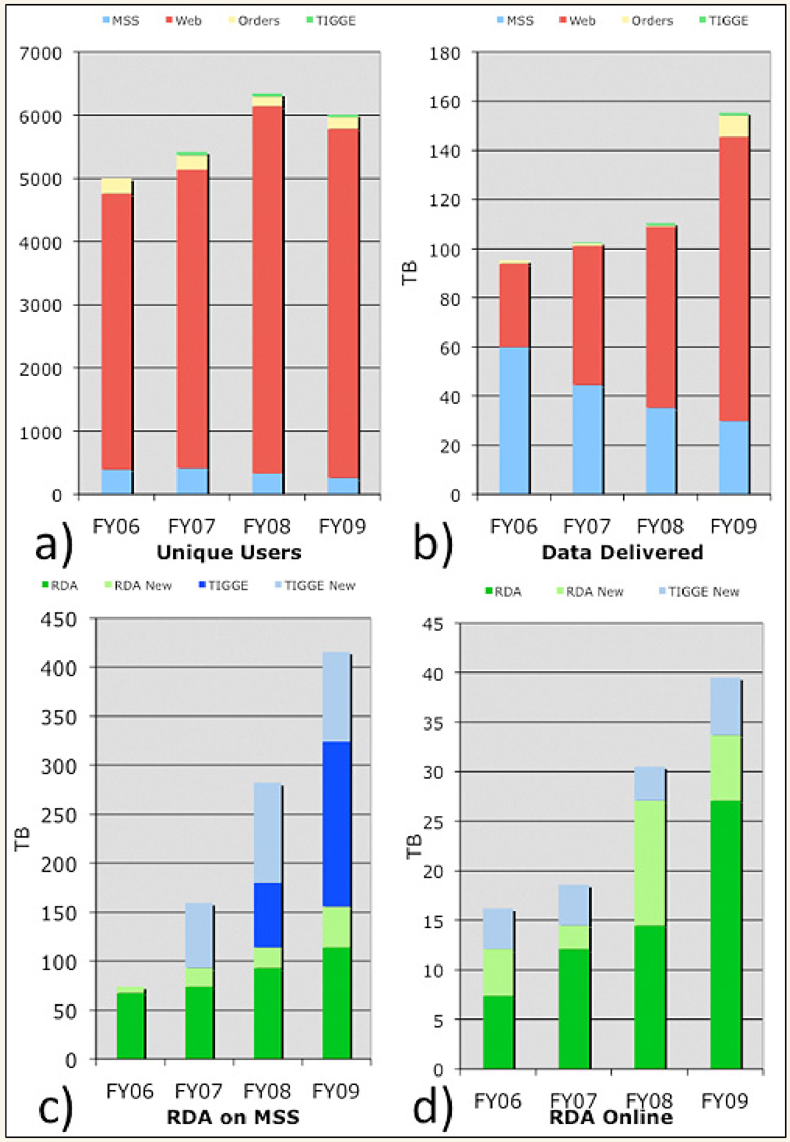
Research Data Archive

The Research Data Archive (RDA) is a key part of the CISL Strategic Plan computing imperative for data curation, because it provides an information resource through a large collection of datasets that support scientific studies in climate, weather, Earth Systems modeling, and increasingly other related geosciences. 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 worldwide 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-FY2009:
a) The number of unique users specified by access pathway: the NCAR MSS, 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 MSS archive, showing annual growth.
d) The amount of data on public 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 FY2009, about 6,000 unique persons were provided 155 TB of data through various primary access pathways: the NCAR MSS, 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). The web user group is the largest; 5,500 people downloaded 115 TB of data. The number of users who access the data directly at NCAR from the MSS is smaller, but their per capita data access amount is higher, 260 individuals and 30 TB, respectively. On average, each MSS user accesses six times as much data as a Web user. These metrics indicate that the RDA is known as a world data resource on the web, and when it comes to accessing large significant reference datasets, working directly on CISL computational resources is more effective.

A simple measure of data content development is archive growth. The RDA expanded by over 130 TB in FY2009 (see chart c). TIGGE is part of the RDA, but it is shown separately because it alone added 92 TB. This overshadows the 42 TB increase in the remaining part of the RDA, which is nevertheless very important and doubled in size from the previous year (chart c). The most-requested datasets from the RDA are available online through web servers. The current online data is about 40 TB (chart d), an increase of 10 TB over the previous year. Again, TIGGE is shown separately and does not change much between years because it is capped at a rolling three-week archive with only the most current data. Older TIGGE data are copied and managed from the MSS.

As a whole, the RDA is constantly changing, curation extends and adds to existing datasets, stewardship improves the documentation, creates systematic organization, applies data quality assurance and verification, and develops access for the users. Many routine tasks and background infrastructure developments are necessary to maintain the RDA. Some of the major accomplishments for FY2009 were:

- Daily data acquisition from NCEP has been expanded and reconfigured using robust standardized scripting with database monitoring. This is a key improvement because these data are heavily used to support WRF research worldwide.
- Operated and maintained the TIGGE Archive and access on a 24×7 basis.
- Applied data corrections to historical upper-air sounding datasets as part of an effort that will lead to seamless user access to all RDA soundings.
- Received and began deploying and calculating high-resolution gridded products for the ERA-Interim Reanalysis from ECMWF. Although not 100% service ready now, it is already being used by several major projects.
- Published and now fully supporting access of ICOADS Release 2.5 and for the first time continuing monthly updates.
- Published and now fully supporting the 20th Century Reanalysis, Version 1.0.

Some major activities for FY2010 will include:

- Transition the RDA development and services to a new set of systems as part of the CISL Data Services Redesign initiative. This has the potential to transform the RDA to higher capabilities in data receipt, server-side computing resources applied to meet user data requests, and rapid access to the entire RDA at NCAR and across the network.
- Complete deployment of ERA-Interim and its ongoing extension.
- Receive and publish the 20th Century Reanalysis, Version 2.0.
- Establish and begin action with NCDC and NCEP to received CFSRR (Climate Forecast System Reanalysis and Reforecast) data at NCAR.
- Open user access to a new upper-air sounding database within the RDA.

Strength for the RDA is that its staff, data management practices, and ability to positively effect outcomes in the data arena is nationally and internationally respected. This position is a great advantage when building collaborations that continually strives to provide better scientific data resources and access.

RDA maintenance and development within CISL is supported entirely by NSF Core funding.

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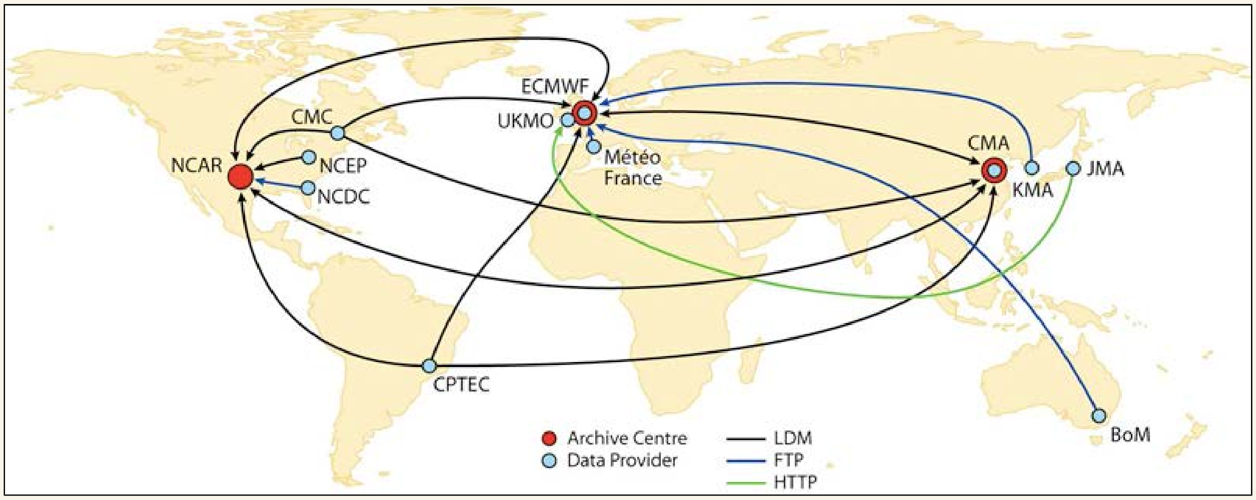
THORPEX Interactive Grand Global Ensemble (TIGGE)



TIGGE Archive Centers (NCAR, ECMWF, CMA) and numerical ensemble weather forecast data providers. The various data transfer methods used in the TIGGE wide area system include Local Data Manager (LDM), File Transfer Protocol (FTP), and Hypertext Transfer Protocol (HTTP). Usage of the TIGGE archive was promoted at the 2009 AMS Annual Meeting and the 2009 THORPEX Science and TIGGE Users Workshop.

The NCAR TIGGE Archive functions in collaboration with two other near-identical centers at the European Centre for Medium-range Weather Forecasts (ECMWF) and the China Meteorological Administration (CMA). Ten globally distributed ensemble weather prediction centers provide data to the TIGGE archive in real time and 24×7. The NCAR TIGGE system is a range of software, hardware, and network communications that receive, archive, and provide user access to the data. The development work began in FY2006 and was completed in FY2009. The growth of the archive is substantial, 245 GB/day.

Briefly, the TIGGE 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 or Climate Forecast-compliant netCDF. To make the system more stable, new servers and additional storage were added in FY2009, and several phases of software development were applied to harden the complex schemes against faults and to build in more automatic recovery processes.

The availability of this weather forecasting research archive has been advertised with articles in EOS, BAMS (submitted and accepted), and at user workshops in FY2009.

The FY2010 objectives for TIGGE are:

- Continue to advertise and prompt usage of the TIGGE Archive for weather research.
- Maintain all aspects of its real-time and archiving operations.
- If possible, enhance data access by offering users customized data extraction from the >250 TB archive. This requires data access rates much higher than currently available from the MSS and dedicated portions of data analysis computing clusters.
- Adapt the system to accommodate TIGGE designed and derived products such as tropical cyclone tracks and extreme precipitation consolidated regional forecasts.

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. TIGGE maintenance and development within CISL is supported entirely by NSF Core funding.

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Science Imperative: Scientific Excellence

The research activities within CISL support scientific computation, numerical methods, geophysical modeling, and the analysis of geophysical data and model experiments. This research is important to maintain an innovative computational and modeling facility at NCAR, and more broadly, to lead the geophysics community in adopting new computational methods and mathematical tools that enhance scientific research. 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. The projects highlighted for this imperative reflect the breadth and quality of this scientific research.

With NCAR's Mesa Laboratory in the center of this photo and NCAR's S-Pol weather radar at the Marshall Field Site in the lower left corner, this panorama of Colorado's Front Range at Boulder provides an iconic image for the scientific questions that motivate the basic research reported in CISL's science sections. The complex topography and ecological diversity in this image suggest the many physical processes that shape our environment. The challenge to computational science and applied mathematics is to simulate these processes directly, when possible, through increasing resolution and more elaborate physical models. Equally important is to use mathematical and statistical approaches to quantify our limited understanding of the Earth System. For example, the observational record for this region is limited to a small number of scattered weather stations. Moreover, state-of-the-art global climate model simulations have spatial resolutions that reduce this entire panorama to just one or two grid points. We are faced with uncertainties not only about the past and future climate for this region, but even about quantifying the details of our present climate. Thus, this image suggests two themes of CISL's research: modeling complexity in physical processes and handling the uncertainty in these processes when they are not well resolved or observed. Photo courtesy of UCAR Digital Image Library.

CISL's science imperative for scientific excellence is primarily supported by NSF Core funding, with supplemental funding supplied by other sources as noted in the following reports.

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NCAR Annual Report | ASP report | CISL report | EOL report | ESSL report | RAL report

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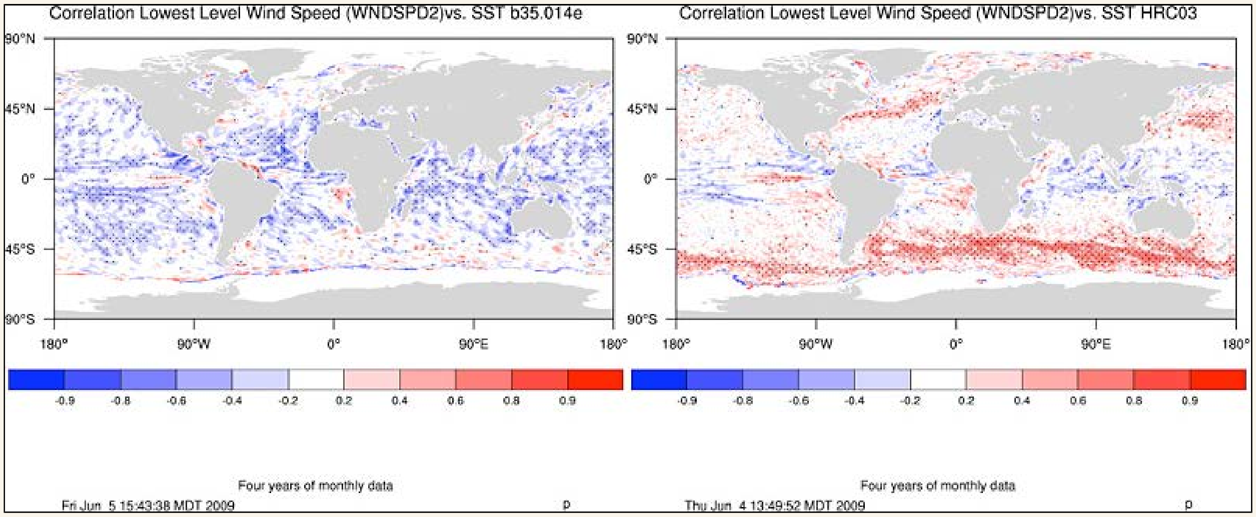
Ultra-high-resolution CCSM



At gyre- to basin-scales, sea surface temperature (SST) and surface winds tend to be negatively correlated. However, recent high-resolution remote sensing observations have indicated that the sign of the correlation is reversed for scales smaller than 1,000 km. Over ocean fronts and eddies, higher winds are observed over warmer SST. An experiment with 0.5° atmosphere and 1.0° ocean models (left) does not capture this relationship very well. But the same atmosphere model coupled to a 0.1° ocean model (right) does an excellent job of reproducing the positive correlation between SST and low-level winds in the vicinity of strong ocean fronts.

Over the last several years we have made concerted efforts to significantly improve the scalability of the various components of the upcoming Community Climate System Model (CCSM4). 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 has focused on improving the simulation rate and reducing the cost to simulate ultra-high-resolution climate. All these improvements have enabled the completion of a 100+ 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 National Institute for Computational Sciences (NICS). This 100+ year control run is part of the NSF-funded PetaApps project to investigate the impact of weather noise within the coupled climate system.

While the analysis of the ultra-high-resolution control run is still ongoing, several preliminary results suggest that there are significantly different characteristics relating to the air-sea interactions. The figure illustrates the difference in correlation between sea surface temperatures and the wind speeds for simulations using a 0.1° versus a 1° ocean. Recent remote sensing observations indicated that surface wind speed has a positive correlation to SST at scales smaller than 1,000 km. Unlike with the 1° ocean, the 0.1° ocean does an excellent job of reproducing the positive correlation.

These advances are significant because it is now possible to simulate the Earth System on currently available supercomputing resources at resolutions that are 100 times as computationally demanding as the current production CCSM simulation. While our current work is focused on addressing the scientific goals defined by the PetaApps project, we view this project as a vehicle to enable ultra-high-resolution climate simulations for the broader climate community. 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. We plan to continue improving the efficiency of the ultra-high-resolution CCSM configuration to address the needs of the PetaApps project, then transfer these advances back into the standard CCSM codebase.

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. Additional funding is provided through the Department of Energy's CCPP program grant DE-FC03-97ER62402.

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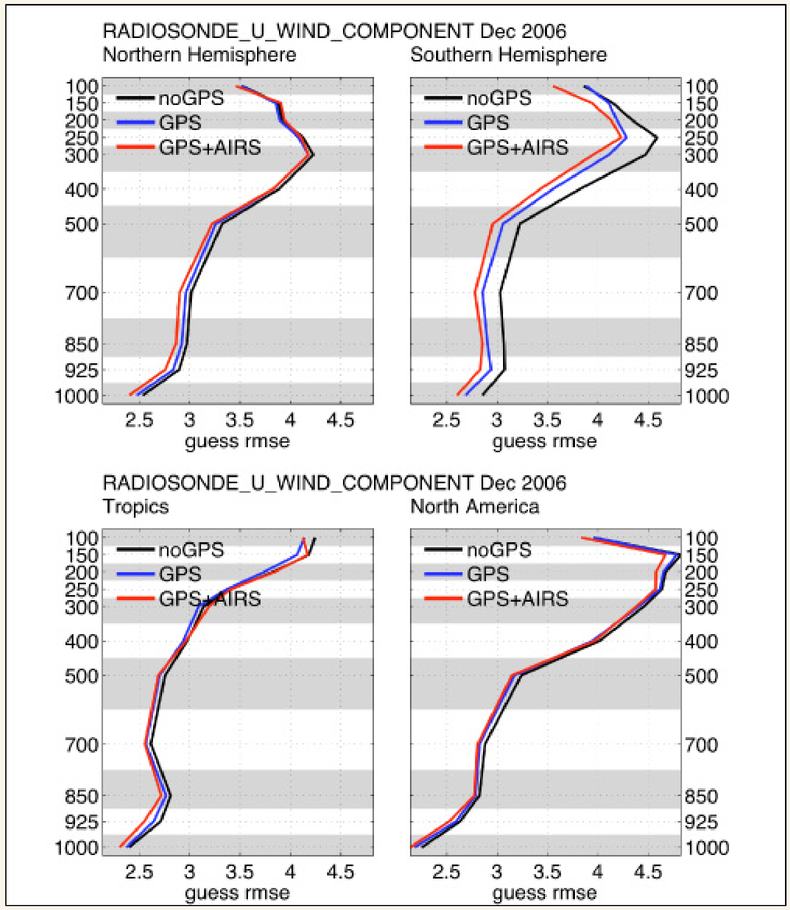
NCAR is sponsored by the National Science Foundation.

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.

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 doing 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.



This figure shows the root mean square error of DART/CAM ensemble mean 6-hour forecasts of radiosonde zonal wind observations as a function of height and region for December 2006. The multivariate capabilities of the ensemble filter assimilation allow the inclusion of GPS observations to improve forecasts of winds, even though GPS observations are only directly impacted by temperature and moisture. Largest impacts are in the southern hemisphere where conventional observations are relatively sparse. The addition of Atmospheric Infrared Sounder (AIRS) retrievals to the assimilation led to small additional improvements.

A broad range of NCAR projects were advanced by DART during FY2009:

- Year-long reanalyses with several versions of CGD's CAM climate model identified and led to the correction of errors related to the diffusion applied near the top of the model. The uncorrected model produced large amounts of gridscale noise that had particularly adverse impacts on simulations with chemical tracers. CGD modelers were able to identify this problem and validate the improved model using DART/CAM assimilations.
- The impact of both COSMIC GPS radio occultation measurements and AIRS retrievals of temperature and moisture were evaluated for large scales by producing a set of one-year reanalyses, each using conventional observations and different combinations of GPS and AIRS. The impact of GPS was found to be large in the tropics and southern hemisphere.
- Researchers in CGD are continuing to use DART/CAM analyses and forecasts to explore mechanisms for the rapid loss of Arctic sea ice observed in the last three years and have identified shortcomings of the cloud parameterizations in CAM related to sea ice.
- WRF/DART has been used to make real-time analyses and forecasts of all 2009 Atlantic tropical storms by researchers in MMM and SUNY Albany.
- Researchers in MMM and COSMIC have applied DART/WRF in the western tropical Pacific over the 2-month TPARC period from 2008 to explore the genesis and evolution of typhoons. The DART/WRF system, which is also being used for parallel tests at Taiwan's Central Weather Bureau, was able to accurately analyze the genesis of typhoons during this period.
- A growing number of university groups are using both DART/WRF and DART/CAM for research and instruction.
- A joint DAReS/University of Wisconsin project is continuing to investigate the impact of advanced hyperspectral infrared retrievals on hurricane prediction.

- Research partners at Caltech have successfully assimilated radiance observations of Mars in the planet WRF Martian general circulation model.

During FY2010, fundamental data assimilation research will focus on developing a theoretical explanation for the use of localization in ensemble assimilation algorithms. Preliminary research suggests that localization can be explained in terms of ensemble sampling error in a Bayesian context. An attempt to develop improved localization algorithms based on this theory will be a focus of future work. Work will continue on evaluating the impact of diverse observation types on analyses of both the global circulation and small-scale features like tropical storms and severe convection. Collaborations with CGD and Los Alamos will focus on generating ocean analyses that can serve as initial conditions for coupled decadal climate predictions.

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 and NASA Grant NNX08A23G.

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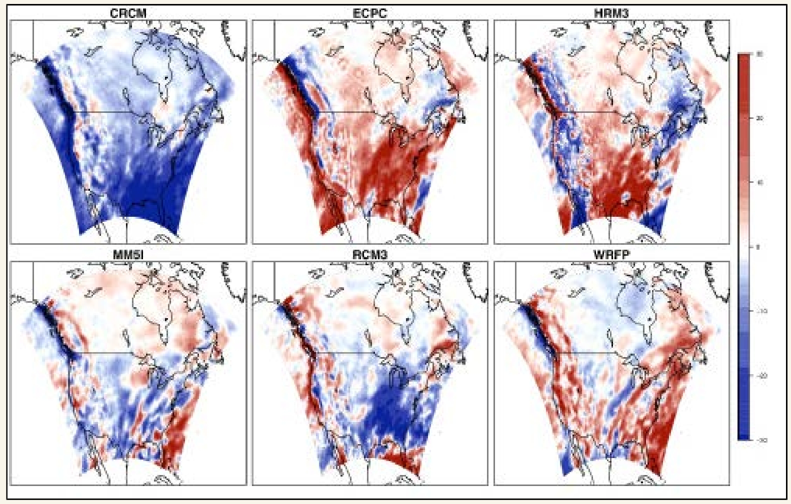
Geophysical Statistics Project



Results of a statistical analysis of extreme precipitation based on the six NCEP-driven regional models from the North American Regional Climate Change Assessment Program. Shown are the deviations in the 100-year return levels from the posterior mean for six models. Despite similar spatial patterns in the return levels, this shows that there are considerable differences in the magnitude of the estimated return levels between models. Differences are given in mm/day.

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, GSP has a strong 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 applications in the geosciences.

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 FY2009, 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
- Stochastic weather generators
- Modeling uncertainty in climate reconstruction
- Impacts of climate and climate change on public health

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

In FY2010, the scientific focus on computer models will continue, in particular through GSP scientists being involved in such NCAR programs as the North American Regional Climate Model Assessment Program (NARCCAP) as well as in collaborations with other computer modeling groups across NCAR. Beyond computer models, GSP scientists will continue to assess the impacts of climate and climate change on public health, to develop methodology for analyzing extremes, to develop methodology for modeling daily weather scenarios, to develop methodology for quantifying the uncertainty in climate reconstructions, and to develop statistical methodology for the analysis of complex, spatial, and spatial-temporal data.

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, and NSF's Collaboration in Mathematical Geosciences.

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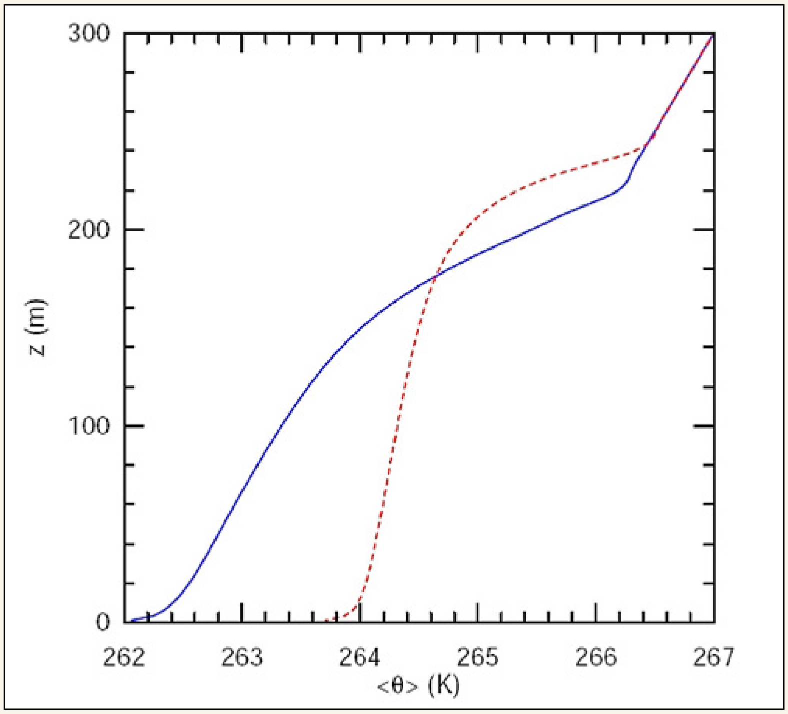
Geophysical Turbulence Program

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).



Vertical profiles of mean potential temperature from large eddy simulations (LES) of the nighttime stratified boundary layer (SBL) over homogeneous (solid) and heterogeneous (dashed) temperature surfaces. The net cooling rate in each simulation is identical. Broadly, the SBL over a heterogeneous temperature surface is deeper, more turbulent has larger velocity variances (and hence larger turbulent kinetic energy TKE), and is better mixed with respect to mean potential temperature compared to its homogeneous counterpart. Detailed statistics of the mean and fluctuating fields are being analyzed to assess how the budgets of temperature variance and TKE are maintained in these cases. The results demonstrate that surface heterogeneity plays an important role in the SBL evolution and that LES can be used to investigate stable boundary layer dynamics.

By design, GTP is an interdiscplinary group of about 40 members that spans many divisions and laboratories at NCAR with a few external affiliates. It encompasses research at NCAR on multiscale 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.

GTP uses seed funds to foster interdisciplinary research at NCAR. In FY2009 GTP sponsored 10 seminars and hosted 8 long-term visitors. Among our many accomplishments, in collaboration with several members of the university community, we emphasize the following:

- Numerical Realizability of Thermal Convection (Piotrowski and Smolarkiewicz, MMM), studying the impact of effective model viscosity on the structure of under-resolved convective fields
- Coupling the Dynamics of Boundary Layers and Evolutionary Dunes (Ortiz and Smolarkiewicz, MMM), using a severe-wind scenario
- A nonlinear perspective on the dynamics of the Madden-Julian Oscillation (MJO) (Wedi and Smolarkiewicz, MMM), testing the hypothesis that eastward-propagating MJO-like structures originate fundamentally as a result of nonlinear (dry) Rossby wave dynamics, using Large-Eddy Simulations (LES)
- Monge-Ampere solvers for semi-Lagrangian trajectory schemes (Cossette, U. Montreal and Smolarkiewicz, MMM), developing a Jacobian-Free Newton-Krylov (JFNK) approach
- Adaptive Meshes for Atmospheric Flows (Kuehnlein and Smolarkiewicz, MMM), developing a linear advection equation in a two-dimensional framework
- Interaction between boundary layer dynamics and chemistry (Villa and Patton, MMM and Karl, ACD), examining in particular ozone, isoprene, and the hydroxyl radical OH, looking at the Amazon Basin
- Stably Stratified Atmospheric Boundary Layer (SBL): An LES study (Mironov and Sullivan, MMM) showing that the SBL is more turbulent over a heterogeneous surface (see figure)
- Methods to measure turbulence from unoccupied airborne vehicles (UAVs) (Oncley, EOL), evaluating two

microelectromechanical systems-based (MEMS) 3-axis angular-rate gyroscopes and 3-axis linear accelerometers

Several papers have appeared or are in preparation, and most of these projects will continue in FY2010. GTP activities advance CISL's strategic imperative to produce scientific excellence by conducting applied mathematics research in turbulence. GTP works to lead the mathematics and geophysical communities in ways that accentuate the contributions of mathematical methods and models to scientific progress in the geosciences.

GTP activities are supported entirely by NSF core funding.

Director's Message

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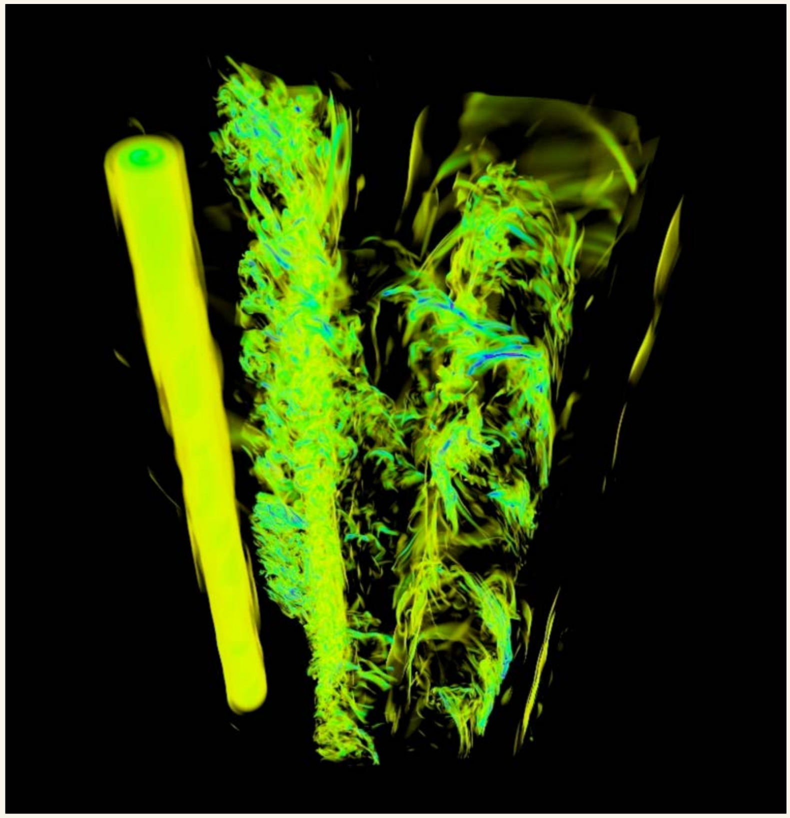
Turbulence science: Numerical algorithms and code development

The Turbulence Numerics Team (TNT) is complementary to the Geophysical Turbulence Program (GTP) and is focused on the accurate simulation and understanding of turbulence for fluids such as the atmosphere, and for charged flows in the presence of magnetic fields. TNT research emphasizes simplified physical systems that still reproduce the complexity and multiscale properties associated with turbulent flow. Supplemental information for this report appears in the links to the Research Catalog in the text.



VAPOR volume rendering of EDQNM-modeled rotating flow's vorticity. Together with the usual tangle of small-scale vortex filaments (right), laminar columns are observed (left) that live for long times and lead to complete self-similarity of the direct energy cascade. The result demonstrates that a flow undergoing strong rotation behaves much differently in cases where helicity (correlation between the velocity and the vorticity) is included, compared to those where it is not.

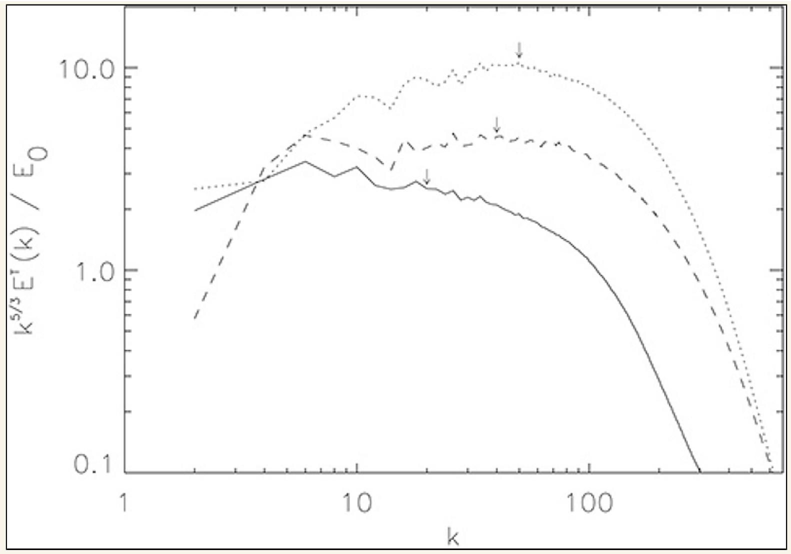
Research on turbulent flows

We have pursued investigations of homogeneous, isotropic, and non-isotropic turbulence and turbulent structures at high Reynolds numbers in a broad variety of fundamental contexts and physical conditions (with or without magnetic fields, with or without rotation, with or without modeling). Through the course of these investigations and analyses, we have made several important statements about the fundamental nature of turbulence.

We emphasize the following accomplishments of the Turbulence Numerics Team (TNT) collaborating with members of the university community:

- The behavior of a fluid undergoing solid body rotation is very different when one includes helicity (correlation between the velocity and its curl, the vorticity): together with the usual tangle of small-scale vortex filaments (right side of VAPOR figure), one observes laminar columns (left side of VAPOR figure) that live for long times and lead to complete self-similarity of the direct energy cascade, thus providing a small parameter for the problem, the adimensionalized ratio of helicity to energy flux to small scales.

- The lack of universality in magnetohydrodynamics in the absence of both a forcing term and a uniform magnetic field: energy spectra compatible with either the classical Kolmogorov law, an Iroshnikov-Kraichnan dynamic, or a weak-turbulence formalism, are observed for three initial conditions having the same velocity field (a Taylor-Green flow), the same three ideal invariants (total energy, cross-correlations, and magnetic helicity) and the same equal kinetic and magnetic energy (see energy spectra figure). The computations are on equivalent grids of $2{,}048^3$ points, imposing the



Total energy spectra top compensated by $k^{5/3}$ and averaged over t=0.5 (~1.5 to 2 turnover times) about the maximum of dissipation as a function of wavenumber for three different sets of initial conditions: solid line for insulating, dash for "alternate-insulating," and dots for conducting. The three different sets of initial conditions for the magnetic field, with identical initial velocity (the so-called Taylor-Green flow), lead to solutions representative of three different canonical descriptions of MHD turbulence. This demonstrates the lack of universality in MHD turbulence.

symmetries of the Taylor-Green flow.

- In view of the very large Reynolds numbers of astrophysical and geophysical flows, it is necessary to use modeling in conjunction with direct numerical simulations. Several types of modeling have been tested, and a parametric study of rotating flows is under way.
- A wavelet decomposition of high-Reynolds-number, low-Rossby-number data into coherent and incoherent contributions demonstrates the utility of the decomposition in that the coherent part contains only 2% of the wavelet coefficients, while representing >90% of the energy and enstrophy. This decomposition also yields a variety of interesting features concerning the flow statistics that may be useful in applying the method to identifying energy transfer between structures.

Several papers have appeared or are in preparation, and most of these projects will continue in FY2010.

Algorithms, numerics, and code development

TNT develops both tools and models that enhance our ability to investigate geophysical turbulence and applies these capabilities to fundamental scientific objectives. TNT members have broad experience in developing a variety of algorithms, numerical schemes, and large development efforts for studying turbulence.

The algorithms, numerics, and code development undertaken by TNT all advance the CISL strategic imperatives to produce scientific excellence and to develop mathematical research codes that improve modeling. For this second imperative, CISL must maintain a portfolio of research models to drive forward basic scientific research in computational fluids and in basic algorithmic research. TNT carries out two action items under this imperative:

- Further develop the Geophysical and Astrophysical Spectral element Adaptive Refinement (GASpAR) platform, a research framework for solving partial differential equations (PDEs) using 2D and 3D scalable adaptive spectral element methods
- Enhance the Geophysical High Order Suite for Turbulence (GHOST) code, a proven and highly scalable suite for computing direct numerical simulations and modeling turbulence by solving the 2D and 3D Navier-Stokes and MHD equations (with and without Hall terms) using the pseudo-spectral method

TNT research and service activities are supported by NSF Core funding.

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Radial basis functions for modeling

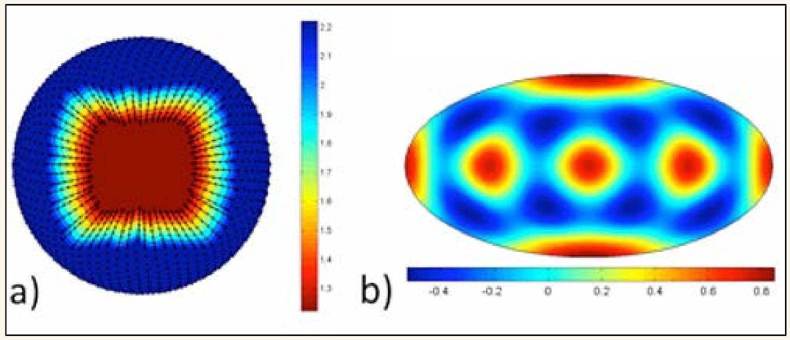

Figure 1: (a) Node layout of the RBF-PS method. (b) Initial perturbation in the latitude-longitude direction (linear decay radially).

While computer technology has advanced dramatically in recent years, numerical schemes currently used for climate and solar modeling fall drastically short of scientists' expectations. Spherical harmonics require large grids to resolve small features, and this is computationally impractical. Spectral element methods can resolve small features, but they require higher resolution near artificial boundaries to achieve high accuracy. Both methods involve high algorithmic complexity and are impossible or awkward to apply to irregular geometries. As a result, geoscientists and computational mathematicians are searching for new options. Radial basis functions (RBFs) offer the geosciences a novel numerical approach for solving time-dependent partial differential equations (PDEs).

Building on the accomplishments of FY2008, the IMAGe Computational Mathematics Group together with Boise State University, the University of Colorado, University of Minnesota, and Uppsala University in Sweden continue research in the developing area of RBFs for climate and solar modeling.

This year saw the completion of a novel hybrid spectral method that combines RBFs and Chebyshev pseudospectral methods (PS) for numerically simulating thermal convection in a 3D spherical shell. This is the first study to apply RBFs to a full 3D physical model in spherical geometry and use them in conjunction with another numerical method. Benchmark comparisons are presented with other currently used 3D thermal convection codes for Rayleigh numbers (Ra) 7,000 and 100,000.

The node layout for the RBF-PS method – the locations at which the solution is calculated – is shown in Figure 1a. RBFs are used on each layered shell in the latitude-longitude direction (θ, φ) and Chebyshev polynomials are used in the radial direction (r) to give a "2+1" tensor-like approach. The red interior is the inner boundary of the 3D spherical shell. The initial perturbation to the fluid is given in Figure 1b.

Table 1 gives comparative results with other methods in the literature for Ra=7,000. Note that the RBF-PS method requires 1 to 3 orders of magnitude fewer nodes (degrees of freedom) than the other methods, while being able to almost exactly match the extrapolated results of the only other method that is a least partially spectral.

Type	No. of Nodes	Nu_{outer}	$\langle V_{rms} \rangle$	$\langle T \rangle$
FE	393,216	3.6254	31.09	0.2176
FD	12,582,912	3.4945	32.6308	0.21597
FV	663,552	3.5983	31.0226	0.21594
SP-FD	552,960	3.6086	31.0765	0.21582
SP-FD	*Extrapolated	3.6096	31.0821	0.21578
Pure SP	36,800	3.6096	31.0823	0.21578

Table 1: Comparison between computational models for Ra=7,000. Nu_{outer} denotes the Nusselt number at the outer spherical shell, $\langle V_{rms} \rangle$ the volume-averaged root mean square velocity, and $\langle T \rangle$ the mean temperature. Extrapolated results are from the SP-FD 552,960 result, based on second-order convergence in r. Results are taken once the standard deviation of all quantities from the last 1,000 time-steps is less than $5(10)^{-5}$, indicating numerical steady-state is reached. FE = finite element, FD = finite difference, FV = finite volume, SP-FD = hybrid spectral-FD, and SP = purely spectral.

Figure 2 gives the final steady-state

solutions. As the Rayleigh number increases, the fluid moves from a conductive regime to a more convective regime, resulting in thinner plumes.

This work advances CISL's strategic imperative to produce scientific excellence. It may soon support CISL's science imperative to develop mathematical research codes to improve models. This development effort at NCAR is supported by NSF grants ATM-0620100 and DMS-0934317.

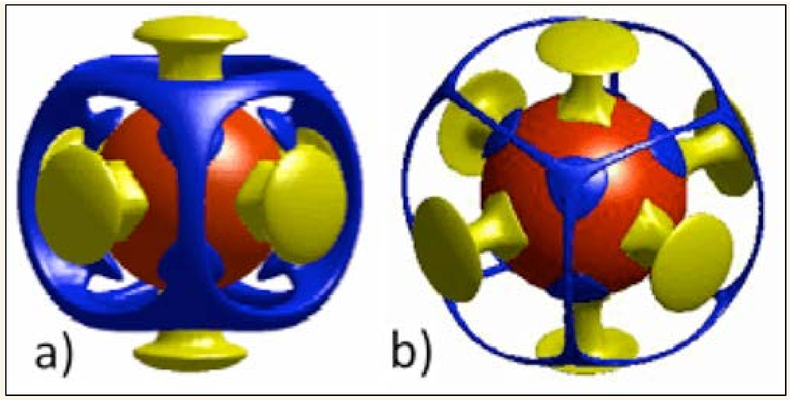

Figure 2: Residual temperature, δT = T(r,η,ω) - <T(r)>, of the steady-state solution for (a) Ra=7,000 and (b) Ra=105. Yellow corresponds to δT = 0.15 and denotes upwelling relative to the average temperature at each radial level, while blue corresponds to δT = -0.15 and denotes downwelling. The central red sphere shows the inner boundary of the 3D spherical shell.

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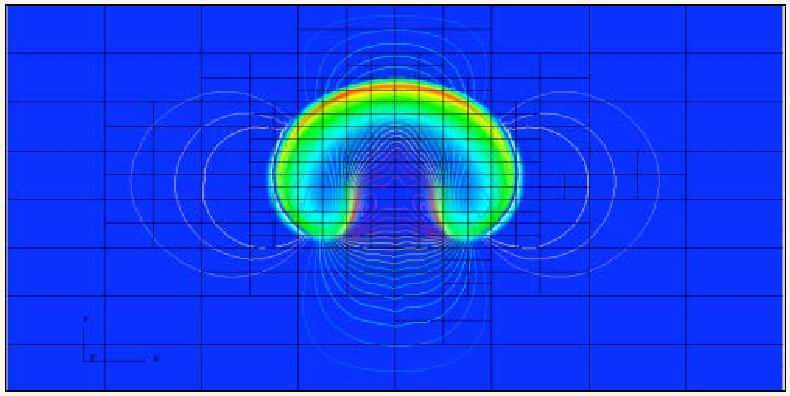
Multiscale simulation techniques

To continue its scientific leadership, NCAR needs a unified simulation environment that can dynamically resolve time and space scales on petascale computers. A framework that encompasses such an environment relieves scientists from becoming fluent in advanced scalable numerical methods and enables them to focus on their research issues. We are progressing toward a unified simulation environment by pursuing novel developments in the areas of adaptive h-p grids, multi-method time-stepping, and Jacobian-free techniques.



This simulation of a rising hot air bubble uses the unabridged equations of the atmosphere (compressible Euler – non-hydrostatic – equations). The resolution is dynamically increased locally where required. The finest resolution is 90 meters. To perform this simulation using a grid with a uniform resolution of 90 meters would require roughly 10 times more compute time. This is a standard test extracted from Wicker and Skamarock (MWR 1992 Vol. 163). The discontinuous Galerkin solver MUSE was employed with 7th degree polynomials on each element. (Click the image to view a 61-MB animation of this simulation.)

Current work toward this goal in IMAGe's Computational Mathematics Group includes the development of a linearly implicit Runge-Kutta time-stepping procedure to accelerate integrations of PDEs common in atmospheric and oceanic models. An h-p mesh adaptation library was developed through a collaboration between the Earth System Modeling Framework (ESMF) group and IMAGe. The library is merged with the ESMF code, and future plans include an official release of the adaptive mesh database. The latter has shown excellent scalability on the IBM Blue Gene/L system, and it is now coupled with a compressible h-p flow solver. Preliminary results with the coupled solver promise unprecedented scalability. The h-p solver is highly optimized and uses C++ "expression templates." This yields a highly cache-efficient code, and at the same time improves readability.

This is demonstrated in the image at right. The first code sample is hard-coded for curvilinear quadrangles. Even if the loops are fully exposed to the compiler, it yields an average optimization. The next code sample is very readable (click image to enlarge) and looks like mathematical statements. It would not change if a triangle was considered instead of a quadrangle. Further, the second code sample runs 4 to 5 times faster than the original one. The coupled h-p solver uses on-chip parallelism in the form of Streaming SIMD Extensions (SSE). (SIMD stands for single instruction multiple data.)

Future work includes adding non-conforming triangles and including the implicit time-stepping procedure described next plus new procedures suited for adaptive meshes as well as diffusion mechanisms and error indicators. Simulations are planned on spherical domains with shallow water and other sets of equations.

This research was recently awarded an NSF PetaApps grant (0904599). It is a collaborative, multi-institutional, international effort (University of Wyoming, Virginia Tech, Universite Catholique de Louvain, Nice Sophia-Antipolis, and University of Geneva).

Streamlined code and faster execution are two benefits of the coupled h-p solver (code sample at bottom) that was developed in FY2009. (Click the image to enlarge it.)

This research intends to develop efficient computational methods for solving multiscale, multidisciplinary physics on petascale systems by using numerical methods that satisfy the following criteria:

- Highly scalable: strong scaling enabling
- A well-defined mathematical background
- Multiphysics capable: generic enough to solve more than a single problem
- Multiscale capable: locally change the resolution for time and space scales

A variety of subprojects have been generated from the development of these techniques.

Spatial scales project

This year the AMR h-p code MUSE can now solve the Euler equations on curvilinear meshes composed of quadrangles. The plan for next year is to include triangles and add support for 3D high-order hexahedrons in a curvilinear box. An adaptive-grid simulation produced by this work is shown at the top of this page. View the animation by clicking on the image of the hot air bubble.

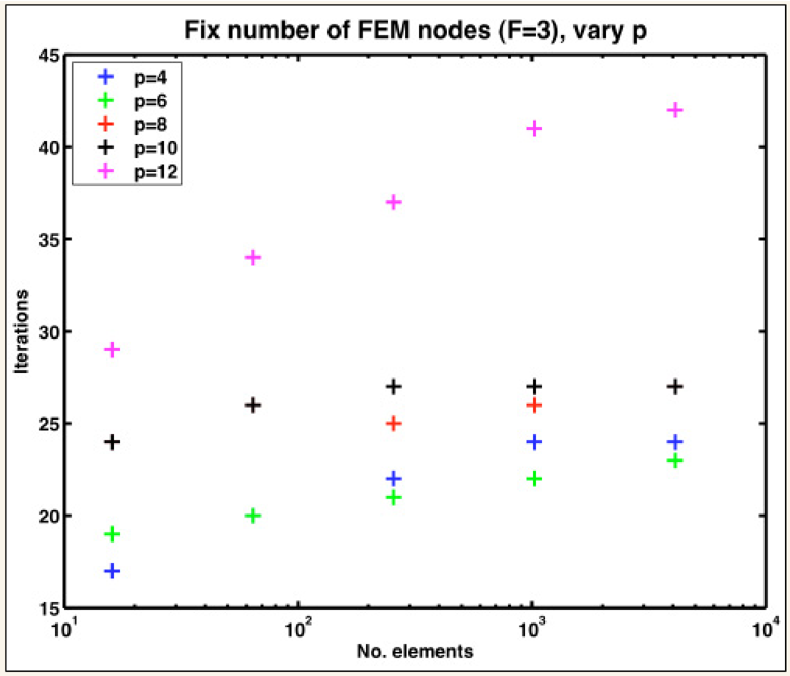
Temporal scales project

Efforts this year focused on incorporating the Euler equations into the adaptive solver. Plans for next year concerning the time-stepping are to include the existing linearly implicit time integration method into the h-p solver and research a multi-rate method suitable for mesh adaptation.

Scalable elliptic solvers project

The quest for an accurate coarse-grid correction for optimized Schwarz techniques started in FY2008 and extended into FY2009. The coarse-grid correction is required to obtain an iterative elliptic solver that yields a number of iterations independent of the number of spectral elements employed or their local polynomial orders.

The addition of a coarse-grid correction yielded good results. Indeed, when the number of elements is increased on the GASpAR mesh below, the number of iterations seems to attain a plateau. This means that it takes the same number of iterations to invert a problem with 330K unknowns as it does with 20K. The results for various polynomial bases are depicted in the plot on the right. Future work on this project includes solving the coarse problem in an efficient way using a library developed at Argonne National Laboratory. The latter will enable solutions to physical problems that were computationally costly to solve (Navier-Stokes and Magnetohydrodynamics).

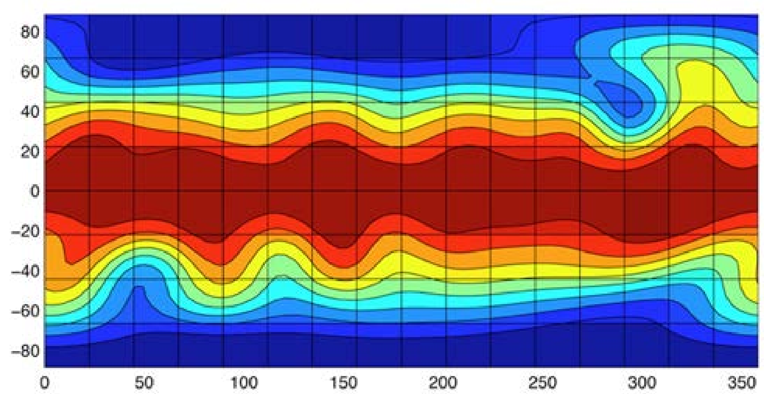


This plot shows the number of iterations required to invert a pseudo-Laplacian. The latter is necessary to enforce divergence-free solutions. The number of elements goes from 4 to 4,096, and the polynomials used on each element are varied from 4th to 12th order of accuracy. The coarse correction consists of a similar problem with much lower order (3rd).

The results obtained with the GASpAR code use a two-level overlapping approach where each element has one or two common layers of points with its neighboring elements (see figure in GASpAR report.). Recently, a non-overlapping spectral element solver was also developed. It was tested in the context of validating the optimal coarse grid correction parameter recently obtained using theory. An experiment with a solution from the shallow water code in the HOMME model was tested with this non-overlapping approach with a coarse grid correction.

The number of iterations plateaus at 29 for any number of elements for an 8th order solution using a 3rd order coarse-grid correction. This implies that very efficient time-stepping procedures could be crafted using this solver. A table and a plot of the solution is shown next. The latter uses four different grids varying the number of elements from 8 to 288.

	4×2	8×4	16×8	24×12
$N = 8,\ M = 3$	24	27	29	29



This visualization depicts the geopotential height field of a shallow water simulation. The test consists of the flow impinging a mountain that triggers most of the waves of interest to climate modelers.

Support

This work supports CISL's strategic plan in various ways. It advances CISL's strategic imperative to produce scientific excellence, and it develops numerical algorithms for petascale and exascale computing. It also supports CISL's science frontier for algorithmic acceleration, and it fulfills a strategic action item to accelerate applications algorithmically by applying adaptive mesh refinement techniques, new time-stepping techniques, and efficient use of processor technology (SSE).

These projects are made possible through NSF Core funding.

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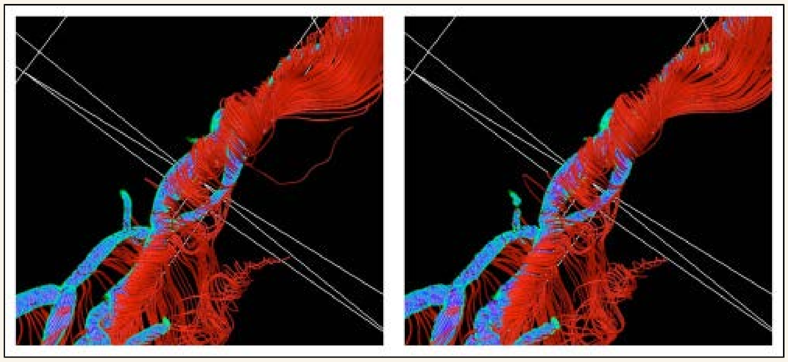
Scientific data compression research

The Scientific Data Compression Research project began in FY2006 and is built on the success of CISL's VAPOR work, which employs a simple wavelet-based, multiresolution progressive data access scheme to facilitate interactive analysis of terascale data sets. This project investigates the application of wavelet-based lossy data compression and more advanced progressive refinement techniques applied across a broad domain of computational science. The methods employed in our data compression research are similar to those now widely used in the compression of digital media. The goals of this work are to:



This image demonstrates Coherent Vortex Extraction (CVE) applied to a Taylor-Green turbulent flow. Both images were created by randomly seeding field lines within regions of high vorticity. However, the image on the left was generated from the original data, while the one on the right was generated by the coherent component of the field, which in this case represents only about 3% of the data. Compression techniques such as CVE may offer one method for researchers to grapple with ever-growing data sets from simulation outputs.

- 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

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, and thus generate 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. Lossy signal compression and progressive data access techniques, such as those ubiquitously used for digital media and now being investigated by CISL, may provide relief for researchers drowning in a deluge of data.

Progress was made on two distinct fronts in FY2009. First, a number of technical issues were resolved to allow the practical application of compression methods based on wavelet coefficient prioritization. These include: identifying an appropriate wavelet family and order for scientific data, satisfactory handling of boundary conditions, developing a space-efficient and computationally efficient wavelet coefficient coordinate encoding scheme, and tuning the performance of quadrature mirror filter banks to achieve acceptable run times. Second, CISL continued collaborations with the University of Colorado's department of Astrophysical and Planetary Sciences to explore a particular application of wavelet-based compression: extraction of coherent vortices (CVE) from turbulent fluid flow. This collaborative work was again assisted by a SIParCS-funded summer intern from UCLA's graduate program in pure math, supporting CISL's education imperatives in both integrating research with education and workforce training and development, while exemplifying CISL's collaboration and mentorship Fabrics.

In FY2010 CISL will continue to push its collaborative efforts with CU on CVE, and will publish the results of this year's work. CISL will look for additional domain science collaborators to further explore the applicability of lossy scientific data compression. Fledgling efforts with researchers from COLA and the Canadian Center for Meteorology will continue to develop. Lastly, CISL will deploy components of this research work as part of the VAPOR application in the form of a next-generation VAPOR data model.

This work advances CISL's strategic imperative to produce scientific excellence, and it prepares a foundation for petascale and exascale computing. CISL's scientific data compression research is funded through NSF Core funds.

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Science Imperative: Develop Mathematical Research Codes to Improve Models

CISL has a science imperative to develop research codes that reinforce and enhance geophysical modeling and community model development for NCAR and the larger Earth System science community. CISL's efforts provide flexible model test beds for research on new numerical and computational methods. These models must be scientifically credible while emphasizing experimentation and rapid prototyping rather than supporting a large modeling community. The final goal is that the most promising algorithms and computational strategies can then be merged back into the more standard NCAR modeling efforts.

CISL's science imperative to develop mathematical research codes to improve models is primarily supported by NSF Core funding, with supplemental funding supplied by other sources as noted in the following reports.

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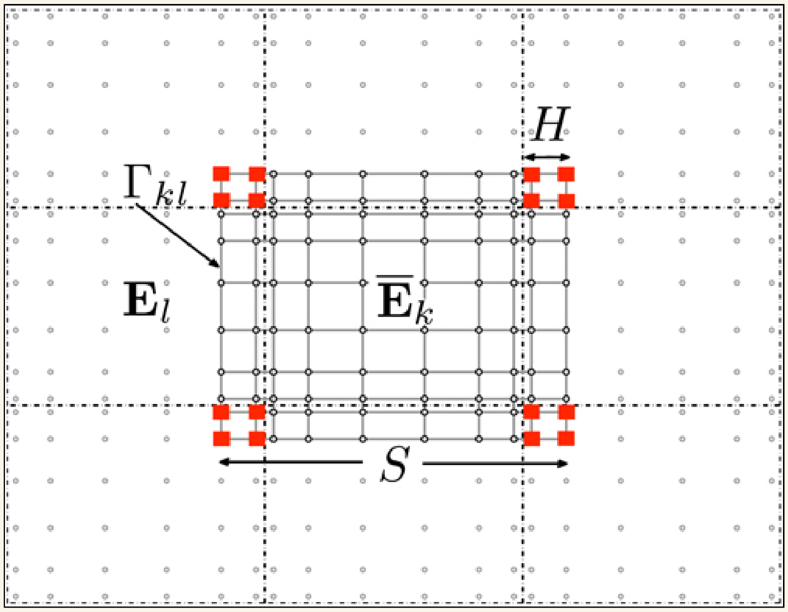
Geophysical and Astrophysical Spectral element Adaptive Refinement code

TNT continues its long-term commitment to develop high-order adaptive methods for use in problems relevant to the turbulence phenomenology community. This work is carried out using the Geophysical and Astrophysical Spectral element Adaptive Refinement (GASpAR) code, which is a framework for solving PDEs using an adaptive spectral element method (SEM).



Schematic showing one overlapping subdomain, E_k with corner nodes represented in red, and E_l representing a non-overlapping neighboring element. The figure highlights the overlapping grid constructed for the overlapping additive Schwarz method developed as one level of the 2-level preconditioner. This figure emphasizes a couple of capabilities of the new preconditioner that are new: namely, the arbitrary corner communication and the arbitrary overlap, H.

In FY2009, we met our primary goals specified in the FY2008 CISL Annual Report. Perhaps most importantly, we added a two-level preconditioner to the code to precondition the pseudo-Laplacian operator that appears in both the MHD and Navier-Stokes solvers. We have provided for a coarse preconditioner that utilizes a low-order finite element (FEM) Laplacian operator on a coarse grid. We have demonstrated optimization (in the sense of a plateauing Krylov iteration count) in the inversion of the high-order (SEM) pseudo-Laplacian operator on grids up to ~20,000 elements for all (fine grid) expansion orders.

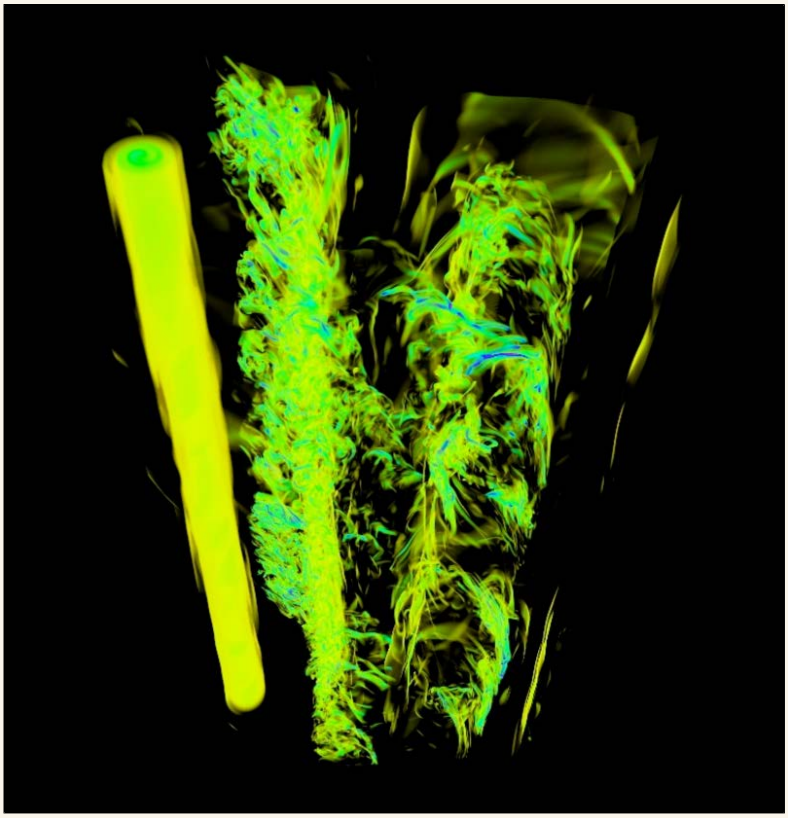
This work on the two-level preconditioning has been carried out in collaboration with the Computational Mathematics Group in IMAGe. Finally, a number of papers were published in FY2009 that utilized GASpAR results.

In FY2010, we anticipate a number of GASpAR developments, and we will address other important issues. We intend to adapt the two-level preconditioner to nonconforming elements. In addition, we plan to continue to adapt the preconditioner communication and computation interfaces to 3D. We will apply the 2D two-level preconditioner to a large 2D MHD problem that must resolve small-scale structures, and that will test the performance of the preconditioning strategy in a real computation.

This work supports CISL's science imperative to develop mathematical research codes that improve modeling by maintaining a portfolio of research models to drive forward basic scientific research in computational fluids and in basic algorithmic research. GASpAR research and service activities are supported by NSF core funding.

Geophysical High Order Suite for Turbulence

The Geophysical High Order Suite for Turbulence (GHOST) code is a highly scalable code used to numerically integrate the hydrodynamic, magnetohydrodynamic, or Hall-magnetohydrodynamic equations in three dimensions with periodic boundary conditions.



VAPOR volume rendering of EDQNM-modeled rotating flow's vorticity. Together with the usual tangle of small-scale vortex filaments (right), laminar columns are observed that live for long times and lead to complete self-similarity of the direct energy cascade. The result demonstrates that a flow undergoing strong rotation behaves much differently in cases where helicity (correlation between the velocity and the vorticity) is included, compared to those where it is not.

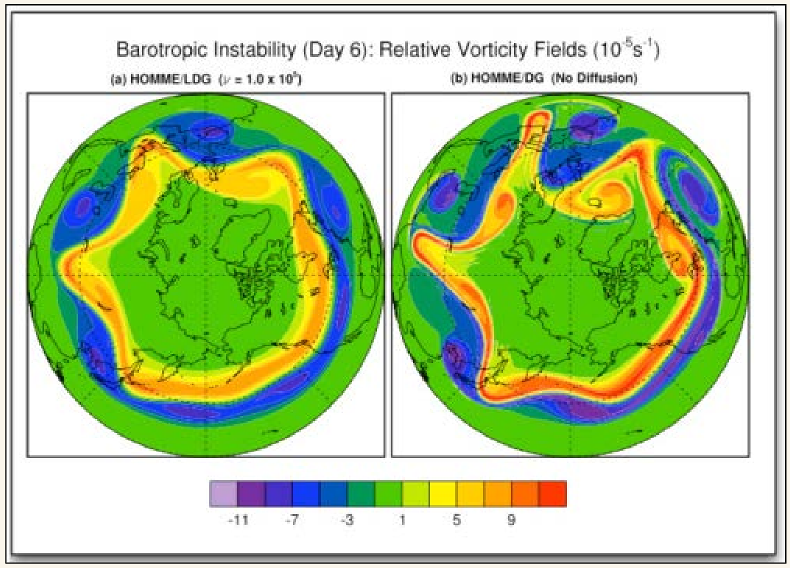
Having succeeded in incorporating the eddy-damped quasinormal Markovian approximation (EDQNM) model into the code in FY2008, we then carried out a parametric study of the flow behavior as a function of the Reynolds (Re) and Rossby (Ro) numbers in FY2009 (see figure). A range of over two orders of magnitude in these parameters was achieved, with a maximum Reynolds number of 10^5, and a Rossby number as low as 3×10^{-3}, which is entirely infeasible with DNS today.

On the software engineering front, we adopted a "virtual" pencil domain decomposition scheme to take advantage of large numbers of cores within compute nodes. In this scheme, we use a hybrid MPI-OpenMP model that discretizes in slabs among MPI nodes, and in "bricks" within the slab among OpenMP threads within a compute node. We have tested this code on NCAR's Bluefire (IBM Power 575) and on up to 4,096 processors using the TeraGrid supercomputers Kraken (Cray XT5) at NICS and Ranger (Sun Constellation Linux Cluster) at TACC. We determined that the code scales well on all of these platforms.

In FY2010, we will continue our optimization of GHOST on systems with high processor counts. We plan to achieve scalability using the hybrid code up to about 60,000 processors. With this, we will be able to apply the code to a number of problems of interest (please see the TNT annual report).

This work supports CISL's science imperative to develop mathematical research codes that improve modeling by maintaining a portfolio of research models to drive forward basic scientific research in computational fluids and in basic algorithmic research. GHOST research and service activities are supported by NSF core funding.

High-Order Method Modeling Environment dynamical core



Simulated vorticity fields over the northern hemisphere for a barotropic instability test at 0.65-degree resolution with the HOMME/DG dynamical core. The left panel shows the diffused vorticity fields using the local discontinuous Galerkin (LDG) method and right panel shows the vorticity fields without diffusion. The diffusion scheme successfully eliminates small-scale features (noise) from the numerical solution and creates smooth vorticity fields.

The future evolution of the Community Climate System Model (CCSM) into an Earth System model will require a highly scalable and accurate flux-form formulation of atmospheric dynamics. Flux form is required to conserve long-lived trace species in the stratosphere. Accurate numerical schemes are essential to ensure high-fidelity simulations capable of capturing the convective dynamics in the atmosphere and their contribution to the global hydrological cycle. Scalable performance is necessary to exploit the massively parallel petascale systems that will dominate high-performance computing (HPC) for the foreseeable future.

The High-Order Method Modeling Environment (HOMME) is a vehicle to investigate using high-order-element-based methods to build conservative and accurate dynamical cores. Currently, HOMME employs the Discontinuous Galerkin (DG) and spectral element 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 100,000 processors of an IBM BlueGene/L. 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 CCSM 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.

Diffusion and dissipation mechanisms play an important role in atmospheric modeling. In a climate model, momentum diffusion transfers energy from the resolved scales into the unresolved scales. Horizontal diffusion parameterizes the energy transfer from wave disturbance into the unresolved scales, preventing spurious accumulation of energy and enstrophy at model grid scale. Because of the inherent complexities of the cubed-sphere geometry (the HOMME grid system) and the high-order Galerkin approach, development of an effective diffusion scheme in the model is challenging. Recently a new diffusion scheme for the HOMME/DG dynamical core has been developed that efficiently eliminates small-scale noise and stabilizes the model for long-term numerical integration. This second-order diffusion scheme is based on the local discontinuous Galerkin method (LDG) and is robust and efficient in parallel applications. The figure shows the effectiveness of the new diffusion scheme in an idealized barotropic instability test.

A major accomplishment for FY2009 was the development and implementation of a novel diffusion scheme in the HOMME/DG dynamical core. Also in FY2009, a multi-tracer transport scheme based on a conservative semi-Lagrangian approach was developed to support future models: the Community Atmosphere Model (CAM) and the Community Climate System Model (CCSM). HOMME/DG has been integrated to the CAM framework, and idealized climate simulations (various long-term validation tests) will be performed in FY2010.

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. The HOMME/DG developmental effort and its integration into the CAM framework is partially supported by the DOE through the CU at Boulder (#DE-FG02-07ER64464). Primary support for HOMME is provided by NSF Core funding.

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Science Frontier: Stochastic and Statistical Techniques for Model Development

The capability to conduct numerical experiments at unprecedented scales or with large ensemble sizes provides an opportunity for mathematical and statistical tools to be more directly involved in geophysical model development. One frontier is the purposeful use of statistical analysis of model experiments to support model building. This activity contrasts with more traditional uses of statistical methods to just validate an existing model; instead model run analyses guide improvements and possibly subsequent model experiments. A statistical approach can add efficiency to model development by reducing the number of runs needed for testing and also provide estimates of empirical relationships among model components where the physical processes are not resolved.

The project highlighted below considers the problem of finding good empirical values for model parameters. However, the longer-term research in this frontier targets more complex model components such sub-grid-scale parameterizations. In this case statistical methods will be necessary to estimate empirical relationships that are inherent in parameterizations from observations or higher-resolution models.

CISL's science frontier in stochastic and statistical techniques for model development is primarily supported by NSF Core funding, with supplemental funding supplied by other sources as noted in the following reports.

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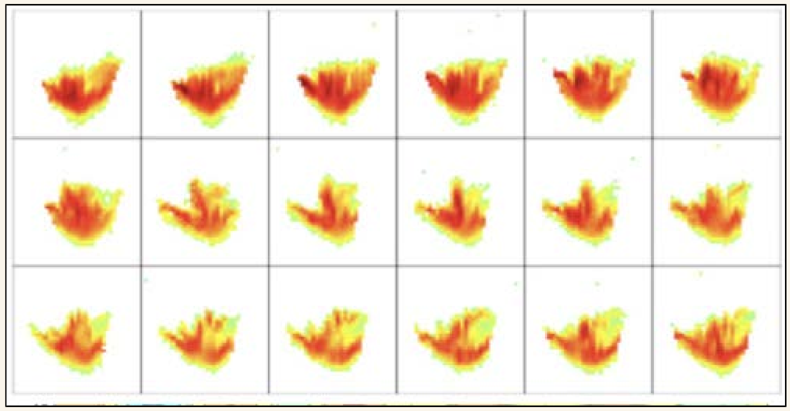
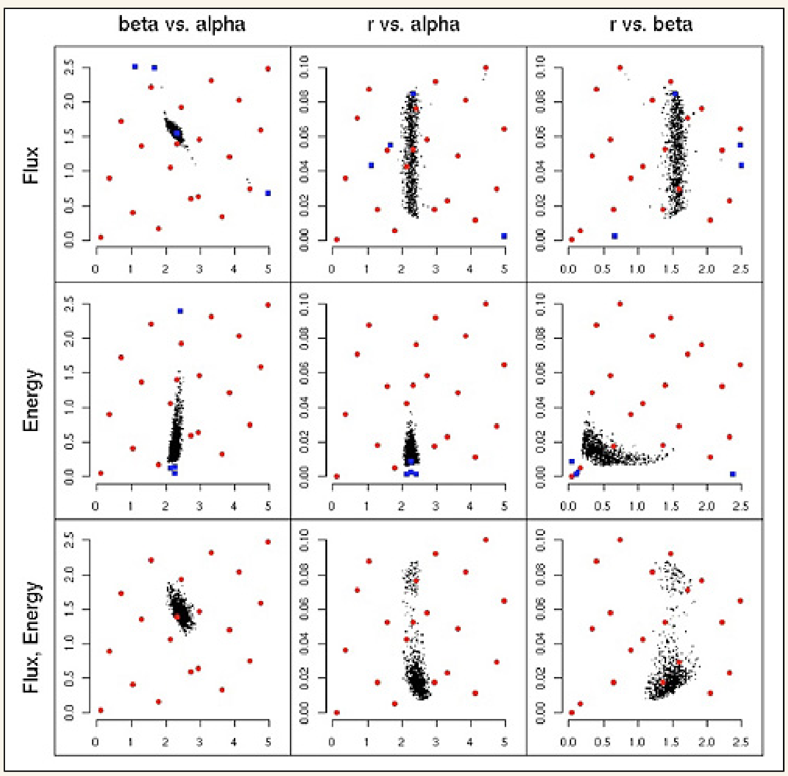
Efficiency and accuracy of model development and testing

The LFM model is a magnetohydrodynamic (MHD) simulation of the Earth's magnetosphere, the region where the Earth's magnetic field impedes the transfer of energy and momentum from solar wind plasma. Understanding how the electric currents and fields behave in the magnetosphere has practical consequences on satellite orbits, radio communication, and GPS systems, especially during disturbances of the magnetosphere. The performance of the LFM model depends on at least three parameters (noted as alpha, beta, and R) that are used to relate MHD parameters to the energy and flux of electrons entering the upper atmosphere. The values of these parameters cannot be derived from first principles and so must be determined from observations and model behavior.



The electron energy field simulated by the Lyon-Fedder-Mobary (LFM) model over 18 time points during the January 10, 1987 geomagnetic storm event showing the complex structure of this process. The calibration of this model for the magnetosphere using statistical methods from the design and analysis of computer experiments is an FY2009 highlight. This application of stochastic methods allows us to estimate the response of a deterministic numerical model to untried parameter values.



The results of estimating the three model parameters (alpha, beta, and R) using electron flux (first row) and energy observations (second row) separately, and the results when they are combined (third row). The columns are the pairwise scatterplots representing projections of the 3D distribution of the parameters. The red dots are the 20 parameter values used for the model runs. Black points are a sample from the statistical analysis indicating the posterior estimates of the parameters based on the data. The scatter in these plots indicates the uncertainty in the parameter values. The blue dots are four possible model runs that take into account the parameter uncertainty and also regions where the discrepancy measure is likely to be low.

This test case for LFM calibration is based on observations from the Polar Ultraviolet Imager of a two-hour geomagnetic storm on 10 January 1987. The LFM model was run at 20 different sets of parameter values following a space-filling design in three dimensions. A discrepancy measure is found for each of these model runs and the observations. The novelty in the statistical analysis is in extending these 20 results to draw inferences about the parameters in the full 3D parameter space, not just at the 20 discrete settings that have been actually run. This extrapolation is accomplished by a statistical model that assumes the discrepancy measure is a smooth function of the parameters and interpolates this measure using techniques similar to those used for spatial data analysis. The results suggest that when energy and flux observations are used, they can constrain two of the model parameters (alpha and beta), but a third parameter linking electric fields with current and electron energy is still uncertain. The analysis also provides information on where to take new model runs to better calibrate this parameter.

Plans for FY2010 include analysis of the LFM model across several storm events and investigating more detailed measures of correspondence between the model output and the observed fields.

This research supports CISL's science frontier in stochastic models of sub-grid-scale phenomena by building accurate, possibly stochastic, models of sub-grid-scale behavior to advance model development.

Specifically, this work fulfills a strategic action item to develop innovative statistical design and analysis techniques to improve the efficiency and accuracy of model development and testing. This work is supported by NSF Core funding.

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Science Frontier: Algorithmic Acceleration

Meeting the grand challenges in simulating the Earth System will require more than just migrating standard algorithms to larger computational platforms. New algorithms, hardware, and computational approaches will all be needed to reach, for example, cloud-resolving resolutions for the atmosphere. The most efficient numerical techniques may not be suitable for a given computer architecture, and this research considers the emerging principle that hardware and algorithms may need to be married to produce an optimal result. Given below are some highlights that demonstrate the variety of computational problems posed by the next generation of geophysical models.

CISL's science frontier in accelerating simulations through algorithmic refinement is primarily supported by NSF Core funding, with supplemental funding supplied by other sources as appropriate.

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Accelerating applications using accelerator-based architectures (coprocessors)

The NVIDIA Tesla Graphical Processing Unit (GPU) is one of the many commodity cards being studied to accelerate computationally intense kernels. Accelerators offer the opportunity to explore the scientific impact of adding local but computationally intense processes (microphysics, for example) to future Earth System models.

Clouds play an essential role in Earth's climate, but to this day remain a major source of uncertainty. Accurate cloud representations are not included in global simulations due to resolution restrictions incurred by computational cost. Our initial examination revealed that Cloud Resolving Models (CRM) are computationally dense, meaning that they do a large amount of computing with relatively little data movement, and they are highly local. Computational kernels with such characteristics are ideal candidates for offloading onto accelerators such as the Graphical Processing Unit (GPU) or BM Cell Broadband Engine (Cell).

Over the past year, CISL's Technology Development Division made significant progress in this area. We extracted a CRM implementation from a custom version of CCSM to enable rapid development work on the CRM implementation in isolation from the other components and complexities of CCSM. The computationally intense kernels were identified and ported to the NVIDIA Tesla GPU. To facilitate porting code to the GPU, we explored several tools that looked promising but proved to be too immature for practical use at present. We will continue to track these tools in the coming year. As most of the code we work with is written in FORTRAN, we developed tools to translate Fortran to C, which is currently one of the primary languages being employed by the broader community developing GPU applications. We discovered that large sections of the CRM code needed to run on the GPU to decrease communication latency. Though we applied a wide variety of advanced GPU optimization techniques to maximize performance, more work is still needed to achieve the levels of performance required to make the Tesla GPU (see image) a viable off-load engine for CRM.

In FY2010 we will re-implement CRM from first principles to mold it into a kernel better suited to achieving high levels of performance on a variety of accelerator architectures. We will also explore other promising kernels that have the appropriate characteristics for employing accelerators. One promising development is NVIDIA's release of the Fermi GPU that provides ECC memory, greatly improved double-precision floating point performance, and a heterogeneous development and debugging environment.

We have also established a partnership with the Barcelona Supercomputing Center that gives us access to MariCel, a heterogeneous multicore cluster based on 72 IBM BladeCenter® QS22 blades.

This work advances CISL's science frontier in algorithmic acceleration by seeking breakthroughs in hardware accelerators that can help produce simulations capable of addressing grand challenges. Specifically, it fulfills a strategic action item to "accelerate Earth-Sun science applications using accelerator-based architectures (coprocessors)." This work is supported by NSF Core funding.

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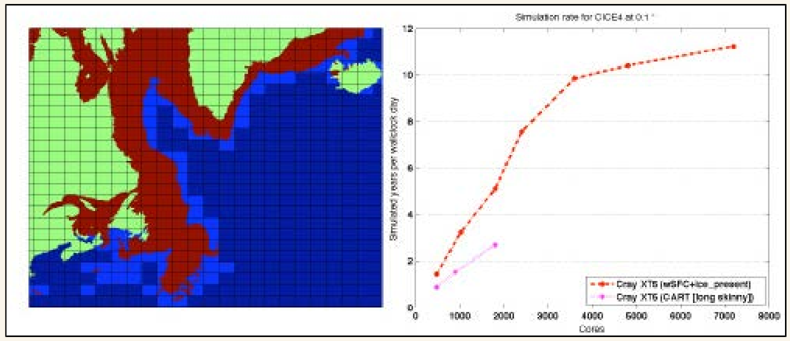
Accelerating applications by making them more scalable



The left panel is a classification of grid points within a 0.1° CICE model over the Davis Strait. Green corresponds to land, blue to ocean, and red to the likely occurrence of sea ice. The right panel is the simulation rate of a 0.1° CICE model on a Cray XT5 using the standard partitioning method versus the weighted space-filling curve-based method (wSFC). Note that wSFC partitioning improves the simulation rate of 0.1° CICE on 1,800 cores by a factor of 1.9. Increasing the scalability of CICE enables ultra-high resolution CCSM to integrate at a rate sufficient to perform 100+ year simulations.

The availability of highly parallel systems has placed a premium on code scalability. NSF has deployed two large "Track-2" systems, a 62,976-core system at the Texas Advanced Computing Center (TACC) and a 99,072-core system at the National Institute for Computational Science (NICS). The availability of these systems provides an excellent opportunity to explore climate simulation at ultra-high resolutions.

We developed a weighted space-filling-curve-based partitioning algorithm (wSFC) to load-balance CICE. This algorithm estimates computational load based on the likely occurrence of sea ice with a sub-domain. The left panel of the figure illustrates a classification of grid points within high-resolution CICE over the Davis Strait. Note that land is green, ocean is blue, and the likely occurrence of sea ice is red. The southern tip of Greenland is in the center of the image, while Iceland is in the upper right quadrant. We allocate one or more sub-domains per MPI task using a probability function based on climatological data that estimates the computational cost. Use of the wSFC partitioning increases the simulation rate of CICE at 0.1° on Kraken, a Cray XT5 system at NICS, from 2.7 to 5.1 simulated years per day on 1,800 cores. The wSFC partitioning also allows CICE to continue to scale up to a rate of 11.2 simulated years per day on 7,200 cores.

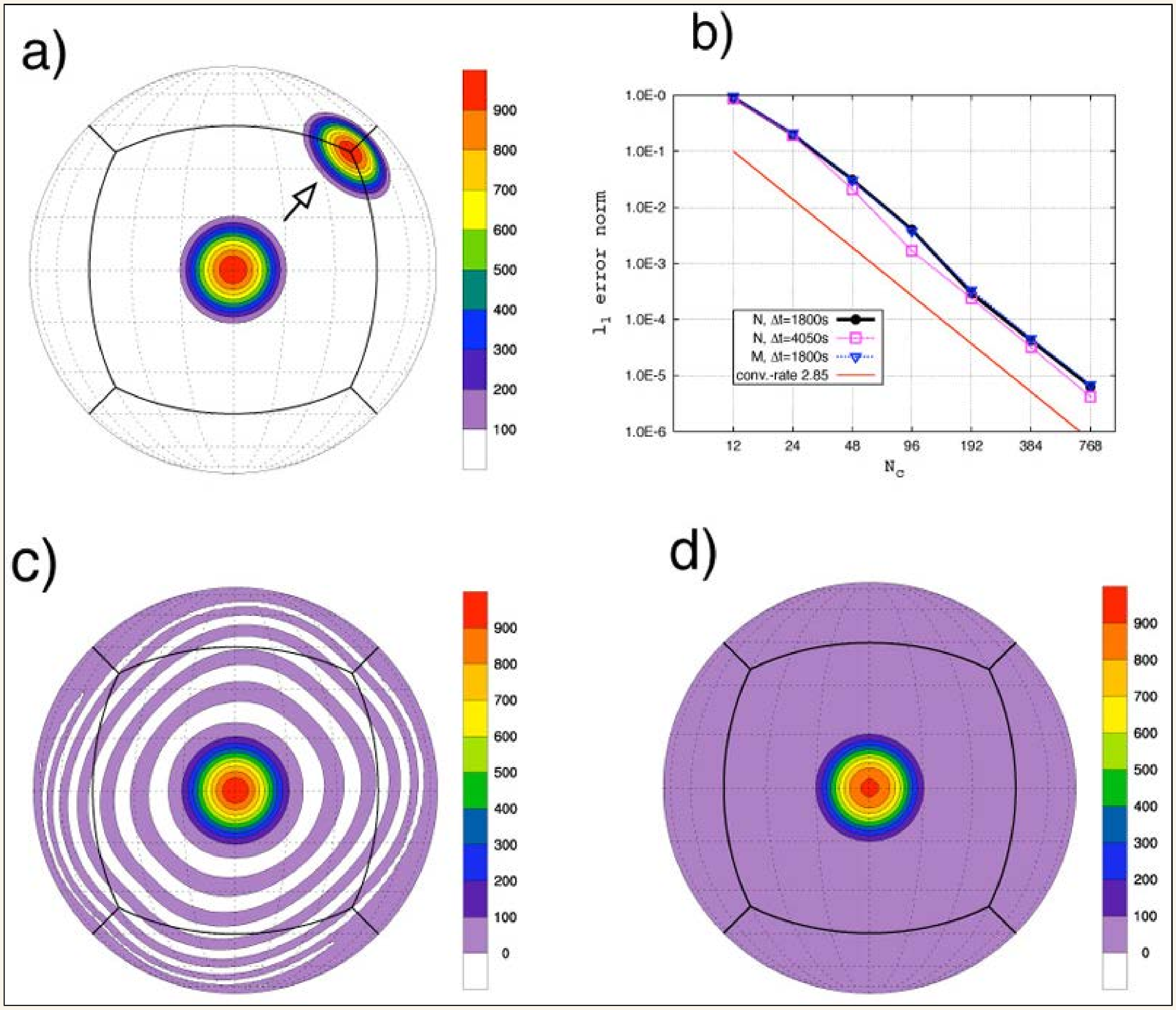
The scalability of CICE at 0.1° has allowed significant increases in the simulation rate and reductions in the computational cost of an ultra-high-resolution CCSM configuration that couples a 0.1° POP and CICE to a 0.5° CAM and LND. During FY2009, improvements in the scalability of component models, system OS, and hardware upgrades have increased the simulation rate of the ultra-high-resolution CCSM from 1.3 simulated years per day to 2.0 simulated years per day. Further, the computational cost has been reduced from 100,000 CPU hours per simulated year to 74,000 CPU hours per simulated year. The increase in simulation rate plus the reduction in cost increases the feasibility of performing 100+ year simulations.

These advances are significant because it is now possible to simulate the Earth System on currently available supercomputing resources at resolutions that are 100 times as computationally demanding as the current production CCSM simulation. 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.

Despite our advances, a number of non-scalable constructs still exist within the CCSM coupled system. In FY2010, we plan to continue improving the scalability of each component model and the entire coupled system by developing the partitioning and decomposition of the computational grid across processors. We also plan to finish adding the Parallel I/O (PIO) library into all component models to provide an extensible flexible parallel I/O capability for CCSM.

This work advances CISL's science frontier in algorithmic acceleration by providing scalability breakthroughs to produce simulations capable of addressing grand challenges. This work is supported by NSF core funding and grants OCI-0749206 and OCE-0825754. Additional funding is provided through the Department of Energy's CCPP program grant DE-FC03-97ER62402.

Accelerating applications algorithmically



In this simulation, (a) shows the initial position of a tracer field (a cosine-bell with a maximum value of 1,000 units). After transporting this field one complete revolution, it returns to its initial position. Discrepancies with the initial values are the numerical errors in the algorithm. The semi-Lagrangian multi-tracer transport algorithm is used for the simulations and a cubed-sphere grid is used for the discretization. Note that the transport purposely traverses the "corners" and "edges" of this grid to make the test more stringent. Part (b) shows the error of the numerical solution as a function of different grid resolutions (Nc) and time steps (delta t). Part (c) is the numerical solution after one complete revolution without constraints on the positivity yielding an non-physical solution. And (d) shows an improved solution with monotonic filtering that avoids spurious undershoots.

A new numerical approach for simulating the simultaneous motion of multiple constituents in the atmosphere as they are transported by the atmospheric flow is a highlight from FY2009. These quantities can be basic physical components of the atmosphere such as water vapor, or they can be specific human-related compounds such as the fine particles released from forest clearing or from urban pollution. This basic problem of determining the path of a substance, or tracer, as it is transported by atmospheric flow is surprisingly difficult because one needs to conserve the quantities being translated while keeping concentrations nonnegative. Its practical significance in modeling is that it allows researchers to attribute the concentrations of tracers at a given location and a given time to their original sources.

In an operational climate model such as the CCSM, transport algorithms (also known as advection algorithms) are responsible for tracking several physical variables and hundreds of chemical constituents. Because of the enormous number of these variables, simulating the transport of these quantities individually is computationally intensive. An efficient strategy that avoids separate advection for each tracer is to use the so-called multi-tracer algorithms optimized for simultaneous transport of a large number of constituents. Technically, a conservative, semi-Lagrangian approach known as incremental remapping lends itself to a

mathematical augmentation that enables reusing the elements of trajectory evaluation and flux reconstruction common to the transport of all tracers. Thus the entire multi-tracer advection can be made extremely efficient and is a new approach to this problem. This transport scheme based on the conservative semi-Lagrangian method has been developed for cubed-sphere geometry to become part of the Community Atmosphere Model (CAM). Distinctive features of this approach are its multidimensionality and compactness that facilitate distributing the computations among large numbers of processors.

In FY2010, the new multi-tracer algorithm will be tested in the HOMME/CAM framework. This involves efficient parallel implementation of the algorithm in HOMME and long-term integration with CAM physics. This will facilitate a thorough testing of the algorithm with dozens of different chemical fields before it is ported to the operational CCSM framework.

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.

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Science Frontier: Large and Heterogeneous Data Sets

The progress of Earth System science hinges on ever more complex and ambitious analyses and assimilations of datasets – and these are growing rapidly in complexity, volume, and diversity. Across observational, simulated, and reanalysis data, all of these aspects pose formidable challenges. To deal with the burgeoning complexity of our data, we have engaged in substantial work in the area of metadata standards, ontology development, and first-generation semantic systems. Data diversity, in terms of formats, protocols, and probabilistic characteristics will be addressed in strategic steps for data assimilation complemented by other software application work (e.g., NCL, PyNGL, VAPOR). As we move toward the era of petascale data, we define R&D thrusts that combine scalable tools and systems along with pattern recognition and machine learning approaches to augment the precious human capital available for analyzing research results.

During FY2009, we made substantial progress – through broad international collaborations – in defining ontologies for climate model metadata and in implementing user interfaces for browse and search that will elevate the research community's ability to analyze petascale multi-model datasets. We drove continued progress in developing analysis and visualization tools that utilize multi-resolution strategies for dealing with very large datasets. These advances, in combination with additional thrusts in the areas of metadata standards for the WMO, regional climate change studies, and the International Polar Year (IPY), serve as a foundation for dealing with the ever-growing challenges of large, heterogenous scientific data.

CISL's science frontier to manage large and heterogeneous data sets is primarily supported by NSF Core funding, with supplemental funding supplied by other sources as noted in the following reports.

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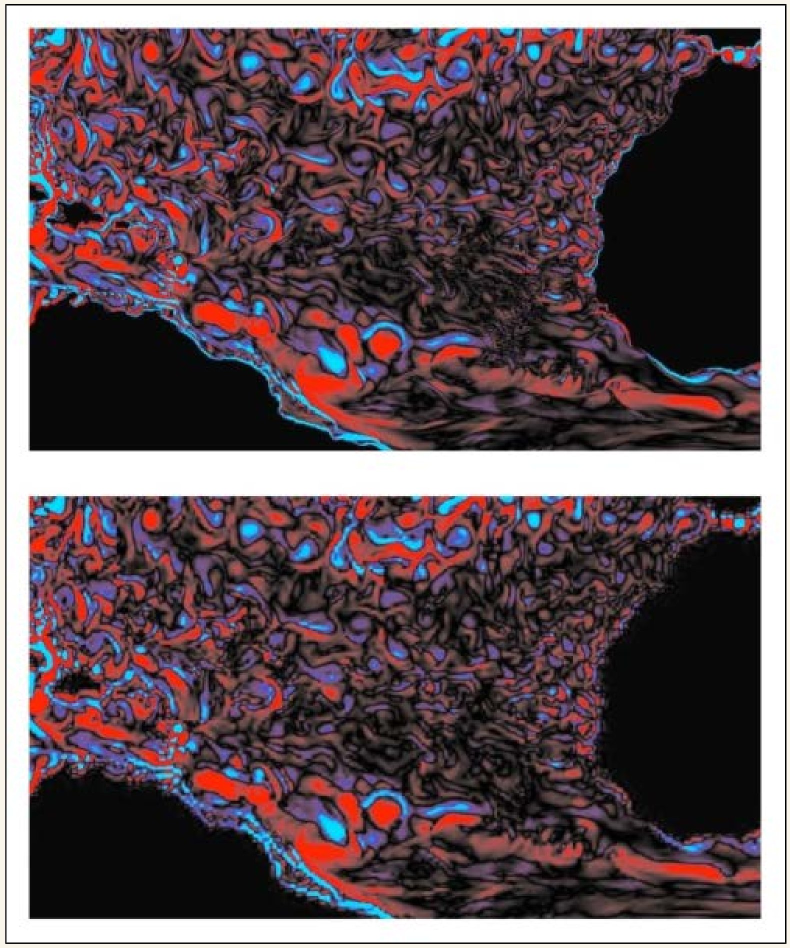
Visualization of large data sets

Computational scientists across a broad spectrum of application domains are benefiting from exponential advances in HPC technologies that are enabling numerical simulations of unprecedented scale. A direct result of the availability of systems with petaflop performance is the ability to produce staggering amounts of data. Unfortunately, the ability of numerical modelers to interactively visualize and analyze data has not kept pace with our ability to generate it. Computing technologies such as secondary storage – essential to, and often the rate-limiting factor for analysis – are on much more modest advancement curves than microprocessor technology. Secondly, few HPC centers are positioned to deploy DAV resources on par with batch computing resources. CISL is thus exploring a variety of approaches for addressing the visualization and analysis of large data sets.



These images demonstrate progressive data refinement applied to the vorticity field from a high-resolution (0.1-degree) ocean simulation with the POP model. The top image shows the original data while the bottom shows a coarsened approximation of the original, substantially smaller, but suitable for interactive browsing. The ability to interactively explore large data sets is essential for curiosity-driven research.

In FY2009, CISL made steady progress toward meeting science frontier goals outlined in the CISL strategic plan in the area of improving scientists' ability to handle large and heterogeneous data sets. CISL successfully partnered with the Texas Advanced Computing Center (TACC), Purdue University, and the University of Utah to win the NSF TeraGrid XD Visualization solicitation. The award will enable the deployment at TACC of the nation's largest-ever visualization and data analysis cluster, and it will also fund collaborative research and development among the partners of software tools capable of fully exploiting the new hardware to visualize and analyze some of the largest simulation outputs. The outcomes of this effort include not only the tools and techniques developed, but the invaluable experience CISL will need to deploy a large-scale data analysis resource of its own, should we choose to do so. In addition to our TeraGrid XD award, CISL has moved forward with research in lossy compression of scientific data. One application of these techniques is progressive data refinement, permitting researchers to interactively browse vast simulation outputs while maintaining access to the data at its full fidelity. Finally, CISL has expanded the capabilities of its VAPOR package to better support the numerical weather community, providing weather researchers with a desktop application suitable of operating on weather data sets of exceptional resolution.

In FY2010 CISL will incorporate research results in lossy data compression and progressive data access into robust, user-friendly tools. A parallel data compression encoder suitable for MPI codes will be developed, allowing modelers to write data directly from their simulation to a compressed or progressive data access file. CISL researchers will explore new partnerships with domain scientists to further vet and evaluate compression-related technologies. CISL will also continue to work with its TeraGrid XD Visualization partners, addressing a number of contractually obligated milestones in the area of large data visualization. Lastly, CISL will integrate the VAPOR multiresolution data model into a variety of other DAV tools – including CISL's own NCL – affording these packages some of the same large-data-handling capabilities found in VAPOR.

Work in the area of large data set visualization and analysis is aimed at satisfying CISL's scientific frontier of understanding large and heterogeneous data sets. As outlined in CISL's five-year Strategic Plan, this work develops new methods and tools to visualize large data sets. It also supports CISL's efforts to prepare for petascale and exascale computing. This project is

supported by NSF Core funds and NSF grant NSF-09-06379.

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Education Imperative: Integrating Research and Education

Building a cadre of students interested in computational science is an essential part of CISL's mission. 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. 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 and education 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 10 SIParCS interns each year and actively recruits for diversity. The RSVP program is visitor driven and operates on a first-come, first-served basis. 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.

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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 10-12-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. An 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.

This photo shows the 14 participants in NCAR's 2009 SIParCS program. Students conducted research in diverse technical areas of numerical algorithms, geostatistics, and computer science. SIParCS aspires to increase the number of trained scientists and engineers capable of using and maintaining 21st-century supercomputers.

NCAR hosted the third annual SIParCS program in 2009. This year the SIParCS intern demographics continued to broaden: the program attracted 14 students from 13 colleges and universities. The applicants came from a nationwide pool including students from the University of Washington, Florida State University, UCLA, and Columbia University – representing the four corners of the continental U.S. The program attracted three students from underrepresented groups in the computational sciences – all female. SIParCS also hosted two students from institutions affiliated with TeraGrid Resource Providers, one from NICS, and one from LSU.

Further, the students' advisors at their home institutions showed increasing interest and involvement in the program. This promises to increase word of mouth about SIParCS and improve the strategic impact of the program through generating new collaborations.

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. CISL's strategy as an educational laboratory focuses on three imperatives: integration of research and education, training and workforce development, and broadening participation. The SIParCS program directly addresses all three. The program supports CISL's primary education imperative and fulfills a strategic action item to integrate research and education to maximally leverage the impact of both.

SIParCS is made possible by NSF Core funding. The program exceeded its target enrollment of 10 students in 2009 through partial financial support of the interns from external sources, including the NCAR Director's Diversity Fund, IMAGe, the National Institute for Computational Sciences, and the University of Wyoming. FY2010 will have similar participation targets, and similar levels of effort in outreach and recruiting.

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IMAGe Theme of the Year education and outreach

The Theme-of-the-Year (TOY) is a series of activities on some aspect of applied mathematics and the geosciences, designed to advance research and education between the mathematical and the geoscience communities. The TOY for FY2009 was entitled Interaction of Simulation and Numerical Methods. A fundamental goal was to connect numerical researchers within IMAGe and NCAR with external groups at multiple national laboratories and the University of Wyoming. It is undisputed that numerical simulation of geophysical processes now plays a central role in understanding the interactions of complex natural phenomena and in making predictions when systems are perturbed.

Some participants from the Frontiers of Geophysical Simulation workshop walking the trails behind the NCAR Mesa Lab after a full day of presentations. This workshop was co-organized by early career scientists in CISL and also by applied mathematicians from Oak Ridge National Laboratory, Sandia National Laboratory, and Université Catholique de Louvain. TOY establishes collaborations around potentially rewarding research activities and encourages contributions from talented young investigators in a variety of disciplines.

Supporting this broad scope of modeling are the numerical algorithms that implement the basic physical equations of fluid flow and thermodynamics with the computational science that links algorithms to particular computing architectures and makes large simulation experiments feasible. It is acknowledged that advances in modeling now depend on numerical and computational advances. The FY2009 TOY addressed this relationship with three workshops:

NCAR/Wyoming Days:

The partnership to build the NCAR-Wyoming Supercomputing Center in Cheyenne has generated closer ties between NCAR scientists and the applied mathematics and computational science faculty at the University of Wyoming. This workshop was successful in bringing these faculty and staff together to identify and to explore common research interests. For example the multiscale simulation environment (MUSE) is an collaboration that includes IMAGe and the University of Wyoming.

Frontiers of Geophysical Simulation:

This workshop focused on the computational and numerical ingredients that are needed for the next-generation climate system models with a focus on Galerkin-based space discretizations. Besides gathering developers of the High-Order Methods Modeling Environment (HOMME), it also included topics on extending numerical methods to adaptive meshes and tens of thousands of cores. A success of this workshop was bringing together groups from various computational centers to discuss common problems in simulating geophysical flows.

Computational Methods for Free Boundary Problems:

This was a synthetic activity involving four leading applied mathematicians and four leading geophysical scientists to give in-depth presentations on the computational and physical aspects of flows that are not constrained by physical boundaries or barriers.

The TOY for FY2010 will be entitled Mathematicians and Climate; it will be co-directed by Chris Jones (University of North Carolina) and Mary Lou Zeeman (Bowdoin College). For essentially every question asked about climate, a mathematical model is the vehicle for extrapolating into the future. It is then essential that the mathematics community be more involved and more mathematicians should be brought into climate change research. This program will use NCAR scientists and facilities as a hub to engage mathematical scientists in substantial problems in climate research. The main activities will be a tutorial workshop on climate processes, a working group that probes the use of data assimilation for developing climate models, and a summer school

in partnership with the Mathematical Sciences Research Institute.

The yearly TOY programs are one of CISL's primary thrusts to fulfill NCAR's core education mission. They support CISL's education imperative to integrate research and education and maximally leverage the impact of both. Intellectually, computational science is interdisciplinary: it is the intersection of computer science, applied mathematics, software engineering, and domain science that gets science done on silicon. Universities are struggling with how to fit computational science research and education into their existing academic structures, and CISL, as an interdisciplinary education laboratory, has unique opportunities to lead and catalyze the development of the computational sciences at universities. TOY programs fulfill one of CISL's strategic action items by encouraging the ever-broader participation of the mathematics community. TOY is supported by NSF Core funding and also seeks grant opportunities to supplement its budget.

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Education Imperative: Workforce Training and Development

CISL must cultivate a cadre of young scientists with the basic skills to use modern supercomputers to answer research questions in the atmospheric and related sciences. To accomplish this goal, NCAR delivers training content synchronously through workshops and training classes, and asynchronously through web content. Two of the principal synchronous activities in CISL include training in scientific data analysis and visualization conducted by the NCL group, and training in MPI, OpenMP, Fortran, and other HPC technologies performed by the Consulting Services Group.

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.

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Training in geoscientific tools

Students at an NCL workshop at the Max-Planck-Institut für Meteorologie in Hamburg, Germany in December 2008. This workshop was by invitation of the institute Director, Bjorn Stevens, who had hosted two NCL workshops when he was a professor of atmospheric sciences at UCLA. These training workshops have been highly successful, and they frequently result in invitations from the international scientific community to teach similar workshops at their organizations.

Staff in CISL/VETS and ESSL/CGD have collaborated for several years to provide a series of training workshops, or "boot camps", for NCL—a free, interpreted language designed specifically for geoscientific data analysis and visualization. A total of 42 local and non-local workshops have been provided to 570 students since the year 2000. These workshops, which are free for students, are four days in length with morning lectures and intensive hands-on labs in the afternoons. A unique aspect of these workshops is that rather than using canned datasets and examples during the labs, students bring their own datasets to the class, and the instructors work with them one-on-one to analyze their datsets using NCL. By the end of the workshop the students have developed nearly complete NCL programs that produce meaningful results from their own data.

A core NCAR value is partnership with the university community, and this was the second year that we offered a free workshop to a qualifying UCAR member university. These workshops have been highly successful (based on attendance, demand, and follow-up survey results). In turn, the workshops have been invaluable to the NCL team, giving them first-hand experience with real-world usage of the software and providing them with crucial information to make necessary software improvements.

These workshops are the key to connecting with scientific users and providing them with the knowledge they need to use these tools effectively in their research. Our community contribution in this area is not simply training to use these tools: it is fundamental training in the important practice of Earth System data analysis.

In FY2009, we taught five workshops: three in Boulder, a free one at the Scripps Institution of Oceanography (a UCAR member university) in San Diego, and one fully funded invited workshop at the Max-Planck-Institut für Meteorologie in Hamburg, Germany. Our international efforts here touch on an NCAR strategic goal of "engaging a broader and more diverse community." The instructors continually revisit the course materials to make improvements, and in response to post-workshop survey results, they restructured the course to free up the afternoons for lab sessions only and to add a series of interactive demos.

In FY2010 we plan to offer 3-5 NCL workshops: two to three to be held locally, one at a UCAR member university, and the rest internationally. Another CISL strategic imperative is to encourage a diverse workforce, and to that end we plan to submit a new proposal in early FY2010 to provide one or more all-expenses-paid trips for students from minority-serving universities to attend NCL workshops. We have been invited back to the Max-Planck-Institut für Meteorologie to teach two back-to-back workshops in FY2010, with the plan that this may become a regularly scheduled course taught by one of their staff members. If time and funds permit, similar training might be extended to the diverse world of scientific Python users, by teaching courses in PyNIO and PyNGL (Python modules based on NCL's file input/output and visualization capabilities).

These training workshops address CISL's educational imperative for workforce training and development, and they fulfill the strategic action items of continuing to teach a total of three to five DAV Boot Camps per year. A second strategic action item is teaching courses in PyNGL and PyNIO. The training workshops are supported by NSF Core funding.

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Training interns in computing at NCAR

Education is a core mission of NCAR. 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. 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.

NCAR supported several HPC training workshops, including the Great Lakes Consortium for PetaScale Computation "Scaling to Petascale Summer School." Funded by NSF through the Blue Waters Project, it was attended by approximately 80 graduate-level students at four sites. Students attended lectures via Access Grid and ran scientific codes on multiple HPC systems, including NCAR's Bluefire system.

Computing skills training

CISL actively participates in mentoring and training student interns, and summer is an especially busy time. In FY2009, we supported a number of internship programs.

We serve as a computing resource for UCAR's Significant Opportunities in Atmospheric Research and Science (SOARS) program. Although a majority of the SOARS protégés in FY2009 were engaged in scientific projects, it is widely understood that simulation is fundamental to today's scientific work. We worked with SOARS this summer to add a new class of mentor – computing mentors – to the existing science, writing, community, and peer mentors. CISL Consulting Services again offered introductory computing classes in topics such as UNIX, NCL, netCDF, and Fortran 90. This summer, approximately 20 SOARS students attended the classes.

A basic UNIX class was also presented to about 20 summer student interns at the request of the High Altitude Observatory.

HPC training and workshops

Because of the paucity of students entering the high performance computing workforce, CISL is taking a more active role in training and workforce development. Cultivating a cadre of young people interested in careers in computational science is an essential part of CISL's workforce development efforts.

As part of the Summer Internships in Parallel Computational Science (SIParCS) program developed by CISL, this summer Consulting Services provided introductory training in parallel programming using OpenMP and MPI.

In addition, Consulting staff supported several HPC training workshops in FY 2009, including the "Scaling to Petascale Summer School," in which approximately 80 graduate-level students ran scientific codes on NCAR's Bluefire system, the Ranger system at the Texas Advanced Computing Center, and the Kraken system at the National Institute for Computational Sciences. CISL worked with organizer Scott Lathrop of the National Center for Supercomputing Applications to set up accounts and reserve 16 dedicated nodes for computing, and a CISL consultant was assigned to work with instructors and students at remote sites to run jobs. We also supported the CAM (Community Atmosphere Model) Tutorial Workshop at NCAR organized by Andrew Gettelman of the NCAR Climate and Global Dynamics Division, and an Ice Sheet Modeling Workshop organized by Jesse Johnson of the University of Montana.

For FY2010, Consulting is developing a 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 teach the course initially at NCAR but will also make the course materials available online via the NCAR MultiMedia services website and possibly via the TeraGrid portal.

Intern training is supported entirely by NSF Core funding.

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Education Imperative: Broadening Participation

CISL's new Strategic Plan elevates education, outreach, and training (EOT) to a core mission of the laboratory, at the same level as the traditional roles of providing supercomputing and data services and doing computational science research. A key element of this role is broadening 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 has aggressively expanded its EOT and diversity efforts in recent years. 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 each served as vibrant, growing, and intersupporting elements in CISL's EOT strategy. CISL has also applied for and made effective use of NCAR Diversity funds. For example, we increased diversity outreach activities, and we also increased diversity participation in CISL's SIParCS program from zero students in 2007 to four students in 2008 using these funds. Three students from underrepresented groups (all women) were recruited in 2009. In 2008 CISL established the practice of supporting one mission-appropriate "diversity" conference each year: in 2008 this was the Colorado Celebration of Women in Computer Science; in 2009, CISL participated in the Richard Tapia Celebration of Diversity in Computer Science. UCAR staff also distributes materials at diversity conferences such as the Society for the Advancment of Chicanos and Native Americans in Science (SACNAS). CISL does outreach through site visits and presentations to universities by making contact with audiences at selected universities (Louisiana State Univerity, Lehigh University, and the United Tribal Technical College in FY2009) as a key strategic element of our recruiting activities. SIParCS is also cross listed on the TeraGrid internship website, allowing effective cross-marketing to occur. CISL distributes information at the Supercomputing Job Fair and at conferences such as Supercomputing, AMS, and AGU.

In FY2010 we will take CISL's efforts to broaden participation to the next level: we will use special NCAR Diversity Funds, in most cases along with matching CISL diversity funds, to dramatically broaden and enhance CISL's diversity initiatives across all of its EOT activities. We will do this in five ways:

1. Plan to lower the barriers to training access by providing travel funds to two NCL data analysis and visualization workshops or other CISL cyberinfrastructure-related training workshops for students and staff from U.S. minority-serving institutions.
2. Leverage matching CISL diversity funds for our visitor program (RSVP) to encourage university research visitors from diverse backgrounds to visit CISL and NCAR, perhaps in concert with SIParCS or IMAGe's Theme of the Year (TOY) programs.
3. Further expand CISL-based outreach activities to include participation in additional diversity-oriented conferences and institutions. Specifically, CISL staff will conduct up to four outreach visits to minority-serving institutions or diversity conferences in FY2010.
4. We will use use the NCAR Director's funding to build a critical mass of diversity candidates large enough to enhance the diversity-friendly environment of our SIParCS internship program.
5. We plan to use some of the funding to cover costs related to SIParCS diversity intern professional enrichment, such as participation in or giving presentations or posters at technical conferences, paper publication costs in peer-reviewed journals, or for modest follow-on salary costs to complete a project after the end of the summer.

CISL's education imperative for broadening participation is supported by NSF Core funding with supplemental funding from other sources as noted above.

Education Imperative: Outreach

Outreach is a gateway activity: it is the conduit through which all other goals occur, examples include integrating education and research, broadening participation, and developing the workforce. 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:

- Reaching a larger and broader audience
- Making our message more impactful and compelling
- Better communicating our accomplishments and the excitement of working in CISL

As described in this section, in FY2009 CISL has invested heavily in modernizing its Visualization Laboratory, has significantly expanded its outreach efforts at mission-appropriate conferences, and directly encouraged people from underrepresented groups to pursue careers in the computational sciences.

CISL's education imperative for outreach is supported by NSF Core funding, with supplemental funding supplied by other sources as appropriate.

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Visualization Laboratory outreach efforts

Boulder area students from Mountain View Preschool prepare to watch a 3D presentation in CISL's Visualization Lab. CISL's outreach efforts reach a broad and diverse community including government and corporate visitors, university and K-12 students, and pre-schoolers. NCAR staff provide dozens of presentations each year to educate audiences and encourage their interest in the geosciences. (Photo courtesy Ryan McVeigh.)

CISL's Visualization and Enabling Technologies Section (VETS) operates a visual computing center that is used to conduct many of CISL's education and outreach 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. In FY2009, the facility was newly equipped with a high definition, 3D, 1920 × 1080 resolution, active stereo projector and a 12 × 7-foot screen. This system can display imagery and presentation materials simultaneously from multiple sources including user laptops, digital media systems, and video conferencing platforms.

The Vislab remains an important resource for CISL's education and outreach efforts through the support of classes, meetings, and educational activities to thousands of staff and visitors. Activities in the Vislab span from advanced collaboration environments that foster geographically distributed research and communication, to supporting a sizable outreach program that provides 3D presentations to a wide range of student, governmental, and scientific visitors each year. 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 a venue by film crews who perform on-site interviews with NCAR scientific staff.

In FY2009, the Vislab continued to provide support for 3D demonstrations to help educate visitors about NCAR research and environmental and scientific issues such as global climate change and severe weather. Staff installed a new h.323 video conferencing technology that expands CISL's ability to communicate with key partners, and they continued their productive partnership with the NCAR Public Visitor Program to provide K-12 audiences with engaging 3D visualizations of environmental and Earth System science. In all, the Vislab supported over 170 meetings and demos to approximately 2,400 visitors and users in FY2009. Major upgrades to the Vislab's computing and projection systems were also completed this year. Initial plans were to make modest investments to upgrade the Vislab's Access Grid and display systems, then implement a more substantial upgrade next year. However, additional funds allowed us to accomplish many of our FY2010 plans. We made significant changes to our projection, audio, display, video conferencing, switching, and control systems. Vislab staff upgraded the Access Grid hardware, installed a new Polycom video conference system, replaced the audio and telephone conferencing systems, added a new digital media display system, and modernized our projection system by replacing five aging projectors with a single, high resolution, stereoscopic projector and a new display screen. These enhancements simplify the maintenance and control of the Vislab, enable the production and sharing of more compelling visualizations and presentations, and broaden our collaboration capabilities to a wider community.

In FY2010 the CISL Visualization Lab will continue to provide support for 3D demonstrations to help educate NCAR visitors and the public about NCAR research and environmental and scientific issues. We will continue to provide video conferencing capabilities and a venue for scientific interviews with the broadcast media as well as digital materials upon request for broadcast and educational purposes. We will also continue our productive partnership with the NCAR Public Visitor Program to provide K-12 audiences with engaging 3D visualizations of environmental and Earth System science. Additionally, we will explore performance enhancements to the Vislab's new movie playback system by investigating attaching a RAID device, taking advantage of enhanced presentations afforded by our new projection system, and investigating methods to improve the Vislab experience by exploring mechanical sound mitigation options and sound cancellation technologies to suppress projector fan noise.

The Vislab and VETS staff play an important role in advancing CISL's education imperative for outreach. This work fulfills the strategic action item for CISL to tell NCAR's story to the world. Specifically, it will continue and expand successful partnerships

with the NCAR Public Visitor Program, Office of Government Affairs, and others to engage a broader and more diverse scientific community. The Vislab will create new and engaging visualization material and environments that will help captivate the interest of K-12 audiences and educate scientific, corporate, and government visitors about NCAR research and important and relevant environmental and Earth System science. The Vislab also upgrades and expands our collaboration and display technologies as needed. This project is supported by NSF Core funding.

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Outreach activities at conferences

James Done of NCAR's Mesoscale and Microscale Meteorology Division, presented "Hurricane Modeling using the Advanced Hurricane-research WRF Model" as part of NCAR's exhibit at SC08 on 18-19 November 2008. CISL conducts outreach activities using exhibit booths at the yearly Supercomputing conference, the TeraGrid conference, and other venues. By representing NCAR's science and technology efforts every year at gatherings of researchers, CISL shares its expertise with and gains valuable insights from the research community.

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 other NCAR research in science, computer science, applied mathematics and statistics for the geosciences, and technology. At the height of its conference outreach program, CISL staff provided demonstrations and presentations at several conferences each year, including Supercomputing, the American Meteorological Society, the American Geophyscial Union, and others. In recent years, CISL has focused 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.

In FY2009 and in coming years, CISL provides TeraGrid external relations support at the Supercomputing and TeraGrid conferences. Also in FY2009, CISL supported and participated in the Tapia Celebration of Diversity in Computing conference in Portland, Oregon on 1-4 April 2009 (see photo above). During FY2008 and into FY2009, CISL organized and hosted the 10th LCI International Conference on High-Performance Clustered Computing in Boulder, Colorado.

The LCI conferences provide an international forum to share information on management, administration, and scientific computing techniques for high performance clustered computing. LCI conferences offer advanced technical training for those interested in deploying high-performance computing clusters. The conference at NCAR focused on the challenge of breaking the petascale barrier and examined the promise of new technologies such as multi-core processors, acceleration coprocessors, advanced interconnects and high-performance I/O solutions. It also explored potential scaling and performance modifications necessary for systems, data, and applications to achieve petascale performance.

This summary lists the conferences that CISL staff actively supported in FY2009:

- SC08, Austin, Texas, 15-21 November 2009
- 10th LCI International Conference on High-Performance Clustered Computing, Boulder, Colorado, 9-12 March 2009
- Tapia Celebration of Diversity in Computing, Portland, Oregon, 1-4 April 2009
- TeraGrid'09, Arlington, Virginia, 22-25 June 2009

CISL's conference 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 undertaken using NSF Core funds.

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Education Frontier: Transforming Education, Outreach and Training

CISL is beginning to leverage information technologies to transform education, outreach, and training. High performance computing has emerged as an essential research tool in science, technology, engineering, and mathematics. IT in general has global reach, powerfully amplifies the scale and impact of EOT efforts, can connect widely distributed groups for educational purposes, and levels playing fields. However, universities across the country are struggling with integrating high performance computing in their educational programs. One reason is that the computing power driving this "computational science revolution" demands increasing power, space, and cooling for the equipment. The revolution is becoming a facilities headache for universities. Furthermore, the architecture of these systems is increasingly complex, with intricate memory hierarchies and high levels of parallelism: features that increase programming complexity. Graduate students' ability to complete their dissertations is, in many cases, increasingly constrained by their access to high performance cyberinfrastructure and their skill as programmers, or even worse, as system administrators.

CISL will begin exploring several possible ways to address these challenges:

- We could create interactive web-based training/education portals and integrate them with science gateways. Currently, educational materials, data, tools, and modeling infrastructure are distributed and managed independently. The science gateway concept offers the promise of simplified use (and therefore less training required) by integrating and prepackaging all of these components. However, this could be a costly enterprise: for example, producing interactive training materials requires two orders of magnitude more time to produce than to use. Even worse, training materials for high-end systems have a short shelf life. CISL will investigate ways to reduce the cost of constructing and maintaing useful, up-to-date, interactive educational materials.
- We will investigate new ways of using Grid technology to develop active education and research partnerships with universities in computational Earth System science. CISL's interest in working with regional university partners is based on a vision that building computing-based collaborations with these universities would foster the growth and development of a regional Grid cyberinfrastructure around the proposed NCAR-Wyoming Supercomputing Center. This could entrain students and faculty at local universities around issues of common interest, such as regional climate change, hydrology, ecology, and renewable energy, and it would foster the growth of a regional workforce qualified to tackle the computational aspects of such common interests. To date, CISL has created partnerships (of varying depth and formality) in the computational sciences with numerous Front Range colleges and universities. CISL staff have organized joint colloquia, retreats, and mini-symposia with the region's colleges and universities; provided advice and input on system procurements; consulted on facility design options; and supported or participated in collaborative grant proposals.
- In FY2009, CISL's Outreach Group began researching social networking technologies as vehicles for outreach activities. In FY2010, CISL will begin leveraging YouTube®, LinkedIn®, and other social networking technologies to encourage interns to report on their work experiences and connect with research professionals. NCAR is already packaging science segments and visualizations into video and establishing a presence in the social media. Social networks are also being used to enhance professional connections to the UCAR community.

CISL's exploration of the education frontier for transforming EOT is supported by NSF Core funding.

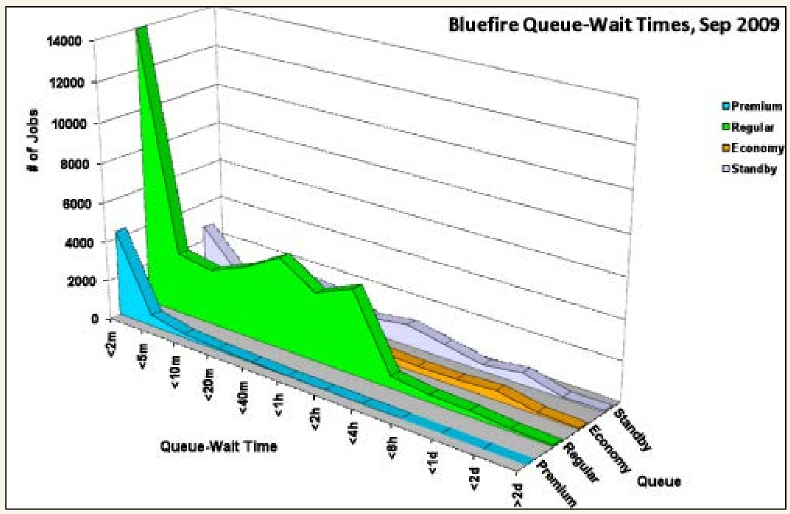
Service Fabric

CISL's Fabrics are shared values that guide our actions and bind us together as a unit. Service is a core Fabric that contributes to our success as a Laboratory. We strive to measure and inculcate this Fabric throughout the organization. The metrics listed below are specific to CISL's mission; they supplement the standardized metrics CISL reports in the NCAR Annual Report.

Serving the scientific community is a CISL core value, and it is one of the highest priorities of NCAR's facilities, research, and operations units. The Service Fabric is characterized by the following behaviors: valuing the science mission; understanding and empathizing with the user experience; listening and communicating effectively; and delivering services fully consonant with user requirements. CISL recognizes the role of a service mindset to its mission and uses its staff to a) analyze user requirements and needs, b) maximize use of facility resources for the science mission, c) share expertise within the internal and external service communities, and d) implement best practices to ensure the delivery of services and projects in an effective, efficient, and transparent manner.

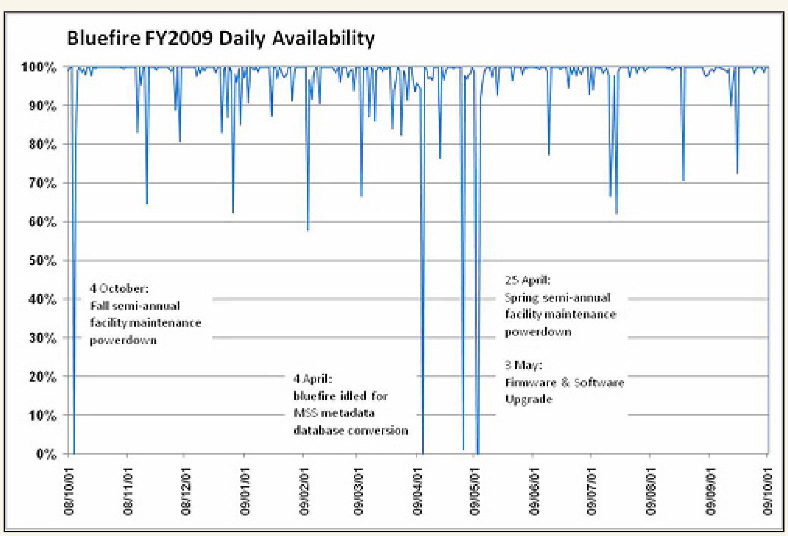
Metric 1: System uptime, queue wait times, MSS response times, MSS archive policies, trouble ticket resolution metrics

During FY2009, CISL continued real-time monitoring of HPC and archival storage systems not only for the subsequent analysis of system workload and behavior, but for real-time operational event monitoring and notification. The former provides the basis for long-term analysis of computing and storage trends while the latter enables a more rapid notification of and response to operational issues when they arise.



Monitoring job queue-wait times on NCAR HPC systems and analyzing trends are ways CISL evaluates the quality of its service to the user community.

Overall system utilization, individual job utilization and job-based and system-wide computational efficiency are monitored continuously, and daily, weekly and monthly reports are generated. Some analyses, such as a daily accounting of jobs that used Bluefire inefficiently, are provided to CISL's Consulting Services Group who can then work with individual users to improve the performance of their applications.



Real-time monitoring of the Bluefire system's operational health allows CISL to track overall system availability to users. Incident analysis and component failure tracking also provides insights into trends observed during routine monitoring.

The primary HPC workhorse during FY2009 was the IBM Power 575 cluster Bluefire, which exhibited an average 94.8% availability and 90.0% system-wide user utilization during the fiscal year. Real-time monitoring, failure and incident analysis, and enhanced operational and administrative procedures allowed CISL to rapidly respond to component failures and performance issues.

With the operational commissioning of the AMSTAR equipment, CISL's Mass Storage Systems Group began transitioning over 6 TB of data stored on older media to the new higher-speed, higher-density technologies. All new MSS data began being stored on the AMSTAR equipment in January 2009, and the HPSS test bed became operational during the spring of 2009. The operation, administration, and management of these

systems, as well as the plans to migrate archival storage to HPSS by 2011, require constant monitoring of system load, responsiveness, and performance.

The NCAR Research Data Archive (RDA) expanded with nine new data collections and numerous routine updates (66 collections received monthly, or more frequent, updates during the fiscal year). Most notably, a portal interface to access TIGGE data was completed that allows user-selectable subsetting (spatial, temporal, parameter), regridding, and output options. During FY2006, the RDA was modified to require user registration. This enhanced CISL's ability to track user activity and characterize it in many ways, including the geographical distribution of users and data dissemination. For more information on RDA activities, see this year's Research Data Archive report.

CISL's Consulting Services Group (CSG) augmented their trouble ticket system to provide better statistics on speed of problem resolution and other key metrics, and to provide metrics similar to the TeraGrid's help-desk metrics. An example of some average metrics is given in the following table; the Computer Production Group (CPG) initially reviews all tickets and either resolves problems or for more complex problems, passes them to CSG. Further enhancements of the trouble ticket system and its monitoring and metrics analysis capabilities are envisioned for FY2010 in anticipation of the NWSC operational transition.

FY2009 CISL Consulting Services	CPG	CSG
Number of tickets	1,607	856
Number of incident updates	7,718	4,193
Average resolution time (days)	0.61	5.13
Average number of staff on ticket	1.7	1.1

During FY2010, CISL intends to continue real-time monitoring of our HPC systems and their workload, and to characterize workload performance, system responsiveness, and reliability. We will also investigate additional ways to identify outlier cases such as underperforming applications.

In conjunction with the procurement processes for the HPC and related equipment for the NWSC, CISL will establish Science Advisory Panel and technical and business evaluation teams to guide the development of technical requirements based on the scientific needs of CSL, NCAR, the University community, and NCAR's Wyoming partners. These teams will guide and develop key metrics that will be used not only to articulate the technical requirements for the equipment, but also the criteria for evaluating vendor proposals.

Also during FY2010, the Mass Storage Systems Group will begin transitioning from the locally developed MSS software to HPSS. Adoption of HPSS will align NCAR with external partners and is expected to reduce costs associated with continued development and maintenance of the MSS data archive system. Constant analysis of system performance and responsiveness will be performed, along with user satisfaction assessments. New web-technology-based systems will be implemented to allow user queries, forums, news, and blogs to assist users and administrators with the MSS-to-HPSS transition, with new HPSS metadata analysis, and with data repository manipulation.

The RDA and its user-level accessibility will continue to be enhanced during FY2010. This will allow more automated and efficient practices consistent with standard metadata and data access methods, and it will allow further refinement of RDA access and usage metrics. Usage metrics gathering and analysis will continue, with an eye toward identifying areas where end-user utility and data accessibility can be enhanced.

Metric 2: User surveys

During FY2009 CISL surveyed UCAR network users and the user communities for VAPOR and the National Centers for Environmental Prediction. CISL also began work on a user satisfaction survey to evaluate its effectiveness in providing computational and data storage needs for its HPC users and to identify specific strengths and weaknesses. CISL will conduct this survey during FY2010. The results of this HPC user satisfaction survey will help guide CISL in its transition of operations from the NCAR Mesa Laboratory to the NCAR-Wyoming Supercomputing Center.

NETS survey of UCAR staff

CISL's Network Engineering and Telecommunications Section (NETS) surveyed UCAR staff between 1 August and 1 September 2009. The survey is being used to evaluate and improve networking services at UCAR. Partial responses were received from 196 people, and 179 people completed the survey. NETS is evaluating the results in conjunction with NCAB, the Network Coordination and Advisory Board.

VAPOR user community survey

The VAPOR (Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers) user community was surveyed between 25 September and 9 October 2009 with 144 people participating. The primary purpose of the survey is twofold:

1. Help CISL determine which features of the VAPOR suite are being used (and why unused features are not being used). This information may lead to changes in documentation, training, and example utilities that we offer.

2. Help CISL determine and prioritize new areas of development for future VAPOR releases.

Other surveys

During FY2009 CISL assisted UCAR with multiple surveys of the National Centers for Environmental Prediction (NCEP) user community to inform a review of NCEP undertaken at the request of the atmospheric science research community.

Plans for FY2010

In FY2010, CISL will:

- Complete the analysis of the FY2009 NETS survey, review areas of concern with NCAB, and work on improvements.
- Complete the analysis of the FY2009-10 VAPOR survey and fold user needs and requests into VAPOR development plans.

During the first quarter of FY2010, develop and conduct a survey of CISL's HPC user community on HPC services to:

- Obtain in-depth evaluation of select HPC services to identify impediments to user research progress. Also identify areas of excellence to ensure they are maintained.
- Contact users who have concerns to further understand their needs, unless they have requested that their responses be anonymous.
- Improve processes and user services based on HPC survey results during the remaining quarters of FY2010.

Metric 3: Community service activities

CISL staff serve the research community in a variety of ways. The following table summarizes our FY2009 service, and full details are available in a spreadsheet accessible at the end of NCAR's annual Metrics Highlights report.

Number of staff	Type of service
5	Editorships
72	External committee service
230	Scientific and technical presentations
6	Colloquia, symposia, and tutorials hosted
11	Conferences and workshops hosted
9	Teaching appointments
9	Advisors on graduate research
15	Dissertation or thesis committee memberships
26	Advisors to students and postdocs
1	Appointments as affiliate scientist
5	Service to K-12 schools
1	Awards from external organizations
2	Fellowships

Metric 4: CISL Incentive Awards for service

Twice each year, CISL recognizes outstanding staff performance by presenting awards at all-staff meetings. In FY2009, 12 staff received awards for outstanding service:

Awardee	Reason for service award
Anderson, Bryan	Spring/Nextel replacement project
Chastang, Julien	Prototype portal for the 2008 ASP Colloquium
Cinquini, Luca	Prototype portal for the 2008 ASP Colloquium
Custard, Jeff	FRGP representative on the Quilt CIS RFP
Elahi, Irfan	IBM Power575 Bluefire system installation
Fisher, Joan	Managing CISL office relocations during the NCAR Mesa Lab Refurbishment Project
Genty, Marc	HPSS installation

Ghosh, Siddhartha	IBM Power575 Bluefire system installation

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Innovation Fabric

CISL's Fabrics are shared values that guide our actions and bind us together as a unit. Innovation is a core Fabric that contributes to our success as a Laboratory. We strive to measure and inculcate this Fabric throughout the organization. The metrics listed below are specific to CISL's mission; they supplement the standardized metrics CISL reports in the NCAR Annual Report.

Innovation is the transformation of creative ideas into better products and services or new approaches for solving problems. It is expressed as an attitude of curiosity, creativity, and skepticism toward the status quo. The integration of operations, technology transfer, and scientific research (often in matrixed projects) within CISL facilitates innovation because our staff is encouraged to see opportunities and problems from new and broader perspectives. All external research proposals are reviewed at the Lab level, and this also presents an opportunity to make connections between new ideas and needs in other parts of the Lab. Working within the Mesa Lab facility's power constraints and accommodating an exponential growth of archival storage have created an ongoing climate of innovation: power is related to UCAR's carbon footprint, and storage must meet the I/O requirements of petascale simulations. We recognize and reward innovation among staff at the semi-annual CISL town meetings.

Metric 1: CISL Incentive Awards for innovation

Twice each year, CISL recognizes outstanding staff performance by presenting awards at all-staff meetings. In FY2009, two staff received awards for innovation:

Awardee	Reason for service award
Baerenzung, Julien	Modeling of high-Reynolds-number flows with solid body rotation
Oehmke, Bob	Delivery of higher-order interpolotion for CCSM IPCC runs

Metric 2: Early adoptions of new technologies and evaluations of emerging standards

In coming years, CISL will strive to:

- Evaluate major procurements with respect to innovative components
- Track unique services, functions, and products that are not provided by other HPC centers and research groups
- Track energy efficiency relative to other data centers

Leadership Fabric

CISL's Fabrics are shared values that guide our actions and bind us together as a unit. Leadership is a core Fabric that contributes to our success as a Laboratory. We strive to measure and inculcate this Fabric throughout the organization. The metrics listed below are specific to CISL's mission; they supplement the standardized metrics CISL reports in the NCAR Annual Report.

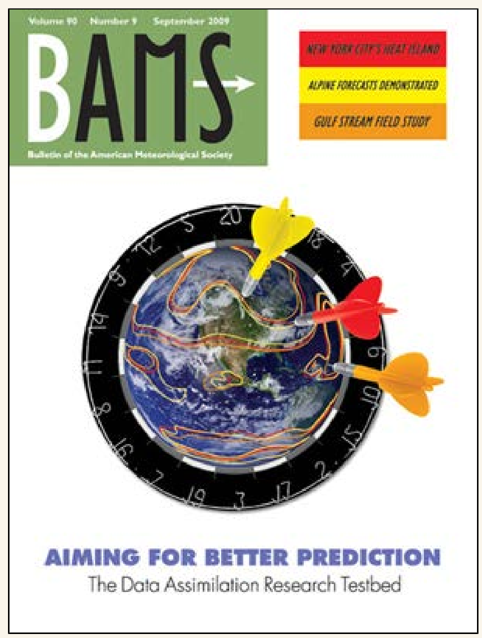
Leadership is defined as a process by which a person or group a) influences others to accomplish an objective, or b) directs the organization in a way that makes it more cohesive and coherent. A willingness to lead is an essential characteristic in a rapidly changing and forward-looking field such as information technology. Within CISL, leadership means asking what the next big thing is, or what needs to be done, then taking steps to bring those things about. Ways in which leadership can be measured as a quality, both internally and externally, are through stature among peer organizations, awards for excellence, and participation in formal leadership training.

Metric 1: Community service activities led and panels chaired

CISL staff are frequently asked or invited to make presentations on topics for which they are considered experts. They also participate on or provide chairperson guidance to advisory or steering panels that peer organizations use to establish directions for future endeavors. In FY2009, CISL staff served as chair or co-chair of eight external scientific, technical, policy, and educational committees.

Metric 2: Awards and other forms of recognition received from outside organizations

Staff members sometimes receive recognition, in the form of awards, for efforts within their area of expertise. In FY2009, artwork by graphic designer Candice Murray of CISL's Outreach Services Group was placed on the cover of the September 2009 issue of the Bulletin of the American Meteorological Society. The cover story is an article about IMAGe's Data Assimilation Research Testbed (DART).



IMAGe's Data Assimilation Research Testbed (DART) is featured in the September issue of the Bulletin of the American Meteorological Society. Artwork by Candice Murray of CISL's Outreach Services Group was selected for the cover. Developed and maintained at NCAR, DART provides software tools for data assimilation education, research, and development.

Metric 3: Staff participating in formal leadership training

As CISL staff advance in their careers, they are encouraged to take formal leadership training as appropriate. UCAR provides two such programs, the UCAR Leadership Academy and the Executive Leadership Program. Neither program was held in FY2009, so no CISL staff participated. For FY2010, three CISL staff are enrolled in the UCAR Leadership Academy.

publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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Collaboration Fabric

CISL's Fabrics are shared values that guide our actions and bind us together as a unit. Collaboration is a core Fabric that contributes to our success as a Laboratory. We strive to measure and inculcate this Fabric throughout the organization. The metrics listed below are specific to CISL's mission; they supplement the standardized metrics CISL reports in the NCAR Annual Report.

Collaboration is very important to an interdisciplinary laboratory: it fills holes in resident expertise, infuses new ideas, and amplifies CISL's impact. It manifests itself through a spirit of inclusion, openness, and a resistance to the "not invented here" syndrome. CISL strives to maintain strong collaborative relationships at all levels: within CISL divisions and sections, across NCAR laboratories and UCAR programs, and outward to the academic programs of universities, scientific research laboratories, and peer international research and computational facilities.

Metric 1: Collaborators and visitors attracted to CISL

Formal collaboration programs within CISL are promoted through activities such as RSVP and IMAGe's Theme-of-the-Year (TOY). The number of visitors to CISL and NCAR are recorded to quantify these collaborations. In addition, CISL has historically maintained collaborations with visitors from universities, federal research laboratories, and international research facilities; the types of collaborations include:

- Co-investigators on agency proposals
- Co-investigators on innovative research topics that result in co-authored reports and/or peer-reviewed scientific papers
- Memos of Understanding (MOUs) that allow for common facility challenges and/or successes to be shared and discussed

In FY2009, CISL conducted formal collaborations with 53 partner organizations.

IMAGe hosted 56 visitors, and the rest of CISL hosted 16, for a total of 72 visitors in FY2009.

Metric 2: Visits made by CISL staff to universities and government laboratories for collaborative purposes

CISL will begin tracking this metric in FY2010.

Metric 3: Collaborative proposals written and funded

CISL staff maintains strong collaborative relations with internal and external colleagues by writing proposals for funding from multiple external agencies. These proposals request funds for projects that act to benefit NCAR or the collaborators or both. We carefully track the success, and resulting awards, of these proposals to provide guidance for future responses and submissions to agency announcements of opportunity.

In FY2009, CISL's Technology Development Division (TDD) and IMAGe submitted 25 collaborative proposals and 8 were funded during the fiscal year.

Metric 4: Joint appointments

In FY2009, TDD and IMAGe supported seven staff on joint appointments with other NCAR divisions and UCAR programs. TDD supported one joint appointment with an outside institution.

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Mentorship Fabric

CISL's Fabrics are shared values that guide our actions and bind us together as a unit. Mentorship is a core Fabric that contributes to our success as a Laboratory. We strive to measure and inculcate this Fabric throughout the organization. The metrics listed below are specific to CISL's mission; they supplement the standardized metrics CISL reports in the NCAR Annual Report.

All parties gain by mentoring: those being mentored benefit from the experience and insight of the mentor; for the mentor, it inculcates a culture of giving, reinforces the habit of service, and encourages lifelong learning. Seen this way, SOARS and the CISL summer internship and visitor programs (SIParCS and RSVP) are opportunities for improving and enriching our work experience through mentorship. CISL has a respectable history of providing mentors in these programs.

Metric 1: CISL staff involvement in formal mentoring roles

In FY2009, CISL staff members served as:

- Research mentors for 14 SIParCS interns
- Writing mentors for 2 SOARS proteges
- Advisors on graduate research to 9 graduate students
- Advisors to 2 graduate research assistants
- Advisors to 9 undergraduate research assistants

In FY2010, CISL will investigate ways to formalize the mentorship of CISL staff by CISL staff. Relevant practices include supervisor-to-employee mentoring, succession planning, and peer mentoring.

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Diversity Fabric

CISL's Fabrics are shared values that guide our actions and bind us together as a unit. Diversity is a core Fabric that contributes to our success as a Laboratory. We strive to measure and inculcate this Fabric throughout the organization. The metrics listed below are specific to CISL's mission; they supplement the standardized metrics CISL reports in the NCAR Annual Report.

Promoting diversity in CISL's workforce not only improves the breadth of perspectives, approaches, and experience we bring to solving our problems, it also maximizes the size of the applicant pool. In CISL, the diversity fabric is characterized by an environment that welcomes, values, and respects different backgrounds, points of view, and lifestyles.

CISL's contributions to training a diverse workforce depend partly on the quality of mentorship throughout the lab. The visitor programs also provide a useful platform for enhancing diversity as well as advertising research and training opportunities at universities with large populations of students from under-represented groups.

Metric 1: Track and review diversity of CISL new hires

Record keeping for this metric will begin in FY2010.

Metric 2: CISL staff visits to universities and conferences for encouraging a diverse visitor pool

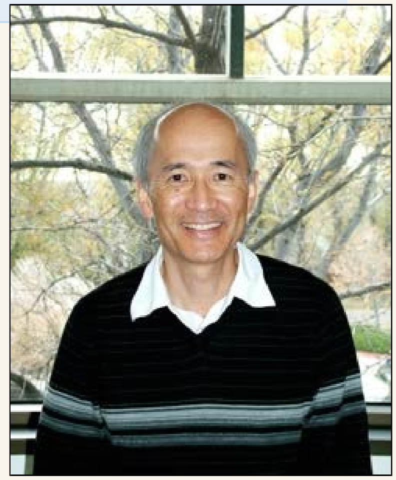
In FY2009, CISL supported and participated in the Tapia Celebration of Diversity in Computing conference in Portland, Oregon on 1-4 April 2009. At CISL's information table, Matthew Woitaszek, Janice Kauvar and Marijke Unger (CISL Outreach Group) spoke with more than 200 participants over the course of four days, encouraging faculty members to nominate students for NCAR programs, answering questions about the scientific research NCAR enables, and discussing with students how they can hone their skills working with us. As shown in the photo, CISL distributed printed information about computing at NCAR, internship opportunities and professional development programs including SOARS and SIParCS, and TeraGrid science highlights from recent years.

CISL will again support at least one participation-broadening conference in FY2010.

Janice Kauvar (Outreach Services Group Head and CISL Administrator, at right) and Matthew Woitaszek (Scientist I in CISL's Computer Science Section, center) engaged participants of the Tapia Celebration of Diversity in Computing conference, where over 400 students, faculty, and sponsors assembled to discuss how to encourage and increase opportunities for underrepresented groups in the computing field. NCAR sponsored participation for four students at the conference, and CISL hosted an information table promoting internship opportunities and professional development programs at NCAR. CISL has an established practice of supporting one mission-appropriate conference each year to broaden participation in computational science, applied mathematics, and the geosciences.

DIRECTOR'S MESSAGE

Welcome to the Earth Observing Laboratory's 2009 Annual Report



Dr. Roger Wakimoto is Associate Director of NCAR for the Earth Observing Laboratory

When NCAR was established nearly 50 years ago, it was charged by the National Science Foundation with providing observing facilities and associated services for the community of university atmospheric scientists, with emphasis on large and expensive facilities that are better provided centrally rather than by a single university group. This part of the NCAR charge now rests primarily 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 I came to EOL in 2005 we refined this mission statement into our "Three D's" that are currently in our logo: Development, Deployment, Data Services. This year we have officially added a forth "D" to describe the concept that underpins all our efforts to fulfill the first three: "Discovery."

Earlier this year when we wrote our Laboratory Strategic Plan we framed our activities as a lab in the context of not only our mission statement but of our "Four D's". This annual report describes the efforts we undertook in 2009 to carry out the objectives described in our Strategic Plan.

Development

Cynthia Bradley, an engineer in EOL's Design and Fabrication Services, conducts a test installation of the new AVAPS III dropsonde dispenser she is designing for the Global Hawk Unmanned Aerial Vehicle (UAV).

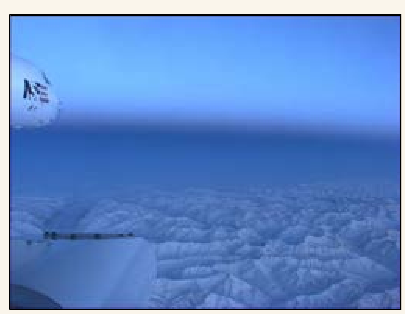
EOL's Development activities are described by Imperative III of our Strategic Plan: "Anticipate future needs resulting from changing priorities, aging equipment or emerging opportunities, and develop new technology (instrumentation, software, and infrastructure) to meet those needs."

Many of our efforts in FY2009 revolved around NSF/NCAR Gulfstream V (G-V) enhancements including the development of instruments specifically for use on the G-V; underwing pods large enough to safely carry larger instruments such as remote sensing equipment; the design, installation, and certification of optical windows suitable for instruments such as the High Spectral Resolution Lidar.

EOL also began work with National Oceanic and Atmospheric Administration (NOAA) / Unmanned Aerial System (UAS) to develop the next generation Airborne Vertical Atmospheric Profiling System (AVAPS) III Dropsonde system for installation on one of the Global Hawks as well as on the NSF/NCAR G-V (see figure to the left). This will have 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.

EOL is also continuing its efforts to support the research community by acting as a resource of information regarding research instrumentation through the Facilities for Atmospheric and Earth System Research Database (FAESR) formerly known as the NSF Facilities Assessment Database.

Deployment



Deployment activities in EOL are so vast and varied that they encompass 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."

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 maintain their readiness for our vigorous deployment schedule. Imperative I also encompasses major upgrades that become necessary due to old technologies becoming obsolete or new technologies that promise increased efficacy of the

instrument. Two notable Imperative I projects we began in FY 2009 are the modernization of the NSF/NCAR C-130 avionics package and the upgrades to the Electra Doppler Radar.

The G-V flies over the Brooks Range in Alaska during the HIPPO Campaign. The wing-mounted camera that took this photo recorded images such as this one every few minutes throughout the entire campaign.

Imperative II deals with the heart and soul of EOL's mission to support the atmospheric research community. Imperative II capsulizes the frequent field projects we conduct that are supported by the NSF. We describe six such field programs in the Imperative II section, including a landmark study called the HIAPER Pole-to-Pole Observations (HIPPO) Campaign which deploys the NSF/NCAR G-V Research Aircraft in the first comprehensive, global survey of atmospheric trace gases, covering the full troposphere, from the Arctic to the Antarctic, in all seasons and multiple years.

Data Services

EOL is committed to data processing, quality control, and archival for field projects as part 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, formerly known as CODIAC) to access and browse products and data from field projects while integrating with the Community Data Portal.

Discovery

We take seriously our responsibility to promote curiosity about Earth science and to inspire development of the next generation of observational scientists and engineers. In FY 2009 we undertook a lot of activities in support of 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.”

We conducted four EOL educational deployments to educators wishing to gain access to observational facilities for classroom instructions and hands-on learning. In June 2009 approximately 130 people from universities and agencies all over the United States participated in our second NSF Observational Facilities Users Workshop, which focused on training students in atmospheric sciences about observational facilities and techniques. 2009 was another record year in terms of applicants for EOL’s Summer Undergraduate Engineering Internship Program, which focuses EOL’s outreach efforts on the engineering community in a manner analogous to what UCAR/NCAR currently does for young scientists.

Director's Message

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DEPLOYMENT

EOL is committed to facilitating the operational, technical, logistical and data support to effectively drive progress on all fronts of atmospheric research. A large part of this involves providing the observing facilities, systems and services that are beyond the capabilities of most universities or smaller groups. The NSF-funded Lower Atmospheric Observing Facilities (LAOF) that EOL manages include research aircraft, ground-based and airborne remote sensing systems, sounding systems, in situ sensing systems, and many instruments that can be deployed with them.

In addition to managing NSF's LAOF, EOL has nearly 50 years of experience providing comprehensive and scalable project management support services to the NSF-supported scientific research community and others. In this capacity we provide cientific, technical and administrative support services for the purpose of planning, organizing and implementing research programs and associated field projects worldwide.

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.

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 maintain their readiness for our vigorous deployment schedule. In the run-up to each deployment campaign, all involved instruments undergo 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 unforseen environmental conditions in order to meet the Principal Investigators' (PI's) scientific objectives for the experiment.

Imperative I efforts also encompass major upgrades that become necessary due to old technologies becoming obsolete or new technologies that promise increased efficacy of the instrument. Two such tasks undertaken by EOL during FY 2009 were the modernization of the NSF/NCAR C-130 avionics package and the upgrades to the Electra Doppler Radar.

NSF/NCAR C-130 Research Aircraft Modernization

The NSF/NCAR C-130 Research Aircraft is known in the atmospheric research community as the "workhorse" of airborne research platforms; it has been involved in over 40 campaigns since its debut in 1985. Its avionics package was installed when the airplane was built in 1984. Since the Original Equipment Manufacturer (OEM) support for much of the avionics package was discontinued in 1998 it has become increasingly challenging to obtain parts and overhaul support for the avionics components.

Modernization of the avionics package will improve performance reliability and ensure compatibility with the next-generation air traffic control system being installed by the Federal Aviation Administration. Because the new ATC system is GPS-based, the C-130 will be able to access increased airspace, particularly over the oceans and in areas without good radar coverage. These upgrades will ensure the trusty C-130 "workhorse" will remain an active platform for atmospheric research.

ELectra DOppler RAdar (ELDORA)

Airborne radar platforms play a critical role in advancing our understanding of cataclysmic storms that are either too remote or occur too infrequently for

Related Links and Images

IMPERATIVE I

Efforts to modernize the avionics package for the NSF/NCAR C-130 will improve performance reliability and ensure compatibility with the Federal Aviation Administration's next-generation air traffic control systems.

Airborne radar platforms such as the ELectra DOppler RAdar play a critical role in advancing our understanding of cataclysmic storms that are either too remote or occur too infrequently for ground-based radars. EOL began upgrades dar began upgrades

IMPERATIVE II

HIAPER Pole-to-Pole Observations (HIPPO) Campaign

The NSF/NCAR G-V in American Samoa during the first phase of the HIAPER Pole-to-Pole Observations (HIPPO) Campaign.

ground-based radars. The ELDORA radar has been a vital component of NSF Lower Atmospheric Observing capabilities since it debuted in 1993 in the Solomon Islands during TOGA Coupled Ocean-Atmosphere Response Experiment (TOGA COARE). More recently it was flown during the THORPEX Pacific Asian Regional Campaign (T-PARC) in 2008, which studied typhoons across the Northwest Pacific Ocean.

In FY2009, EOL began its upgrades on ELDORA's critical hardware, data system, and display to enable the radar to operate at its optimal performance through the year 2016.

Imperative II

Support observing needs of research programs at a level that serves NSF, university, and NCAR program needs.

Imperative II deals with the heart and soul of EOL's mission to support the atmospheric research community. In a nutshell, Imperative II is all about how EOL deploys its observing systems in the frequent field projects supported by the NSF or otherwise conducted by the atmospheric science community. To accomplish this, we employ and train the required staff, assist PI's during project planning and preparation, support the observing programs by operating facilities and instruments, and preserve the quality of the collected data for decades.

Among the field campaigns conducted during FY 2009 were the HIAPER Pole-to-Pole Observations (HIPPO) Campaign, VAMOS Ocean-Cloud-Atmosphere-Land Study (VOCALS), Verification of the Origins of Rotation in Tornadoes EXperiment (VORTEX) II, Profiling of Winter Storms (PLOWS), Wyoming Airborne Integrated Cloud Observations (WAICO), and Airborne Detector for Energetic Lightning Emission (ADELE).

HIAPER Pole-to-Pole Observations (HIPPO) Campaign

HIPPO is a landmark study for many reasons, not the least of which is it is the first time scientists have attempted to systematically map global distribution of carbon dioxide and other greenhouse gases in the atmosphere. The program provides the first comprehensive, global survey of atmospheric trace gases, covering the full troposphere, from the Arctic to the Antarctic, in all seasons and multiple years. HIPPO missions transect the mid-Pacific ocean and return either over the Eastern Pacific, or over the Western Atlantic. The data collected during the campaign will be used to refine atmospheric chemistry, global climate, and other Earth-system models.

Data from the three-year field project will help scientists quantify the natural and human-generated sources of greenhouse gases and track where the gases are absorbed. Findings will lead to improved predictions about climate change and help policy makers determine how to minimize future levels of greenhouse gases in the atmosphere.

The first mission took place in January 2009, flying a route that covered 44,700 km (27,760 miles) over 21 days. The flight began from the Rocky Mountain Metropolitan Airport (where EOL's Research Aviation Facility is located) to Anchorage, Alaska, the North Pole (up to 85 degrees North) round trip, back to Anchorage, Honolulu, Hawaii, to Pago Pago, American Samoa to Christchurch, New Zealand, to the South Pole (up to 67 degrees South) round trip back to Christchurch, NZ, to Papeete, Tahiti, to Easter Island, Chile, to San Jose, Costa Rica, and finally back to the Rocky Mountain Metropolitan Airport.

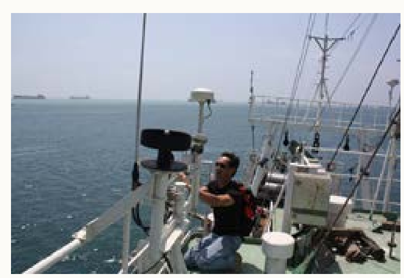
The next phase will take place in November 2009.

G-V outside the hangar in Anchorage Alaska during the HIPPO Campaign.

The G-V flies over the Brooks Range in Alaska during the HIPPO Campaign. The wing-mounted camera that took this photo recorded images such as this one every few minutes throughout the entire campaign.

VAMOS Ocean-Cloud-Atmosphere-Land Study (VOCALS)

VOCALS researcher logs data onboard the NSF/NCAR C-130.



EOL Field Technician Tim Lim installs an antenna onboard the R/V Jose Alaya in Chile for the VOCALS campaign.

VAMOS Ocean-Cloud-Atmosphere-Land Study - RegionalExperiment (VOCALS-REx)

150 scientists from 40 institutions in eight nations took part in the VAMOS Ocean-Cloud-Atmosphere-Land Study - Regional Experiment (VOCALS-REx) in fall 2008 seeking to better understand physical and chemical processes central to the climate system of the Southeast Pacific (SEP). This particular climate system has proven difficult to simulate by state-of-the-art Coupled Atmosphere-Ocean General Circulation Models (CGCMs) used for climate change projections and El Niño forecasting.

VOCALS-REx focused upon understanding the processes that control precipitation, including the role of atmospheric aerosols, their transport from the land to the ocean, and their depletion by the clouds themselves. In addition, an unparalleled combination of in-situ and remotely sensed cloud measurements were used to tackle outstanding satellite remote sensing problems and shed light into coupling processes between the ocean, atmosphere and land.

In support of this project, EOL deployed its NSF/NCAR C-130 and two GPS Advanced Upper-Air Sounding (GAUS) systems to northern Chile during the months of October and November 2008. EOL installed one GAUS system at the University Arturo Prat campus located in Iquique, Chile, and deployed a second GAUS on the Research Vehicle Jose Olaya. VOCALS effort included an intensive educational component though UCAR's “Windows to the Universe” (W2U) Web site, which included daily postcards from various participants, regional climate science and an in-depth look at the instrumentation.

Students release a weather balloon to gather data on the vertical atmospheric profile on the coast of Chile for the VOCALS campaign.

Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX II)

The first accurate recorded prediction of a tornado in the Midwest's infamous Tornado Alley occurred in 1948 when two Air Force officers noticed some weather that seemed similar to the weather that developed into a tornado in their region just a few days prior. Their observations were so convincing that their superior officers issued a warning and the next day a tornado struck the mostly-evacuated base.

Since then, there have been ceaseless efforts to improve upon the success of that first prediction - and for good reason. The deadliest of these storms can claim dozens of lives and wreak economic havoc on the areas they inflict, to the tune of millions or even billions of dollars per storm. And still nature continues to elude even the brightest of minds; our current forecasting capabilities give a mere 13 minute average lead time and a 70% false alarm rate.

The second phase of the VORTEX campaign was perhaps the largest, most ambitious attempt to explore tornadoes and answer some of our most basic, yet vexing, questions:

- How, when, and why do tornadoes form? Why some are violent and long lasting while others are weak and short lived?
- What is the structure of tornadoes? How strong are the winds near the ground? How exactly do they do damage?
- (and most importantly,) How can we learn to forecast tornadoes better?

In May and June 2009, EOL deployed two mobile GAUS trucks (including one supply truck) and several DOWs to support these efforts. Though many storms were observed, 2009 wasn't a bumper season for tornadoes. However, the one tornado that was seen (near Chugwater, WY), was noted to be easily the most documented tornado in history, with all the sensors observing it - the VORTEX "armada" had 50 vehicles loaded with over 100 scientists.

VORTEX II researchers hope the data they gather will further clarify understanding of the relationship between tornadoes, their parent convection, and the larger-scale environment. Better insight into these relationships is essential if reliable long-term predictions are to be made of

VORTEX II

The Center for Severe Weather Rearch's Doppler on Wheels (DOW) positions itself to receive radar data from a tornado near Chugwater, WY, during the VORTEX II campaign.

Checking conditions for a ballon launch during the VORTEX II campaign.

The Mobile GPS Advanced Upper-Air Sounding System (MGAUS) team prepares to launch a balloon during the VORTEX campaign.

changes in the frequency and geographical distribution of tornadoes due to climate change. The third field phase is planned for May - June, 2010.

Profiling of Winter Storms (PLOWS)

Adverse road weather, mainly during the winter months, is responsible for nearly 7,000 deaths, 600,000 injuries and 1.4 million accidents per year. A single blizzard can cause up to 3 billion dollars worth of damage. PLOWS research is targeted directly at improving 0-48 hour prediction of winter storms. The study area is Illinois and nearby states, particularly examining fronts and other structures (e.g. precipitation bands) around the storms. The lead PI for the project is Prof. Bob Rauber at the University of Illinois at Urbana-Champaign (UIUC), with co-PIs Greg McFarquhar (UIUC), Brian Jewett (UIUC) and Kevin Knupp (Univ. Alabama-Huntsville)

In February and March of 2009 EOL deployed a Mobile Integrated Sounding System (MISS, including balloon-borne radiosonde soundings) to this first field phase, which was a precursor to the larger and longer deployment in the winter of 2009-2010.

Wyoming Airborne Integrated Cloud Observations (WAICO)

Most people's observation of clouds is limited to a delightful summer meditiation on what shape one might take or how it might morph as it is buffeted by the wind. But researchers who study clouds know that their studies have far-reaching implications in almost every branch of earth system science. It has been hypothesized that clouds play a critical role in how our climate changes. At this time though, clouds are also difficult to describe mathematically in climate models. Our knowledge of cloud properties could prove to be the key in our ability to understand both long-term and short-term climate change.

WAICO is one such field project that seeks to improve upon airborne cloud observation capabilities by integrating and testing the elastic lidar, the Wyoming Cloud Radar (WCR), and the microwave radiometer on the University of Wyoming King Air along with in situ cloud probes for cloud studies. In Spring 2009, the University of Wyoming King Air flew WAICO missions in Wyoming air space with the goal to improve airborne cloud observation facilities and provide a comprehensive data set for algorithm development and cloud study.

Airborne Detector for Energetic Lightning Emissions (ADELE)/SPRITE

The sheer number of lightning strikes that occur on our planet is staggering. With nearly 2,000 thunderstorms roiling somewhere in the world at any given moment the number works out to be more than 100 strikes per second. Lightning can reach temperatures exceeding 50,000 degrees and it can travel miles within seconds. The energy contained in a single bolt is enough to power a 100-watt bulb for three months straight. Some studies suggest that gamma rays may precede lightning initiation; other studies that gamma rays are generated as a consequence of the lightning strikes. A key goal of the ADELE project was to determine which of these two possibilities takes place in nature.

Sprites are ionospheric discharges at altitudes of 30-80 km. They are exceedingly brief, lasting only a few milliseconds, and they occur above thunderstorms. Though sprites have considerably less direct effect on human life than lightning, since they occur well above the altitudes of lighting, they can tell us a great deal about atmospheric chemistry. Sprites are often mistakenly referred to as a type of lightning but are really high-altitude, large-scale electrical discharges that occur in the vicinity of, and well above thunderstorms.

ADELE/SPRITE combined two concurrent research projects: ADELE operated during the day, studying gamma rays near convective. SPRITE missions were flown at nighttime, studying formation of sprites over thunderstorms up to 200 km away from the aircraft. EOL deployed the NSF/NCAR G-V out of

A small representative of the full VORTEX II "armada" of research vehicles prepares for the day. There were 50 vehicles in all, carrying over 100 researchers.

Profiling of Winter Storms (PLOWS)

Adverse road conditions in the winter are responsible for nearly 1.4 million accidents per year. Researchers hope that data from PLOWS will help forcasters improve predictions of winter storms.

The NSF/NCAR Mobile Integrated Sounding System (MISS) parked by the water tower in Tomah, Wisconsin during the PLOWS experminent.

This graph shows the locations of the NSF/NCAR MISS during PLOWS. A) The Champaign IL airport, where the system was tested on two occasions during the program, B) Tomah, Wisconsin and C) Walcott, IA. [click image to enlarge].

Wyoming Airborne Integrated Cloud Observations (WAICO)

Melbourne, FL in August and September 2009 to support these projects.

Researchers will use the data gathered from ADELE/SPRITE to better understand the physics of lightning – specifically, how lightning is initiated. Data collected from ADELE will shed light on the role of electron runaway in this process. ADELE will also address the question of how common electron runaway is in thunderstorms and lightning events. The ADELE instrument is akin to a very fast Geiger counter. By precisely timing the number of gamma particles that arrive at the aircraft and comparing these to the times of lightning as observed with ground-based networks, the researchers hope to better understand the basic physics of lightning initiation.

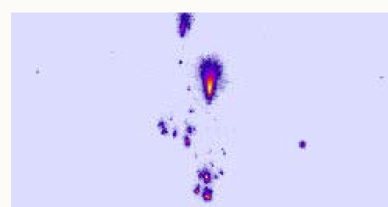
Even though sprites are considerably more rare, researchers observed more than 30 of them during nighttime missions, and considered nearly a dozen of those to be particularly outstanding. The sprites were captured using two high-speed cameras (10,000 frames per second), of which one had a grating in front of it to get spectral resolution of the light as a function of altitude. In the past, researchers sampled high-speed images of sprites from mountaintops, but the atmosphere's thickness prevented them from observing the level of blue light in sprites; measurement of light at different wavelengths can be used to determine which types of molecules have been ionized and made available for chemical reactions above the ozone layer.

Cloud physics have far-reaching implications in almost every branch of earth system science. Our knowledge of clouds may well prove to be the key to our ability to understand climate change.

The University of Wyoming King Air carried and tested a variety of instruments during WAICO. Researchers hope to use the data gleaned from the missions to improve airborne cloud observation facilities. [photo courtesy of Vanda Grubisic, Desert Research Institute.]

Airborne Detector for Energetic Lightning Emissions (ADELE) / SPRITE

Scientists designed the Airborne Detector for Energetic Lightning Emissions (ADELE) to learn more about how lightning is initiated during thunderstorms.



This sprite image was taken during the SPRITE campaign, with a high-speed camera (10,000 frames per second). The original is black and white but researchers used colors to increase the dynamic range. The feature center right is Jupiter. Photo © H.C. Stenbaek-Nielsen, University of Alaska Fairbanks, and M.G. McHarg, US Air Force Academy.

This shot, taken from the NSF/NCAR's wing-mounted camera, shows off the aircraft's vertical range as it cruises near the earth's tropopause, well above the storm clouds below. This made the G-V particularly well-suited to observe Sprites during the night time missions.

Deployment

Postal Address: P.O. Box 3000, Boulder, CO 80307-3000 • Shipping Address: 1850 Table Mesa Drive, Boulder, CO 80305 • Contact

DEVELOPMENT

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. Providing the community with new and updated instrumentation, as well as support for these tools, ultimately help researchers achieve their science goals.

This imperative calls 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 and instruments.

Imperative III

Anticipate future needs resulting from changing priorities, aging equipment or emerging opportunities, and develop new technology (instrumentation, software, and infrastructure) to meet those needs.

Imperative III differs from Imperative I primarily in that Imperative I focuses on maintaining our current store of capabilities while Imperative III bids us to set our sights on the future, anticipating what will be and even further into the future of what may be. Imperative III could also be called our "Research and Development" efforts.

In FY 2009 much of EOL's R&D has gone toward NSF/NCAR Gulfstream V (G-V) enhancements including the development of instruments specifically for use on the G-V, underwing pods large enough to safely carry larger instruments such as remote sensing equipment, the design, installation, and certification of optical windows suitable for instruments such as the High Spectral Resolution Lidar. EOL is also continuing its efforts to support the research community by acting as a resource of infomration regarding research instrumentation through the Facilities for Atmospheric adn Earth System Research Database.

Facilities for Atmospheric and Earth System Research Database (FAESR)

The task of planning for new facilities is difficult without the context of the entire suite of instruments available to the community. The Facilities for Atmospheric and Earth System Research Database (FAESR) database, previously called the NSF Facilities Assessment Database (FADB), has been a public resource for nearly a year. It is intended to provide descriptive information on atmospheric and earth system science facilities and instrumentation in a consistent, easy-to-read format as a resource for the broad atmospheric science and related communities. This database is enhancing community awareness of both existing and new and emerging atmospheric facilities and will be a valuable reference tool for other partners, including governmental agencies looking to utilize or share such science facilities.

In FY2009 EOL continued to improve this database by maintaining an editorial board to update the newly-launched FAESR database. In August 2009 EOL conducted a quality control project to ensure the data in the entries are current, correct and complete. Outreach plans are also underway to generate increased interest in the atmospheric research community to submit new entries.

Front Range Observational Network Testbed (FRONT)

FRONT, formerly known as the "National Radar Facility" or the "Integrated Weather Radar Facility" integrates CSU-CHILL and NCAR/EOL S-Pol systems

Related Images

IMPERATIVE III

G-V Infrastructure Developments

Large Wing Pods

This image shows the undercarriage of the NSF/NCAR G-V as it ascends during a test flight of the new under wing pods. The two new large pods were flown successfully with the four smaller existing pods.

This image shows a screen shot of monitors within the G-V as it approached its final ascent in a test flight of the new under-wing Large Wing Stores in July.

The innovative, tear-drop-shaped pods can carry up to an additional 800 pounds of scientific instruments and are designed with a detachable middle portion that is easily accessible from beneath the wing.

Front Range Observational Network Testbed (FRONT)

to streamline development and operations for expanded science and education opportunities and forms one engineering development team whose efforts benefit both NSF S-band radar facilities. The shared engineering and scientific activities between CHILL and NCAR/EOL S-band research radars provide the scientific community with opportunities to: 1) conduct target of opportunity scientific field experiments, 2) maintain a long-term mesoscale test bed for assessing instruments, data quality procedures, sensor integration, numerical models, networking capabilities and derived products, 3) provide a framework or magnet for local field campaigns, and 4) conduct continuous hands-on education.

Among its FY2009 efforts, EOL continued its strategic partnership with Colorado State University (CSU) and replaced the S-Pol's original aging digital receiver, processor and radar control hardware referred to as the VIRAQ. The receiver and processor functionality is being replaced with a system know as HAWK, which uses Sigmets RVP8 radar receiver/processor.

The antenna control and radar control subsystems are being replaced with similar systems that will also be used in the CSU-CHILL. Evaluation of S-Pol antenna performance has been completed. A new home-based field site (i.e., when S-Pol is not being used in a remote NSF field experiment) has been identified and site infrastructure and preparation is beginning with an S-Pol relocation date of Winter 2010. The new field site will allow dual Doppler measurements between CSU-CHILL and S-Pol.

Remote operation of radars and perusal of archival data is an important aspect of the software development required to integrate NCAR and CSU facilities. In FY2009, remote operation between deployments began for S-Pol. These capabilities will not be fully realized until the radars are networked, however. In FY2009 we enabled remote monitoring of the radar system's health, including the power generation and data recording.

G-V Infrastructure Developments

Though the NSF/NCAR G-V has successfully carried out several major campaigns since it burst onto the research scene in 2006, EOL is in the midst of several major development efforts. Notable infrastructure projects of this nature in FY 2009 was the construction, installation, and certification of under-wing pods for carrying large research equipment, and the development of optical ports to allow for downward and upward looking remote sensing equipment.

Large Wing Pods

The Large Wing Pods, also called "Large Wing Stores" were built and tested in FY2009 and are currently in the process of being certified. Each pod can carry up to an additional 800 pounds of scientific instruments. These innovative, tear-drop-shaped pods are designed with a detachable middle portion that is easily accessible from beneath the wing. When pod-mounted instruments are employed, more room is available on board for additional personnel or instruments a critical function in a plane where space is at a premium. Alternatively, instrumentation can be attached directly to the pod to gather data during flights.

Test flights for the new pods were successfully conducted in July 2009. No problems were identified with the wing stores, and the aircraft was able to fly through its full flight envelope. The G-V was taken slightly above 51,000 feet with the two large and four small pods installed. Reports are currently being filed with the FAA for the Supplemental Type Certification (STC), and we expect to have the STC for the 2-large/4-small pod configuration by late 2009.

FRONT
Front Range Observational Network Testbed

FRONT, formerly known as the "National Radar Facility" or the "Integrated Weather Radar Facility" integrates CSU-CHILL and NCAR/EOL S-Pol systems to streamline development and operations for expanded science and education opportunities and forms one engineering development team whose efforts benefit both NSF S-band radar facilities.

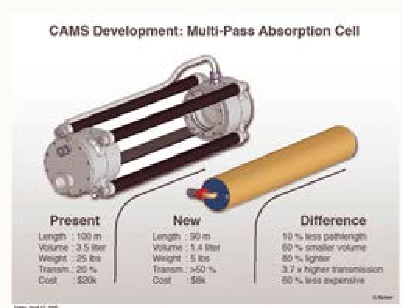
Development Projects

AVAPS III for Global Hawk

Global Hawks can fly at altitudes up to 65,000 feet for more than 31 hours at a time, allowing researchers to observe and measure more remote locations of the earth's surface than ever before.

Cynthia Bradley, an engineer in EOL's Design and Fabrication Services, conducts a test installation of the new AVAPS III dropsonde dispenser she is designing for the Global Hawk Unmanned Arial Vehicle (UAV).

CAMS



Optical Ports

The major task remaining for the G-V is certification of the optical windows, which will allow operation of remote-sensing equipment like the High Spectral Resolution Lidar. EOL began the purchase, installation, and testing of these windows in FY 2009. This project will require construction of holders for the optical glass and construction of a test structure similar to that in the G-V that can be used for pressure-chamber tests to demonstrate the ability of the glass to withstand the pressure that will be encountered in high-altitude flight. Three 20-inch apertures with double-paned optical glass for safety will be put into service as a result of this project.

The optical ports will allow for deployment of downward- and upward-looking remote sensing equipment and will be used for testing the High Spectral Resolution Lidar (HSRL, see below) and and other anticipated research in FY 2010.

Development Projects

Global Hawk

The Global Hawk is a high altitude, long-endurance unmanned aerial vehicle built by Northrop Grumman in Los Angeles CA. Global Hawks can fly at altitudes up to 65,000 feet for more than 31 hours at a time. The ability of the Global Hawk to autonomously fly long distances and remain aloft for extended periods of time means that measuring, monitoring, and observing remote locations of the earth’s surface are now possible. This will have 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. EOL is working with National Oceanic and Atmospheric Administration (NOAA) /Unmanned Aerial System (UAS) to develop the next generation Airborne Vertical Atmospheric Profiling System (AVAPS) III Dropsonde system for installation on one of the Global Hawks as well as on the NSF/NCAR G-V.

In FY2009, EOL began its tasks to design and fabricate an automated dropsonde system to be integrated on board of one of the Global Hawks that is jointly funded and managed by the National Aeronautics and Space Administration (NASA) and the NOAA/UAS program During a flight, the fully automated system will launch approximately 50 sondes, receive and process transmitted data from each sonde, and transmit the data during flight to a ground receiving station. A prototype launching system has been designed and fabricated. EOL has also made significant progress on the next generation dropsonde during FY2009.This project will continue through FY 2010.

Compact Atmospheric Multi-species Spectrometer (CAMS)

The need to measure soluble and reactive trace gases like formaldehyde (an important precursor of hydrogen radicals and ozone) in the upper troposphere and lower stratosphere has been identfied as an important element in understanding atmospheric chemical processing and transformations.CAMS was designed in response to this community need. This new instrument will rely on the same state-of-the-art advancements employing difference frequency generation (DFG) technology as other EOL airborne infrared absorption spectrometers, but with major upgrades and innovations for operation on the G-V platform.

EOL made great strides FY 2009 to complete the basic CAMS instrument for operation on the NSF/NCAR G-V. EOL has built and tested sub-components (e.g., a multipass cell, data acquisition hardware and software, incorporation of multi-laser channels, etc.) We anticipate completing this instrument by the end of FY2010 and test flights will commence in 2011, well in advance of a possible 2012 deployment.

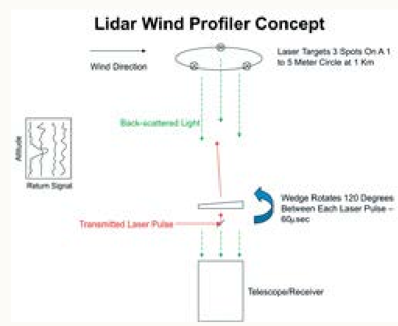
Lidar Wind Profiler

Lidar technology has the potential to provide wind measurements with better time resolution, much better altitude resolution, and free of the problems of

The Compact Atmospheric Multi-species Spectrometer (CAMS) was developed in response to a need to measure soluble and reactive trace gases like formaldehyde (an important precursor of hydrogen radicals and ozone) in the upper troposphere and lower stratosphere. [click image to enlarge.]

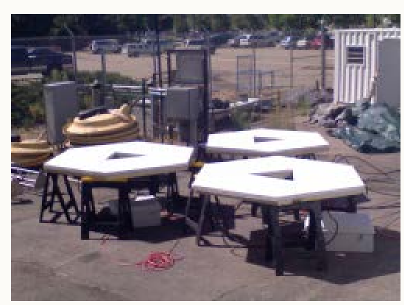
Lidar Wind Profiler

REAL transmitter, the rotating wedge assembly (front) and the collecting telescope (beneath the wedge). Construction of the Lidar Wind Profiler system was completed in early FY2009, and pilot studies commenced in summer of FY2009. Data are being analyzed and pilot study completion is anticipated within the next several months.



Schematic of the Wind Profiler concept. Lidar technology has the potential to provide wind measurements with better time resolution, much better altitude resolution, and free of the problems of clutter (from the ground, birds, targets in sidelobes) and interference (from an increasingly full radio spectrum) when compared with other boundary layer profilers. [click image to enlarge.]

449 MHz Wind Profiler



The prototype hexagonal antenna modules of EOL’s new 449 MHz wind profiler radar undergoing testing at

clutter (from the ground, birds, targets in sidelobes) and interference (from an increasingly full radio spectrum) when compared with other boundary layer profilers. This makes it particularly effective at profiling lower in the atmosphere.

The Lidar Wind Profiler development project utilizes EOL's Raman Shifted Eye Safe Aerosol Lidar system (REAL) system coupled with a rotating wedge assembly to transmit three parallel near-infrared beams (around 1.5 mm) vertically. Aerosols advecting across the three beams generate time resolved backscatter radiation which is collected by a telescope and detected by a near-infrared detector. By crosscorrelating the time series from the three beams and knowledge of the distance between the beams, one can extract horizontal winds at a number of different heights.

Construction of the Lidar Wind Profiler system was completed in early FY2009, and pilot studies commenced in summer of FY2009. Data are being analyzed and pilot study completion is anticipated within the next several months.

449 MHz Wind Profiler

EOL is advancing its wind profiler technology with a project to develop new 449 MHz wind profiler radars. EOL currently operates four 915 MHz wind profilers as part of its Integrated Sounding Systems (ISS). These legacy profilers provide good measurements in the boundary layer, however have reduced coverage in cold and/or dry conditions and usually cannot probe higher than 3 or 4 km. EOL, in collaboration with NOAA/ERSL and the University of Oklahoma, has begun to develop next generation wind profilers with greater flexibility and expanded coverage. These new systems are based at 449 MHz and will use a modular design. Each radar module can operate semi-independently with their own transmitter, receiver, and data system. The modules can be combined together to produce radars of varying capability to match the needs of a particular experiment.

For example, for an urban basin or a severe weather study the modules might be distributed in groups of three modules over a wide area to probe the boundary layer throughout an extended region. For a middle atmosphere experiment, such as a tropospheric/stratospheric exchange study, all modules would be gathered together to probe to very high altitudes.

A prototype three module system has been constructed to test concepts and components. Over the next two years EOL intends to refine the design and construct at least four additional modules, which we anticipate will provide a system capable of probing up to mid-tropospheric altitudes. Ultimately, a total of at least 19 modules are planned which could be deployed, for example, as six 3-module boundary layer profilers or two 7-panel mid-troposphere profilers or one 19-panel full troposphere system. These would be deployed with surface energy balance and mini-Doppler lidars to provide complete coverage from the surface to the tropopause.

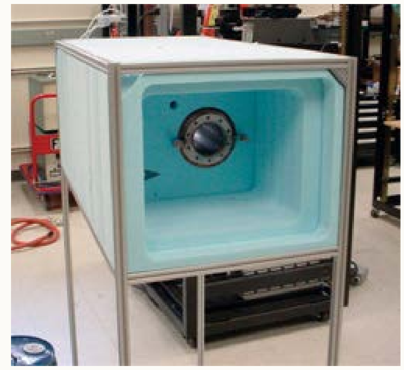
Water Vapor Reference Sounding System

Numerous studies and reports call for a water vapor reference sonde as a transfer standard to connect past, present, and future balloon-borne data acquired around the world. In developing and validating such a system, the scientific community will also gain important calibration and quality control tools for operational radiosondes, sensor test beds for new sensors, as well as HIAPER-based systems.

In partnership with Southwest Sciences (SWS) Incorporated, EOL has developed a test chamber into which known water vapor mixing ratios can be introduced under a variety of conditions representative of relative humidities, pressures, and temperatures prevalent throughout the troposphere and lower stratosphere. A diode laser hygrometer developed by SWS will be cross compared under these conditions with the known input mixing ratios over several months. The goal is to develop confidence in the accuracy of the retrieved mixing ratios from the diode laser instrument, and this information will lay the foundation for a balloon-borne instrument.

NCAR Foothills Lab in Boulder.

Water Vapor Reference Sounding System



Test Chamber Enclosure for the Water Vapor Reference Sounding System. Numerous studies and reports call for a water vapor reference sonde as a transfer standard to connect past, present, and future balloon-borne data acquired around the world. In developing and validating such a system, the scientific community will also gain important calibration and quality control tools for operational radiosondes, sensor test beds for new sensors, as well as HIAPER-based systems.

Holographic Detector of Clouds 2 (HOLODEC 2)

HOLODEC 2 (visible on the right, with yellow stripe) installed on the G-V for testing. HOLODEC 2 is specialized instrument that uses digital holography to measure tiny cloud droplets. Holography is a process by which 3-D images can be stored and reproduced using laser light and projected onto a 2-D surface.

Laser Air Motion Sensor (LAMS)

LAMS Optical Head installed under G-V wing. Accurate measurement of wind speed and direction is a fundamentally important measurement for virtually all atmospheric field experiments for the G-V.

EOL anticipates a number of potential scenarios, including: 1) establishment of a permanent set of hygrometers and procedures by which to cross-calibrate balloon-borne systems; and/or 2) formation of a permanent hygrometer testing facility at NCAR to generate and measure with unequivocal accuracy water vapor mixing ratios representative of conditions from the lower troposphere to the stratosphere up to 30 km for testing balloon-borne systems.

The testing facility for the water vapor reference sounding system is complete and undergoing numerous tests. Our primary focus over the next year will be to fully characterize the test chamber and incorporate testing of the commercial diode laser units, provided that any problems discovered with these units can be addressed by the vendor. If significant problems are discovered or persist, we will discontinue their testing and focus exclusively on the test chamber. This effort will be completed sometime in FY2010.

Holographic Detector of Clouds 2 (HOLODEC 2)

HOLODEC is specialized instrument that uses digital holography to measure tiny cloud droplets. Holography is a process by which 3-D images can be stored and reproduced using laser light and projected onto a 2-D surface. Scientists have applied holography to the study of cloud particles for several decades using photographic plates, a time-consuming process that involves scanning film in a lab to search for particles. HOLODEC 2 uses digital technology, making the process of applying holography to cloud particle measurements much more efficient.

Another important feature of HOLODEC 2 is that, in addition to resolving particles as small as 4-8 micrometers, it samples a 10-cubic-centimeter region around a cloud droplet, unlike other cloud particle instruments. This will help scientists study the environment that surrounds cloud droplets, for while scientists have measurements of how clouds behave on large scales, they know less about processes on the scale of cloud droplets, which is where clouds begin.

HOLODEC 2 was completed and ready for flight tests in summer 2009. It was successfully flown on two G-V test flights in early August. Additional aircraft testing of HOLODEC was conducted in September, and subsequent data analysis, which will be carried out in FY10, has commenced.

Laser Air Motion Sensor (LAMS)

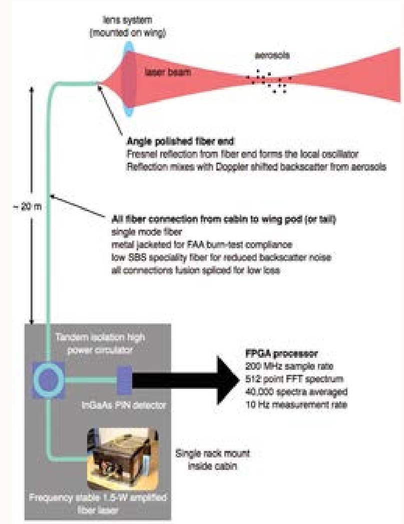
Accurate measurement of wind speed and direction is a fundamentally important measurement for virtually all atmospheric field experiments for the G-V. Historically this measurement has been accomplished with a 5-hole radome gust probe which measures differential pressure at the surface of the aircraft radome. However air flow around the G-V radome and fuselage, which are not symmetric, are expected to result in significant errors in wind velocity estimates.

EOL is developing laser doppler velocimeter to measure aircraft wind speed and direction in undisturbed air flow in front of the aircraft. Ground validation tests have been performed successfully and development continues to improve instrument performance. Initial flight test demonstrated first principles in high scattering environments.

HIAPER Cloud Radar (HCR)

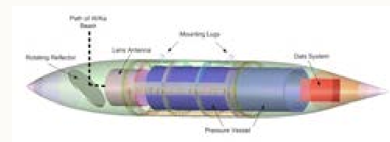
The HIAPER cloud radar (HCR) is an airborne millimeter-wavelength radar that will serve the atmospheric science community by providing remote sensing capabilities to the NSF/NCAR G-V. It can also be deployed in a vertically pointing configuration, co-located with the HSRL (High Spectral Resolution Lidar) in a 20' Seatainer.

Develpment of the HCR continued in FY2009. The transmitter has been purchased and will be packaged for installation in a pressure-sealed vessel in the pod. Work will continue on the remaining components, and EOL anticipates being able to test-fly this new radar in 2010.



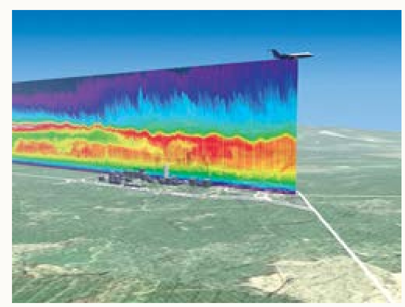
Technical approach of the LAMS. EOL is developing laser doppler velocimeter to measure aircraft wind speed and direction in undisturbed air flow in front of the aircraft. [click image to enlarge]

HIAPER Cloud Radar (HCR)



The HIAPER cloud radar (HCR) is an airborne millimeter-wavelength radar that will serve the atmospheric science community by providing remote sensing capabilities to the NSF/NCAR G-V. [click image to enlarge]

High Spectral Resolution Lidar (HSRL)



HSRL operations from the G-V aircraft. The HSRL is used to make reliable and accurate measurements of atmospheric extinction, backscatter coefficients, optical depth, and discrimination between ice and water clouds.

High Spectral Resolution Lidar (HSRL)

The HSRL is used to make reliable and accurate measurements of atmospheric extinction, backscatter coefficients, optical depth, and discrimination between ice and water clouds. The HSRL works by measuring laser returns and depolarization from aerosol and molecular scattering simultaneously.

The molecular scattering is used as a calibration target which is available at each point in the lidar return. The instrument is currently in a ground testing phase and scheduled to begin flight tests in February 2010. The HSRL will be converted to an airborne instrument suitable for operation on the G-V.

HIAPER Airborne Instrumentation Solicitation (HAIS) Instruments

A relatively new addition to the suite of research tools that NCAR provides the wider science community, G-V instrument installation continued in FY2009. HAIS development, testing, and use continued in FY2009. G-V updates foster expansion of the research capabilities that EOL provides to Earth system investigators. With these G-V updates in place, researchers will be able to conduct vital studies in currently inaccessible regions of the Earth's atmosphere.

All HAIS instruments are scheduled for completion by the end of 2009, including the Quantum Cascade Laser Spectrometer (QCLS), Chemical Ionization Mass Spectrometer (CIMS), High Spectral Resolution Lidar (HSRL), Three-view Cloud Particle Imager (3V-CPI), and GPS instruments. All will be flown during the July 2009 test period. The Trace Organic Gas Analyzer (TOGA) and Time-of-Flight Aerosol Mass Spectrometer (ToF-AMS) are also scheduled for FY2009 delivery, but flight tests for these instruments may extend into another 2010 flight-test program.

Three additional HAIS instruments will be accepted and placed into service by December 2009. The three new instruments entering operation are Purdue's GPS-occultation instrument (GISMOS), the HIAPER Atmospheric Radiation Package (HARP), and the Microwave Temperature Profiler (MTP). All have flown successfully in tests, and all have already provided support for research projects. Along with five similarly advanced instruments that were accepted previously, these represent a significant increase in the ability of NCAR/EOL to support airborne research with advanced instruments.

Testing of the remaining HAIS instruments will be conducted before March 2010, and it is expected that the remaining instruments will be accepted and placed into operation shortly after that time. Future requests for the G-V make heavy use of these instruments – even those not yet operational – so these new capabilities are being put to use rapidly by the user community.

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Related Links or Images

DATA SERVICES

The datasets collected in EOL-supported field campaigns have value that extend far beyond their immediate use by the project team, and NSF policy requires that they be preserved and made available to other users who may pursue research questions apart from those that justified the original project. Modern data-access mechanisms increase the importance and usefulness of preserving datasets and of ensuring that the scientific community has open access to them. In response, EOL has enlarged the scope of data services to extend from the planning stage through collection and quality control to long-term archival. EOL also provides stewardship for a select set of data that are not collected by EOL observational facilities.

Imperative IV

Provide comprehensive data services, open access, and long-term stewardship of data.

EOL Metadata Database and Cyberinfrastructure (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 collection of tools and databases created and used by EOL's Computing, Data and Software Facility and the external community. EMDAC updates will make data management easier for EOL facilities. EMDAC will allow better archive and data access capabilities to the user community.

In FY2009, NCAR solicited community feedback in order to continue developing the EMDAC to meet user requirements and enhance current infrastructure to streamline overall internal data management activities. A preliminary EMDAC data plan was developed. Issues addressed included:

- Metadata database consolidation and standardization,
- Interface improvements for data access, ingest and distribution,
- Standardization of data formats used by EOL,
- Revise field catalogs, improving connections to post-project archives in future,
- Develop, distribute and support interfaces to fourth generation languages (4GLs, e.g. Matlab/IDL, NCAR NCL) and supply Application Programming Interfaces (APIs) to community-developed codes used in the analysis of our datasets,
- Scalability to handle growing data volumes (e.g., from platforms such as the HOLODEC, the Integrated Weather Radar Facility (IWRF), HAIS instruments, as well as model and satellite data) via subsetting during distribution,
- Centralize and improve data metrics collection and reporting,
- Establish long-term data stewardship processes.

Field Programmable Gate Array (FPGA) Digital Transceiver

In FY 2009 development resumed on the Field Programmable Gate Array (FPGA) based digital transceiver, with substantial progress achieved in creating a general purpose, four channel digital transceiver for radar and lidar applications. This high performance system integrates flexible FPGA firmware with modularized host software that can be deployed in a wide

variety of measurement systems.

A complete package of down conversion, transmit pulse synthesis and complex timing functions are provided by a single commercial radio card which can be hosted in the most common computer busses. The transceiver development is nearing completion for deployment in the HIAPER Cloud Radar and the 449 Mhz wind profiler systems. Application to future EOL remote sensing platforms is envisioned.

Atmospheric Sounding Processing Environment (ASPEN) Software

To enhance the effectiveness of dropsonde measurements for hurricane surveillance EOL has teamed with the NOAA Hurricane Research Division on a project to add new capabilities, upgrade the quality control algorithms, and modernize the underlying software architecture of this radiosonde processing tool. The improvements will also benefit EOL radiosonde operations, as well as being made available to the wider Aspen user community. Substantial preliminary work was completed in FY2009, and the project will continue through through FY 2010 and 2011.

Aircraft Mission Coordinator Station

EOL has developed a new capability to keep the aircraft mission coordinator abreast of current conditions and hazardous weather. The aircraft mission coordinator station was designed to integrate real-time information including aircraft cameras, flight track, weather radar and cockpit radar into a single display station to facilitate in-flight decision-making. It is being designed with an eye towards missions like PREDICT and DC3 where flying near severe storms will be required. This tool will allow investigators to achieve scientific objectives while maintaining crew safety.

NCAR In-Situ Data Acquisition System (NIDAS)

Concurrent development and deployment of the NCAR In-Situ Data Acquisition System (NIDAS) continued during this past year. NIDAS is now used on the NSF/NCAR G-V and C-130 aircraft, the Integrated Surface Flux System (ISFS), and for the surface measurements of the Integrated Sounding System (ISS). To support of these platforms in FY 2009 NIDAS was deployed on the G-V for the ADELE/SPRITES/HEFT-09 and first phase of the HIPPO field campaigns, on the C-130 at VOCALS, on the ISS in support of pre-PLOWS, EDUCT and PLOWS, and on the ISFS at Niwot Ridge.

Supporting these platforms involves continual modifications to support upgrades to instrumentation and communications systems. Developments have also included increased support for remote instrumentation control and calibration, a preliminary version of a graphical user interface for system configuration, improved system testing, and support for wireless sensor networks.

Future plans include expanding the use of NIDAS on other platforms. Several outside users have expressed interest in using NIDAS for their surface measurements. Plans also include using NIDAS for ancillary measurements on EOL radar and lidar systems. Other developments include keeping abreast of advancements in Linux support of real-time applications.

Arctic Data Projects

EOL in collaboration with CISL, Unidata, and the National Snow and Ice Data Center (NSIDC) have developed an Arctic Observing System (AON) archive system (Cooperative Arctic Data and Information Service [CADIS]) using the NCAR Community Data Portal (CDP) for AON PI data submission and access. CADIS also provides access to supporting datasets and has established linkages with other arctic data systems (through international standardized discovery-level metadata).

Under NSF Program Solicitation NSF 09-599, Organization of Projects on Environmental Research in the Arctic (OPERA), it is proposed to expand CADIS prototype developments into a broader arctic data system. This will encompass all of EOL's arctic data holdings such as the ARCtic System Science (ARCSS), Bering Sea Ecosystem Study (BEST), and legacy focused process studies, such as the Surface Heat Budget of the Arctic Ocean (SHEBA) and Shelf Basin Interactions (SBI). Further details on CADIS can be

found at: http://www.aoncadis.org/.

T-28 Archive

The South Dakota School of Mines and Technology (SDSMT) armored T-28 aircraft has been operated as a national facility under a series of five cooperative agreements between SDSMT and the National Science Foundation (NSF) Lower Atmospheric Observing Facility program. During this period the aircraft supported 18 field programs mainly under NSF sponsorship, but also including field programs sponsored by the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA).

In 2005, after the T-28 program was completed, the EOL, SDSMT, and NSF began discussions to ensure that the data, software, and visualization programs would be archived and made available to the scientific community for the long term. In addition to the migration of the aircraft data, a concerted effort was made to locate, read, and include as many other supporting field project datasets as possible to enhance interpretation of the T-28 data and support further research. The archive (and all supporting documentation) is available at: http://www.eol.ucar.edu/projects/t28/ .

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DISCOVERY

EOL takes its responsibility to promote curiosity about Earth science and to inspire development of the next generation of observational scientists and engineers seriously. The laboratory is in a unique position to foster educational and training opportunities for the next generation of observational atmospheric scientists and engineers, and to inform and excite the public with the impact of observational research.

Bright young students in science and engineering can be motivated to pursue careers in observational meteorology through exposure to NSF observational facilities and instruments, and to EOL development activities. The public can better understand 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. The mechanisms EOL provides to support and inspire high school students and teachers, and undergraduate and graduate students and faculty will ensure the field of atmospheric science remains vibrant well into the future.

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.)

NSF Deployment Fund for Educational Campaigns

EOL has conducted five educational deployments since a portion of the NSF Deployment Pool has been made available to educators wishing to gain access to observational facilities for classroom instructions and hands-on learning experience in FY 2008. Four of those deployments occurred in FY 2009:

- University of Nebraska Dows for Education and Outreach (UNDEO) was 14-day on-campus deployment of a Doppler on Wheels (DOW) for classroom-instruction and hands-on experience operating the DOW. The project, which took place in November 2008, provided undergraduate and graduate students in the *Radar Meteorology* class an opportunity to use a sophisticated research radar to collect invaluable data and familiarized future PIs with a valuable platform in the NSF deployment pool they may wish to utilize in their future research.
- Education in Complex Terrain Meteorology (EDUCT) was a deployment of EOL's Mobile Integrated Sounding System (MISS) to the University of Virginia in April 2009 to support two meteorology classes. The *Mountain Meteorology* class included an observational section based at the Shenandoah Park meteorological station, where the university operates a lidar, an instrumented tower and other facilities. MISS staff visited the park area to make a series of measurements together with the students and collected data to be used in a number of student projects. MISS also visited the main campus in Charlottesville and gave a demonstration to the *Weather and Atmosphere* class. A total of about 70 students participated.
- The Advance Study Program (ASP) Colloquium (see below.)
- Yampatika was a Weather and climate course for 5th and 6th graders in Routt and Moffat Counties in January/February of 2009. Yampatika was a 3-day program where classes visited Storm Peak Laboratory to

Related Links or Images

NSF Deployments for Educational Campaigns

University of Nebraska Dows for Education and Outreach (UNDEO)

The University of Nebraska Dows for Education and Outreach (UNDEO) was 14-day on-campus deployment of a Doppler on Wheels (DOW) for classroom-instruction and hands-on experience operating the DOW.

Education in Complex Terrain Meteorology (EDUCT)

Mobile Integrated Sounding System (MISS) to the University of Virginia in April 2009 to support Education in Complex Terrain Meteorology (EDUCT).

MISS staff visited the Shenandoah Park area to make a series of measurements together with UV students and collected data to be used in a number of student projects.

ASP Colloquium

make weather measurements and participate in classroom activities. As part of this exercise, EOL's Mobile GPS Advanced Upper-air Sounding (MGAUS) system toured six schools, making a sounding at each and interacting with students in the classroom. Nearly 400 students participated.

EOL continues expanding the number of activities related to NSF Facility Requests for Education. Changes in FY2009 include increased funding to the deployment pool for educational requests, new guidelines that encourage PIs to integrate K-12 outreach to local community. Finally, EOL is now actively soliciting proposals from Minority Serving Institutions.

Advanced Study Program (ASP) Colloquium

The 2009 ASP summer colloquium, "Exploring the Atmosphere, Observational Instruments and Techniques," ran from May 31 to June 12, 2009. Attendees included 27 students from four countries, as well as more than 70 professors, scientists, and staff members from UCAR, Colorado State University, University of Wyoming, NOAA, University of Illinois, University of Alabama, University of Vienna, and University of Virginia who acted as lecturers, instructors for laboratory exercises, mentors for projects, pilots, scientists, engineers, project managers, computing, technicians, administrators, drivers, etc. The objectives of the colloquium were:

- To introduce advanced graduate students to principles and operation of the NSF Lower Atmosphere Observational Facilities.
- To teach graduate students how to plan and conduct limited experiments using the aircraft, radars, surface station and related instruments
- To guide the graduate student participants in the analysis of the observations they collect.

While understanding observing instrumentation is important, the focus of the colloquium was on allowing the students to gain a deeper insight into the atmosphere and its processes through practical research projects. The facilities involved were the EOL Surface and Sounding Systems, CSU-CHILL and the University of Wyoming King Air.

The colloquium started out with lectures on the boundary layer, atmospheric composition, clouds and precipitation, clear air dynamics, and cloud dynamics, as well as a lecture that covered Colorado weather specifically. Students also received training on instruments and techniques, including Surface (Flux, Sounding, Mobile, Profiler, Radiation); Airborne (State, Winds and Turbulence, Aerosol, Clouds and Precipitation, Trace Gas); Remote (Radar Principles, Airborne Radars, Polarimetric, Applications.) Students also participated in laboratory exercises designed to prepare them for two-day mini field experiments held late in the first week.

Throughout the two week period, with assistance from instructors and mentors, the students described identified scientific objectives, designed field experiments to address those objectives, gathered and analyzed data and presented their findings in a forum after 4 days of analysis. Most of the participating students stayed in Boulder beyond the end of the colloquium to attend the NSF Observational Facilities Users' Workshop the following week.

NSF Observational Facilities Users Workshop

In FY2009 our bi-annual NSF Observing Facilities Users Workshop (NSFUW) took place directly after the Advanced Study Program Colloquium, which focused on training students in atmospheric sciences about observational facilities and techniques. Approximately 130 people from universities and agencies all over the United States participated in the workshop. The NSFUW was conducted in partnership with the University of Wyoming (UW,) Colorado State University (CSU), and the Center for Severe Weather Research (CSWR).

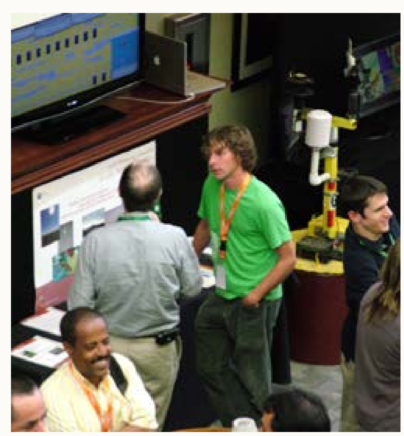
Taking our cue from 2007 NSFUW participant feedback, the major goal for the 2009 workshop was to attract a greater number of early-career scientists and students, and familiarize them with NCAR/EOL capabilities as well as the NSF LAOF request process. EOL got off to a good start by marketing the

Colloquium participants listen to a lecture designed to prepare them for the field phase of the event.

ASP Colloquium students in the field during the two week event.

NSF Observational Facilities Users Workshop

Guy Brasseur delivers a keynote speech on future challenges in earth system observation and modeling during the 2009 NSF Users Workshop. Since this year's workshop was focused on the younger generation of scientists and junior faculty, many of the speeches, lectures and activities were aimed at familiarizing them with opportunities and challenges they would likely face during their careers.



Booth exhibit sessions were a big draw during the 2009 NSF Users' Workshop. Facility managers were

workshop heavily to university faculty and student organizations. Subsequently 35% of participants self-identifying as “novice” users of NSF Facilities on their registration questionnaires. This year we hosted nearly 30 students, up from two in 2007, including participants from the ASP Colloquium.

Keynote speakers were asked to provide their personal view as to the pressing scientific questions in their respective fields and suggest a path forward for observational platforms to answer these questions including suggesting new instrument development. The four keynote speakers were:

- Guy Brasseur - "Earth System Observations and Modeling: The Challenges for Tomorrow"
- Eric Barron - "Implications of the Next Generation of Climate Science."
- Howie Bluestein - "Scientific and Observational Challenges in Mesoscale and Convective-Scale Meteorology."
- Susan Solomon - "Global Climate Change Assessment: a Look Backward and Forward."

Participants responded well to the agenda topics and activities, many which were relevant to a new user, including interactive booth sessions with EOL, UW, CSU and CSWR facilities and personnel. On Sunday afternoon before the workshop formally opened a several dozen early-arrivers attended an open house tour of EOL's Foothills Laboratory and the CHILL Radar at the Colorado State University. At the Foothills Laboratory several In-Situ sensing facilities were operating and the Design and Fabrication Services opened their machine shop to familiarize attendees with our design services and machining capabilities.

Summer Undergraduate Engineering Internship Program (SUEIP)

2009 was another record year in terms of applicants for EOL’s Summer Undergraduate Engineering program, which focuses EOL’s outreach efforts on the engineering community in a manner analogous to what UCAR/NCAR currently does for young scientists.

EOL received resumes from mechanical, electrical and computer, aerospace, optical, environmental, chemical, and industrial engineering students. A total of 2 applications were received, the most applications ever received for any position at UCAR.

Three interns were hired and worked with EOL engineers during the summer of 2009:

- Rose-Gaëlle Belinga is an electrical and computer engineering student from the Auburn University in Alabama. Rose will be working with Charlie Martin in the Computer, Data and Software Facility on upgrading and documenting the Atmospheric Sounding Processing Environment (Aspen) software which is used for analysis and quality control (QC) of sounding data.
- Dan LaGreca worked with Chris Webster in the Research Aviation Facility designing new flight tracking software for EOL's research aircraft that included an image capture system integrated with mapping technologies and a web display that will eventually become EOL's version of a self-contained "Google Earth" available to researchers, students and the general public during field campaigns
- Greg Busch from Ohio State University worked with Chris Burghardt from the Computing, Data and Software Facility to create a LabVIEW that successfully calibrates the sensors used in measuring radiation given off by a "Black Body" with minimal human interaction. A Black Body is a device that ideally absorbs all electromagnetic radiation and in turn expels thermal radiation
- Aeronautical Engineering student Kristen Brenner worked with aeronautical engineer Mark Lord at the Research Aviation Facility to design a fairing for a flat-plate antenna that was used during the ADELE-SPRITE campaign. Kristen also performed weight and balance analysis and component containment of the equipment racks used in

available to discuss instruments, posters, and data displays with participants.

Summer Undergraduate Engineering Internship Program (SUEIP)

The Summer 2009 Summer Undergraduate Engineering Interns and their mentors: (L-R) Mentor Nick Potts, intern Greg Busch, mentor Chris Burghardt, intern Rose-Gaëlle Belinga, mentor Charlie Martin, intern Dan LaGreca, mentor Chris Webster, intern Kristen Brenner, mentor Mark Lord.

EOL Intern Kristen Brenner holds the fairing for the flat-plate antenna she designed during her internship this summer. The fairing was used to secure the flat-plate antenna to the underside of the NSF/NCAR G-V for the ADELE/SPRITE field campaign.

the G-V for ADELE. Her other activities included analysis of "ditching" for the new wing pods - pods must be strong enough to fly on the aircraft yet must also break away or "ditch" in case of an emergency.

Continuation of this highly successful program will be a priority in FY10 and 11.

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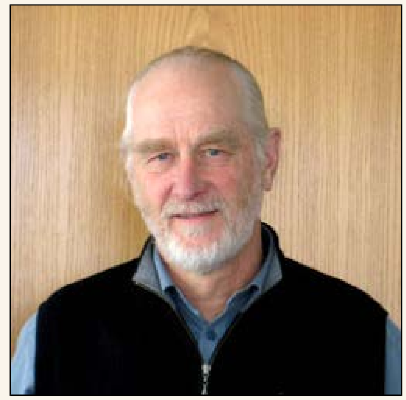
ESSL LAR 2009: DIRECTOR'S MESSAGE

Dear Colleagues:



Greg Holland
NCAR Associate Director
Acting Director, Earth and Sun Systems Laboratory

Preamble: The latter half of FY 2009 has seen substantial changes in the Earth and Sun Systems Laboratory (ESSL), with the High Altitude Observatory leaving to become a new Laboratory and the Atmospheric Chemistry, Climate and Global Dynamics, and Mesoscale and Microscale Meteorology Divisions combining into the NCAR Earth System Laboratory (NESL). The full structure and operating processes for NESL are being developed in close liaison with staff, and remain in transition as I write. However, I can assure you that the NESL will maintain and enhance the tradition of leading-edge, integrative science and major community-facility support that is a hallmark of NCAR. This commitment will extend beyond NESL to include other NCAR laboratories and to our wide range of community colleagues and collaborators.

The year also saw the transformation of TIIMES into a new Integrated Systems Program (ISP). The role of ISP in the NESL is also being developed at the time of writing, but we have assumed direct responsibility for several components of the major elements of TIIMES, working in collaboration with the wider community. These include: BEACHON, UTLS, Water Across Scales and THORPEX. Progress with these activities is included in the LAR details.

Our mission: *To advance the understanding of weather, climate and atmospheric composition and processes; to provide facility support to the wider community; and to apply these to benefit society.*

In performing this mission, we shall continue to:

- Sustain and nurture our fundamental disciplinary programs, while reaching out to engage other disciplines in accomplishing our goals;
- Undertake transformational research, which involves an element of risk but is essential to improving our understanding of the earth system and to our development of major community facilities;
- Engage with community leaders and policy makers to convey research findings, to develop new research directions, and to emphasize the importance of investment in research and major facility development;
- Invest wisely in the maintenance and continuing development of community modeling, instrumental and experimental facilities;
- Develop next-generation tools and techniques utilizing cutting-edge research and in collaboration with the wider community;
- Encourage and promote new, diverse talent into our field through participation in educational programs from K12 through graduate university, and by mentoring students and young scientists.

Laboratory Annual Report: This year we have mapped our LAR to the NCAR strategic plan and this emphasizes the depth and breadth of NESL support for NCAR Priorities and Frontiers. For 2009, our priority activities included:

- Advancing knowledge across a wide range of atmospheric, chemical, solar and climate areas
- Prediction Across Scales and Earth Teleconnections
    - Decadal Global and Regional Climate Prediction, including preparation for IPCC V and time-slice decadal predictions of high-impact weather such as Atlantic hurricanes and western snow pack
    - Nested Regional Climate Modeling
    - Earth System Modeling, including the Model for Prediction Across Scales and the Community Earth System Model
    - Further development and expansion of the Weather Research and Forecasting modeling system
    - Towards an Integrated Model of the Sun

- Hydrosphere-Biosphere Interactions
- Polar Dynamics: Ice and Chemical Composition
- Space Weather

Outlook: NESL has a solid foundation of expertise, facilities and community interactions from which to build as we transition to our new structure. Over the next several months we shall be developing a strategic plan outlining our laboratory priorities and frontiers in support of the recently-developed NCAR strategic plan. As indicated in our mission statement, our priority will continue to be on benefiting society and supporting our colleagues in academia through both advancing knowledge and further development and continued support for our major modeling and experimental facilities

Greg Holland
NCAR Associate Director
Acting Director, Earth and Sun Systems Laboratory

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ESSL LAR 2009: IMPERATIVE I

Promote innovation and creativity within our institution and across the community of atmospheric, solar, and related sciences

A. Conduct discovery-oriented research across the atmospheric, solar, and related sciences to identify emerging issues, develop new approaches, and guide the direction or redirection of ongoing research programs

B. Develop and support collaborative research efforts that combine ecological, hydrological, biogeochemical, and social science expertise with core atmospheric disciplines to address challenging and multifaceted Earth system science problems

C. Enhance supercomputing, observational, and modeling facilities by evaluating new technologies; experimenting with advanced computational architectures; and developing prototype instruments, models, and model components

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Exploring the role of aerosols

The effects of aerosols on climate represent the single largest source of uncertainty in our understanding of global warming. In order to reduce the uncertainty of the role of aerosols in climate and weather, ESSL scientists are conducting both experimental and modeling studies of aerosol formation, composition, and direct as well as indirect radiative forcing.

ACD scientists collaborated with the Jonathan Allen (U. Toronto) to measure the physical and chemical properties of arctic aerosol as part of the OASIS field campaign in Barrow, AK during March – April 2009. Measurements

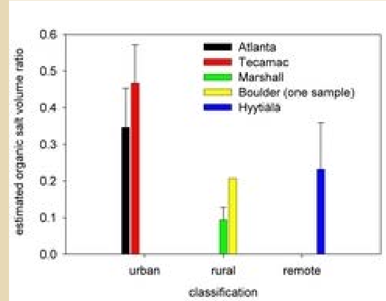

Figure 1. Overview of the molar ratio of organic salts during nanoparticle growth events, grouped according the land type, for representative events in which the TDCIMS performed measurements. Error bars indicate standard deviation of the mean.

High resolution figure

included the size distribution, hygroscopicity, and volatility of ambient aerosol. These data will be used to assess the various sources and sinks of aerosol in the arctic.

During 2009 ACD scientists also continued their ongoing collaboration with Peter McMurry (U. Minn.) to investigate the formation and growth of nanometer-sized particles in the atmosphere. These minute particles form from nucleation of low-volatility vapors, and grow by processes that are, as yet, not well understood. Understanding growth mechanisms is essential because the growth rate determines whether a newly formed particle will ultimately grow to CCN size (~100 nm in diameter) or be scavenged by pre-existing aerosol. This activity culminated in a field campaign co-organized by ACD and U. of Minn. called “Nucleation and Cloud Condensation Nulclei,” or NCCN. NCCN took place from mid-July until the end of August 2009 in midtown Atlanta, GA; its goals included understanding the mechanisms by which particles nucleate and grow in this atmosphere. During the campaign, ACD scientists performed several unique measurements, including the composition of ambient molecular clusters using the cluster-Chemical Ionization Mass Spectrometer (cluster-CIMS), as well as the composition of 8 – 20 nm diameter nanoparticles using the Thermal Desorption Chemical Ionization Mass Spectrometer (TDCIMS). Results from the cluster-CIMS showed that, during nucleation, high concentrations of sulfuric acid neutral clusters (up to the tetramer) were detected. The concentrations of these clusters were highly correlated with SO2 plume, suggesting that sulfuric acid clusters contribute to nucleation. Results from TDCIMS measurements were used to assess the role that organic salt formation plays in nanoparticle growth. Organic salts are ionic complexes formed when an organic base such as an amine combines with an organic acid such as acetic acid. ACD scientists recently analyzed results from this and four other field campaigns and showed that organic salt formation could account for 10-45% of detected particulate organic compounds (Figure 1). These salt compounds thus contribute significantly to nanoparticle growth and must be accounted for in models to accurately predict the impact of new particle formation on climate.

ACD scientists also collaborated with Murray Johnston (U. Del.) to investigate the composition of urban nanoparticles. These measurements were performed in downtown Wilmington, DE, as a part of the Ultrafine Aerosol Characterization Experiment (ULTRACE2009), which took place mid-June through mid-July 2009. Preliminary data suggest a successful measurement campaign, characterized by observations of high molecular weight species in nanoparticles that correlate with local traffic activity.

Funded by: NSF, HEI, DOE.

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Climate change and regional air quality implications

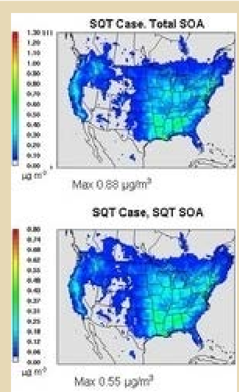

Figure 1: Simulated total secondary organic aerosol (SOA) (Top) and SOA from sesquiterpenes (Bottom) averaged for July 2001.

Globally, secondary organic aerosol (SOA) from biogenic precursors surpasses those from anthropogenic sources. These organic particles impact climate directly by scattering and absorbing of radiation, and indirectly through the modification of clouds and precipitation. These processes exert a substantial influence back upon the earth system through links to the terrestrial carbon and water cycles (e.g., precipitation regulates plant growth and thus emissions of organic compounds). Understanding the feedbacks between the atmosphere and terrestrial environment is key to estimating the impact of climate change on regional air quality.

In the past year, ACD scientists collaborated with Jack Chen, Jeremey Avise, and Brian Lamb (Wash. State U.), Cliff Mass (U. Washington), Donald McKenzie and Susan Fergusen (US Forest Service) to investigate the impact of future climate and land cover on regional air quality in the Pacific Northwest and North Central U.S. The results indicate that U.S. regional air quality (e.g., ozone and particles) will degrade even if U.S. anthropogenic emissions remain the same. The changes are due to a combination of pollutant transport from other countries (primarily China, Mexico and Canada), changes in wildfire emissions, and changes in biogenic emissions. The increased pollution transport is due to predicted increases in emissions in these countries. Wildfire activity is predicted to increase due to a warming and drying climate. Biogenic VOC emissions are expected to increase in

response to higher temperatures. Land use change (i.e. tree plantations, agriculture, and urbanization) scenarios result in dramatic increases in some regions and decreases in other areas. Another collaboration between ACD and RAL scientists and Xiaoyan Jiang and Zong-Liang Yang (U.Texas-Austin) showed that land cover and land use change in the Houston urban area can contribute as much to future increases of ozone concentrations as changes in climate and biogenic emissions. Work with Xuemei Wang (Sun Yat-sen University) highlight the impacts of land use change and resulting heat island effects on ozone concentrations in the Pearl River Delta.

ACD scientists, collaborating with researchers from the University of Colorado, have also created a new emissions inventory of sesquiterpenes from vegetation using the Model of Emissions of Gases and Aerosols from Nature (MEGAN). These emissions were input to a regional chemical transport model so that the impact of these compounds on secondary organic aerosol (SOA) concentrations could be evaluated. The results, plotted in Figure 1, show that sesquiterpenes from vegetation roughly doubled the amount of SOA simulated when compared to simulations without sesquiterpenes; however, the model still underpredicted particulate organic matter when compared to observations.

In particular, the amount of SOA is underpredicted by an order of magnitude in current models (see Fig. 2 blue lines) although they accounts for 10-50% of the submicron aerosol mass. Understanding processes involved in the formation of SOA is therefore an urgent task in order to improve their representation in models and reduce uncertainties in climate predictions. ACD scientists collaborated with researchers from the University of Colorado (Jose Jimenez) and the Paul Scherrer Institute, Switzerland, to investigate the contribution of various formation pathways and precursors to observed levels of SOA in Mexico City during the MILAGRO 2006 project. The model SOA predictions from anthropogenic (i.e. aromatics, alkanes), biogenic (i.e. monoterpenes and isoprene) and biomass-burning SOA precursors, have been compared to AMS and 14C measurements. It has been found that SOA formation from aromatics and alkanes (< C10) could explain less then 20% of observed SOA. Study also suggest that SOA concentrations found in the Mexico City basin were strongly influenced by regional SOA (~1.5 µg/m3) of biogenic origin which is formed over the coastal mountain ranges and advected around the Central Mexican Plateau (see Fig. 3). Unlike anthropogenic contribution, SOA formation from biogenics seems well captured by the model as show on Figure 3. Finally, the study indicates that emissions and the chemistry of semi-volatile and intermediate volatility primary organic vapors could lead to a substantial increase in predicted SOA concentrations (a factor of 3-5) and explain the gap with observations. However, many uncertainties in the representation of the evolution of these species exist and current parameterizations need to be further adjusted as well as simplified for the use in climate models.

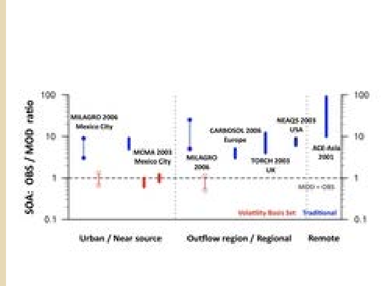

Figure 2: Comparison of observed to predicted SOA ratios as determined in the present study (MILAGRO 2006) and reported in recent studies. MCMA 2003 summarizes results reported by (Volkamer et al., 2006, Dzepina et al., 2009, and Tsimpidi et al., 2009); CARBOSOL 2006 refers to (Simpson et al., 2007); TORCH 2003 refers to (Johnson et al., 2006); NEAQS 2003 (de Gouw et al., 2005); ACD-Asia 2001 (Heald et al., 2005). In blue are represented estimates of the traditional SOA approach, while red refers to the volatility basis set.

High resolution figure

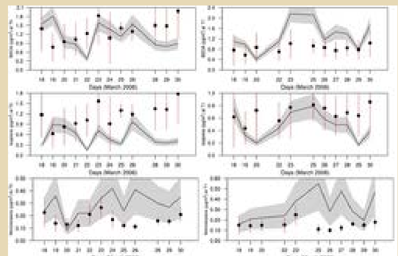

Figure 3: Measurement-derived (black line) and model-predicted (black dots) daily-averaged concentrations of biogenic SOA at T0 and T1 including the total BSOA, BSOA from isoprene and BSOA from monoterpenes.

High resolution figure

In order to improve on uncertainties relating to the indirect effects of aerosols on climate, ACD scientists have added a new aerosol scheme using a modal approach to the global models. Current evaluations of this scheme focus on evaluating warm cloud indirect effects, and on adding ice cloud formation to the models.

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Chemistry-climate coupling: Past and future

In continuation of the work performed under FY2008, we have performed long-term transient simulations 1850-2005 with CAM coupled to interactive tropospheric and stratospheric chemistry. This simulation is driven by emissions varying with time and location to capture changes in industrialization over that period. We are also performing simulations beyond 2000 (up to 2100 and possibly 2300) driven by the newest IPCC scenarios (called “Representative Concentrations Pathways”, and for which we worked with Integrated Assessment Modelers to generate emissions useful for chemistry simulations) to simulate future changes in ozone and aerosols. Comparison with recent ozone trends at the surface indicate that the model does quite well at reproducing present-day conditions but might overestimate the observations prior to 1980-1990. Further analysis is on-

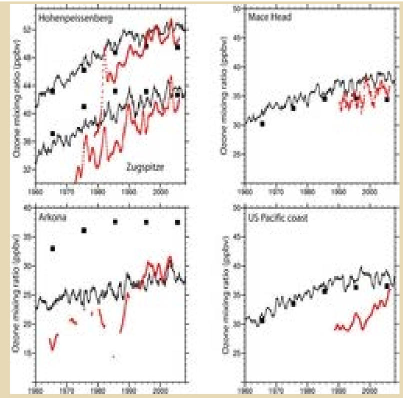

Figure 1. Surface ozone trends from CAM-chem (solid line), GISS (black squares) and observations at a variety of stations in the Northern Hemisphere (red lines, data provided by D. Parrish, NOAA).

High resolution figure

going, including comparison with ice-core data (hydrogen peroxide).

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Community Climate Systems Model: Advancing Climate Science

Overview

Each year much effort is devoted to further development of the Community Climate Systems Model (CCSM), and soon the Community Earth System Model (CESM), and those efforts in and of themselves lead to discoveries about the processes that contribute to climate and its fluctuations. Beyond this, even more is learned about the climate system by applying the CCSM to various outstanding problems concerning the character of the climate and the mechanisms that control its behavior. To this end, members in every section of CGD use the CCSM to investigate a broad range of issues. Below are examples that demonstrate the breadth of topics considered in FY2009.

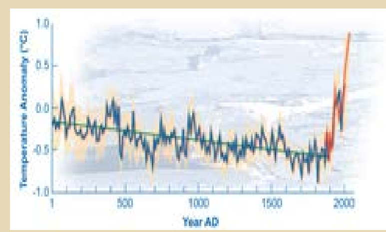

Figure Caption: New research shows that the Arctic reversed a long-term summer cooling trend and began warming rapidly in recent decades. The blue line shows estimates of summer season Arctic land temperatures over the last 2,000 years, based on proxy records from lake sediments, ice cores and tree rings. The shaded area represents variability among different Arctic sites. The green line shows the long-term cooling trend. The red line shows the recent warming based on actual observations. A 2000-year transient climate simulation with NCAR's Community Climate System Model shows the same overall temperature decrease as does the proxy temperature reconstruction, which gives scientists confidence that their estimates are reasonably accurate.

High resolution figure

Recent Accomplishments

CCSM: Annular Modes

A 40-member ensemble of CCSM3 forced with the SRES A1B greenhouse gas and ozone recovery scenarios has been used to project atmospheric circulation trends during the 21st century. The results show that the annular modes, the leading structures of high latitude circulation variability in both hemispheres, exhibit significant shifts toward the positive phase in the Northern Hemisphere and negative phase in the Southern Hemisphere. However, there is considerable spread in the distribution of the trends amongst the individual ensemble members, most of which can be accounted for by internal atmospheric variability which is inherently unpredictable on long time scales.

CCSM: Polar Regions

Continued development of the terrestrial carbon cycle model, including the capability of simultaneously simulating both dynamic natural vegetation and anthropogenic land cover change, is intended. As the model matures, a primary scientific theme to examine will be natural and human-mediated changes in land cover and ecosystem functions and their effects on climate, water resources, and biogeochemistry. With the introduction of the Integrated Assessment Modeling (IAM) group to the Climate and Global Dynamics Division, we will begin to design an IAM-CCSM interface.

The CCSM project continued to take a lead on model developments for polar regions and on studies related to polar climate variability and change. This included the investigation of mechanisms leading to rapid summer Arctic ice loss, the potential that these have to represent "tipping point" or threshold behavior, and the interaction of these events with polar cloud conditions. Studies using CCSM also examined the seasonal predictability of Arctic sea ice cover under different climate regimes. CCSM was used to assess the impact of potential future Greenland ice sheet melt for meridional overturning circulation and climate. Additionally, a 2000-year transient climate simulation with the CCSM corroborated paleo-proxy evidence that recent warming reversed 2000 years of natural Arctic cooling.

Climate predictability

Past investigations of climate change often focused on century timescales, but nearer term changes are of equal interest to society and scientifically distinct in that the initial state of the system may influence its evolution. To estimate the predictability of climate on decadal time scales a 40-member ensemble of integrations was performed with CCSM in which the years 2000 to 2062 were simulated. Each realization was forced by the same SRES A1b sequence of climate forcings, but each had a different initial atmospheric state. A classic measure of predictability is how rapidly two similar states diverge from each other with predictability being lost when the two states are as far apart as two randomly chosen states. Using the CCSM ensemble, for the globe as a whole the limit of predictability for annual means of average upper-ocean temperature is about a decade. There is less predictability of the global sea surface temperature field because of the stronger influence of high-frequency atmospheric variability on surface temperature. Regionally, the predictability of SST can be higher than for the global field (not shown), with the highest levels on decadal time scales over the middle to high latitude ocean areas of both hemispheres, especially in regions where the surface layer makes contact with the deeper ocean beneath.

2010 and Beyond

Applications of CCSM will continue on a wide range of topics, especially as new processes and components are added to the model, soon resulting in the release of the CESM. Examples are provided in the recently published CESM science plan (http://www.ccsm.ucar.edu/csm/management/sciplan09-15.pdf), several of which are briefly summarized below.

Interaction of the Carbon Cycle, Ecosystems and Climate

Land and ocean life can influence climate through a variety of biogeophysical and biogeochemical pathways. Interactions between climate and ecosystem processes, especially in response to human modification of ecosystems and atmospheric CO2 growth, will likely produce a rich array of climate forcings and feedbacks that could either amplify or diminish climate change. Biota will also modulate regional patterns of climate change. Ecosystems are the focus of many carbon sequestration approaches for mitigating climate change, and are the central elements of potential climate impacts associated with food security, water resources, human health and biodiversity. However, the magnitude of these climate-biota interactions (and in some cases even the sign) are not well constrained, and are critical scientific unknowns affecting the skill of future climate projections.

Decadal Climate Projections and Forecasts

Efforts to predict the evolution of climate over the next several decades that take into account both forced climate change and natural decadal-scale climate variability are in their infancy, and many formidable challenges exist. For example, climate system predictions on the decadal time scale will require initialization of models such as CESM with the best estimates of the current observed state of the coupled system - a state influenced both by the current phases of modes of natural variability and by the accumulated impacts to date of anthropogenic radiative forcing. However, given imperfect observations and systematic errors in models, research is required in order to establish the best method of initialization, and it is not known what effect initialization has on climate predictions. The brevity of most instrumental records furthermore means that even the basic characteristics and mechanisms of decadal variations in climate are relatively poorly documented and understood. As a consequence, the representation of natural variability arising from the slowly-varying components of the climate system differs considerably among models, so the inherent predictability of the climate system on the decadal time scale is also not well established.

Interaction of Aerosols and Climate

Aerosols affect the climate in a multitude of ways. They directly reflect and absorb solar radiation in the atmosphere, altering the vertical distribution of short-wave radiation available to the climate system. Aerosols also act as cloud condensation and ice nuclei and regulate cloud properties, which strongly alter the short-wave and long-wave radiation budgets of Earth. Increased numbers of cloud condensation nuclei can produce more of the smaller cloud droplets, which increases a cloud's optical depth. Production of these smaller cloud droplets also suppresses the growth of droplets into larger sizes that precipitate out of the cloud, thus leading to clouds with more condensate and/or longer lifetimes. Increased numbers of ice nuclei can accelerate precipitation from clouds, reducing the cloud liquid water content and lifetime. In addition, absorption of solar radiation by aerosol particles in clouds can reduce the relative humidity and evaporate cloud water. All of these changes lead to changes in the cloud's radiative effects on the Earth's energy budget. Quantifying the anthropogenic aerosol impact on climate is important for isolating human impacts on climate change from natural variability.

Interaction of Chemistry and Climate

Changes in the distribution of large population centers are expected to occur over the next decades, with more megacities (population over 10 million) present in developing countries. These represent large "point" sources of pollutant that will lead to significant regional pollution degradation and possible impacts on regional meteorology and climate. Some of those issues will be tackled under the aforementioned decadal prediction experiments. Beyond those pioneering exercises, we expect that this type of regional problem will be particularly suited to an interaction between global and regional chemistry-climate models. Through a newly developed capability of representing size distribution of aerosols, scientists using CESM are now in the position to explore in a more realistic fashion interactions between clouds and aerosols. While many studies can be performed in this framework, there is evidence that the chemical composition of aerosols is a critical element in their ability to act as cloud condensation nuclei. Better representation of the chemistry happening at the

surface and inside the aerosols will be needed to ensure the correct representation of the water uptake of aerosols. To benefit from field experiments, this research area will require an ability of the model to perform simulations at high resolution and with large numbers of chemical constituents, thereby extending the on-going research in regional chemistry modeling.

Role of the Middle Atmosphere in Climate

The role of the middle atmosphere in climate change is currently an open question. Changes in the propagation characteristics of planetary waves in the stratosphere appear to play a role both in stratospheric climate, via dynamical and chemical interactions that affect ozone concentration, and in tropospheric climate by influencing phenomena such as the Northern and Southern Annular Modes. The dynamics of the stratosphere are dominated by the interaction of dynamical forcing due to waves propagating upward from the troposphere and radiative forcing by solar heating due to ozone. Upward-propagating planetary waves affect the stratosphere directly. Small-scale gravity waves can deposit momentum in the stratosphere itself, or in the mesosphere, where they affect the stratosphere through "downward control." Understanding the climate role of the stratosphere is a goal of the WACCM project, which is motivated by the necessity of studying dynamical and chemical processes interactively and comprehensively. WACCM is built upon the software framework of CCSM, in order to benefit from the development of the atmospheric component of the CCSM, and the diagnostic infrastructure that exists for that model.

Role of Ice Sheets, Sea Ice and Land in Abrupt Climate Change

The climate record shows evidence of rapid and extreme temperature change, sometimes in as little as a decade. An abrupt climate change is thought to occur when the climate system passes a threshold, so that a small perturbation can trigger a large response. The mechanisms that cause abrupt changes are not fully understood, and there is general agreement that climate models do not properly represent them. The possibility that an abrupt change will occur in the future due to anthropogenic influences makes the need to better understand their mechanisms an essential element of projections of future climate. Climate models such as CESM will be used both to identify mechanisms and to estimate their future impacts.

Role of Ocean Mesoscale Eddies in Climate

The ocean interacts with other components of the climate system through the direct influence of sea surface temperature on the atmosphere, by transporting energy, water, and material around the globe, and by sequestering dissolved gases such as CO2 in the interior out of contact with the atmosphere. Ocean mesoscale eddies and fronts play a role in each of these processes. The majority of the kinetic energy in the ocean exists at these scales, yet they are substantially smaller than can be explicitly resolved by the standard version of the CCSM ocean component. A central problem in oceanography is to quantify the processes through which eddies and fronts influence the larger scale climate, and to represent these processes through parameterization in climate models.

Interaction with Integrated Assessment Modeling

The identification and evaluation of climate change response options, including both mitigation and adaptation, requires carrying out integrated analyses involving the physical climate system and the ecological and socio-economic systems with which it interacts. Stronger linkages between the CESM and the integrated assessment modeling (IAM) community offer a new means of bringing such integrated research to bear on pressing questions regarding possible responses to the challenge of climate change. IAMs link quantitative models of socioeconomic and biophysical components of climate change, and apply them to policy-relevant questions. Historically, IAMs have incorporated highly simplified representations of the climate system, and the interaction between the IAM and earth system modeling community has been limited. More recently, however, interest in exploring the potential of linking IAMs with earth system models has grown, stimulated in part by a new, IPCC-catalyzed scenario process that includes interactions between these communities, and will play a key role in generating integrated scenario analyses in the run-up to the Fifth Assessment Report. Activities related to CESM that could promote interaction with the IAM community include a range of options, from incremental to ambitious, internal NCAR interactions to collaboration with the wider IAM community, and indirect exchanges to direct model coupling.

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Paleoclimate

Overview

Paleoclimates offer a unique perspective to understand both Earth's climate sensitivity and stability. Observational data 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.

A strong test of the Community Climate System Model (CCSM) is to simulate past climate against records from ice cores, tree rings, and other proxy data.

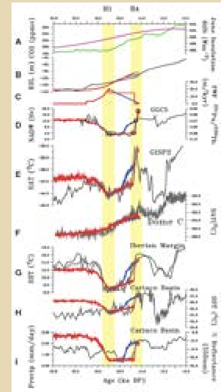

Figure Caption. Model simulation (red) and observational data (black) from the fully coupled transient simulation of CCSM3 for the time period 22 ka to 10ka.

High resolution figure

Magnitudes and rates of past change also provide an important context for future climate changes. Within ESSL, we are exploring past changes over many different time periods: from the distant geologic past, with radically different continental configurations, when the Earth's surface temperature and latitudinal gradients were significantly different from present and levels of atmospheric carbon dioxide, methane, and other greenhouse gases reached levels up to ten or more times present levels; the last million years, when the Earth experienced a waxing and waning of ice ages and levels of atmospheric carbon dioxide, methane, and other greenhouse gases during the ice ages were reduced by half or more from present levels; and the last few millennia with colder periods extensively documented in the proxy record associated with solar fluctuations and volcanic eruptions. Each of these geologic periods gives us an improved understanding of the natural variability of the Earth system and our ability to model feedbacks in the climate system. By comparing climate simulations of Earth's past to the data from geological and geochemical archives, we can evaluate the accuracy of climate models such as CCSM that are used to look at Earth's future. At the same time, geologists have started to use CCSM to understand how their specific data can be understood in a more large scale, dynamical context. CCSM has become a valuable partner to field-based geological research.

Recent Accomplishments

CCSM has recently been applied to the warm world of the Paleocene Eocene Thermal Maximum (55 Ma). This was a time when Earth experienced rapid warming associated with greenhouse gas forcing. Paleodata indicate this was also a time of very low temperature difference between the equatorial and polar regions compared to present. A major accomplishment is the successful simulation of this period with CCSM3. Assuming elevated levels of carbon dioxide, methane and natural background levels of cloud condensation nuclei, the CCSM3 realistically simulates observational data including warm polar waters (20 °C and warmer) and the deep ocean warm waters. This simulation also indicates a Northern Hemisphere source for intermediate water formation (~1000 meters) out of the Tethys Sea. The simulation also captures the observed warm interior continental regions, which have eluded past model simulations.

Proxy records for the deglaciation that started 21 thousand years ago indicate events with large freshwater inputs to the Atlantic Ocean basin as iceberg discharges into the high-latitude North Atlantic, Laurentide meltwater input to the Gulf of Mexico, or meltwater diversion to the North Atlantic via the St. Lawrence River and other eastern outlets. The climate responded, in the North Atlantic region and globally, to these freshwater events, but the responses varied among the events and are not completely understood. Using the CCSM3 the first synchronously coupled atmosphere-ocean general circulation simulation from the Last Glacial Maximum (~21ka) to the Bolling-Allerod (~14.5 ka) was carried out. The model simulation reproduces major features of the evolution of deglaciation indicating that the climate sensitivity of the model agrees with observed sensitivity. The model indicates that the Bolling-Allerod warming was a result of a change in the Atlantic meridional overturning circulation resulting from a sudden termination of fresh water into the North Atlantic region.

2009 and Beyond

Future plans also include sensitivity studies of deep time simulations of the Latest Cretaceous a time period just prior to the massive asteroid impact that led to the demise of the dinosaurs. There will also be a focus on simulating the magnitudes and rates of past climate change on many time scales using the planned NCAR Earth System Model, which will allow us to explore more completely feedbacks with vegetation and ice sheets, atmospheric chemical changes, and the carbon and nitrogen cycles. A version of CCSM3 is also being developed that includes isotopic tracers, which will allow for a more direct comparison between paleodata and model simulations.

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Ecosystem - biogeochemistry - climate interactions

Overview

Biogeophysical and biogeochemical feedbacks between the climate and the biosphere could modify and, in some cases models suggest, enhance climate change. In ESL, we study these feedbacks to help understand projections of future climate. Our primary tool is the CCSM, with the addition of

parameterizations of terrestrial and marine biogeochemical cycles. The work happens within the context of the Biogeochemistry (BGC) Working Group, whose overall goal is to improve our understanding of the interactions and feedbacks between the physical climate and biogeochemical systems under past, present and future climates.

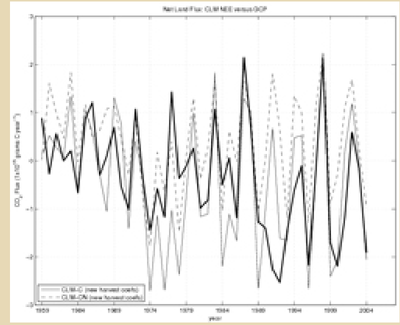

Figure Caption: Simulation of the net carbon flux from the terrestrial BGC model with and without dynamic nitrogen compared to an observational estimate from the Global Carbon Project.

High resolution figure

Recent Accomplishments

CCSM scientists continued to develop models of the global biosphere, including oceanic, terrestrial, and human managed ecosystems. A version of these models is included in the CCSM for use in the simulations for the IPCC 5th Assessment Report.

Model experiments found that the coupling between the terrestrial carbon and nitrogen cycles modifies the carbon cycle-climate feedback. Accounting for the nitrogen cycle limits the CO2 fertilization of photosynthesis and plant growth, while simultaneously increasing plant growth through more soil nitrogen mineralization as the climate warms. Warming also leads to increased soil respiration, so the net CO2 flux at the land-atmosphere interface results from competing processes. We hope to disentangle these processes in order to understand their relative importance and assess the ability of the terrestrial BGC model to simulate the observations.

On the ocean side, additional features have been added to the ecosystem model including: more sophisticated iron sedimentary source, improved iron scavenging parameterization, improved dynamic Si/C and Fe/C ratios within phytoplankton, incorporation of atmospheric N deposition, incorporation of zenith angle aware diurnal cycle of shortwave radiation used for photosynthesis. The ecosystem model, with these new features, has been evaluated and tuned with physical parameterizations used by the ocean model in CCSM4. The model parameters have now been selected for the upcoming IPCC runs that will have a prognostic carbon cycle.

In other developments, dynamic vegetation has now been tied directly to the carbon-nitrogen model of the land BGC model and may be selected as an option when running new versions of the CCSM. Corn, wheat, and soybean models directly coupled to the carbon-nitrogen model, as well as dynamic crop irrigation, are in their test phase.

2010 and Beyond

Continued development of the terrestrial carbon cycle model, including the capability of simultaneously simulating both dynamic natural vegetation and anthropogenic land cover change, is intended. As the model matures, a primary scientific theme to examine will be natural and human-mediated changes in land cover and ecosystem functions and their effects on climate, water resources, and biogeochemistry. With the introduction of the Integrated Assessment Modeling (IAM) group to the Climate and Global Dynamics Division, we will begin to design an IAM-CCSM interface.

While the deficient ocean ventilation of the coarse resolution of CCSM3 has been improved in CCSM4, we still have problems with low oxygen supply to intermediate depth oxygen minimum zones. A high priority for the ocean BGC modelers is to improve the ventilation in the shadow zones of upwelling areas. In partnership with the ocean physical modelers, we will embark on a systematic plan to try to resolve this deficiency.

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Role of oceans in the climate

Overview

Covering 71% of the Earth, the oceans absorb the majority of the solar energy reaching the surface. The heat capacity of the upper three meters of the oceans exceeds that of the entire atmosphere, and the oceans contain approximately 50 times greater inventory of CO2 than the atmosphere. The phase change from liquid to vapor by evaporation at the sea surface is the dominant source of moisture to the atmosphere, and the phase change from liquid to solid in the formation of sea ice has a strong effect on the reflectivity of the Earth's surface. Ocean currents transport roughly equivalent energy from the tropics to polar latitudes as does the atmosphere, and the meridional transports of sea water and sea ice close the global water cycle. Ocean currents and turbulent mixing also transport nutrients from the deep ocean to the sunlit upper layers to support marine ecosystems. Through this capacity for storing and transporting energy, water, and radiatively and biologically active chemical species, the oceans act to moderate, modulate, and initiate climate variability and climate

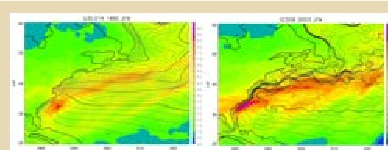

Figure 1. Winter season mean sea surface temperature (contours) and precipitation rate (colors) over the Northwest Atlantic in two CCSM coupled simulations. In the simulation depicted on the left, the 0.5° resolution CAM atmospheric model is coupled to the 1° resolution POP ocean model. In the simulation depicted on the right, the same 0.5° resolution CAM atmospheric model is coupled to the very high resolution 0.1° POP ocean model. As strong SST gradients in the Gulf

change. Instances of abrupt climate change observed in the paleo-climate record and in simulations of future climates with increasing greenhose gases arise from the interactions of sea ice, the hydrologic cycle and the ocean thermohaline circulation. A comprehensive understanding of, and the ability to predict, the behavior of the climate system must therefore be based on an understanding of the physical, chemical, and biological processes operating in the oceans and their interaction with other components of the Earth system.

Stream become realistically represented in the high resolution ocean model, the convergence of the low level atmospheric winds becomes stronger in a band parallel to the SST front, resulting in higher precipitation rates. This association of wind convergence and mesoscale SST gradients has only recently been observed in nature with the availability of high resolution scatterometer based wind products.

High resolution figure

Through research to develop an understanding of ocean processes, and using this understanding in improving their representation in ocean models, ESSL ocean scientists support a broad spectrum of ESSL scientific objectives. These include: prediction of the Earth's energy, water and biogeochemical cycles, and understanding natural and human influenced climate variability, including high impact variations such as sea level rise. In turn, the ESSL objective of understanding two-way scale interactions within the Earth system is central to improving our understanding of how thermodynamic processes, such as sea-ice formation and ocean circulation, features such as coastal upwelling zones, western boundary currents, and meso-scale eddies, are affected by and affect the basin- to global-scale ocean circulation and the large-scale climate system.

Significant increases in computational resources together with improved physics and greater confidence in CCSM climate models at both modest and high resolution have allowed ocean model developments to be evaluated in fully coupled models for their effects on the climate system as a whole. In a number of cases, these coupled model results have been much more profound and widespread than anticipated from consideration of effects on the ocean in isolation. The key factor is for the ocean model changes to produce small, but persistent, changes in near surface ocean temperatures or sea-ice coverage, then for the coupled model to react to these signals in such a way as to amplify the changes.

Recent Accomplishments

The ocean and sea ice model components used for the new Community Climate System Model, version 4 (CCSM4) simulations have been frozen and will be available to the community as part of the upcoming CCSM4 release. In comparison to previously released versions, the ocean model contains many physical and numerical developments, including increased vertical resolution, a near-surface eddy flux parameterization, an abyssal tidal mixing parameterization, a submesoscale mixing parameterization, an improved K-Profile Parameterization, and modified anisotropic horizontal viscosity coefficients with much lower magnitudes than in CCSM3. The new sea ice component contains improved radiative transfer and albedo schemes, a surface melt pond parameterization and the radiative effects and cycling of dust and black carbon aerosols. Much recent effort has been spent assessing the implications of these various improvements for climate processes and simulations.

Work continues on modeling ocean marine ecosystems and biogeochemistry. This has included efforts to more efficiently achieve equilibrated ocean biogeochemistry conditions using mathematical techniques based on Newton-Krylov non-linear equation solvers. Additionally, contributions have been made to analyzing the oceanic sources, sinks, and transport of atmospheric CO_2 and to assessing model simulations against field and remote sensing observations.

Ongoing efforts are investigating ocean processes and parameterization with the use of high-resolution ocean models. Two classes of idealized tracer simulations are providing direct measures of the relative roles of advection and turbulent mixing in the ocean. In the first, transit time distributions (TTDs) provide a probability distribution function for water parcel age. The broader the distribution, the more mixing the parcel has experienced. Comparisons of TTDs from eddy-resolving and non-eddy-resolving simulations show that current parameterizations used in CCSM can be either over diffusive or under diffusive, indicating the need for more directly flow-dependent formulations of the eddy stirring parameterizations. A second class of tracer simulations are providing direct estimates of the global distribution of the full 9 element eddy diffusivity tensor. By providing the full tensor rather than a scalar diffusivity, not only the eddy mixing parameters, but the underlying assumptions of the parameterization can be tested.

2009 and Beyond

Efforts will continue to more fully understand the interactions and collective impact of new model parameterizations on the coupled climate system. Comparisons with ocean tracers, both observed and as simulated by very high resolution models, will provide metrics for judging the impact of these parameterizations on ocean transport and ventilation. Studies of the marine system's role in potential climate predictability on seasonal to decadal timescales is underway. These include investigations on seasonal sea ice predictability and studies devoted to the driving mechanisms and potential predictability associated with the multi-decadal variability of the North Atlantic Meridional Overturning Circulation.

Diapycnal mixing occurs on scales of centimeters to meters and will remain unresolved, and require parameterization, in global ocean climate models for many generations to come. However, coupled climate simulations that do resolve ocean mesoscale variability, on scales of 10s to 100s of kilometers are now on the horizon. Early results from prototype integrations in this class, as illustrated in the accompanying figure, reveal intriguing new classes of ocean-atmosphere interaction. The emerging availability of high resolution remote sensing products for ocean winds, surface temperature, and surface currents will facilitate an assessment of the performance of CCSM in this resolution regime, and the application of CCSM to furthering our understanding of the processes and scale interactions connecting the ocean mesoscale to the global climate system.

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Solar Dynamo Modeling

The magnetic fields that are ultimately the source of the activity that takes place in the solar atmosphere have their origin inside the Sun, where convective, rotational, and other flows of highly electrically conducting plasma contribute to the operation of the dynamo. Work by HAO scientists has shown that the meridional circulation, a large-scale flow directed from the equator to the N and S poles at the solar surface and completing the circuit from the poles to the equator near the bottom of the convection zone, plays a fundamental role in in the dynamo process. It continuously transports poloidal magnetic fields from the surface to the tachocline at the base of the convective envelope where they are differentially stretched by the rotational shear therein to produce new toroidal magnetic fields. Buoyant magnetic flux tubes formed from these fields become the source for new poloidal fields at the surface, thus completing the dynamo cycle. During the last year, HAO scientists made significant progress in efforts to understand the physical processes contributing to dynamo action in the Sun and in solar-type stars.

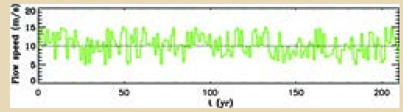

Figure 1a. Random change in meridional flow speed every year.

High resolution figure

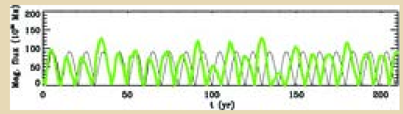

Figure 1b. The corresponding variations in cycle timing, amplitude, and shape.

High resolution figure

As part of their efforts to develop a "sequential data assimilation" technique for use in simulating solar cycles with a dynamo-based solar cycle prediction model, Mausumi Dikpati (HAO/NCAR), G. de Toma (HAO/NCAR), P. Gilman (HAO/NCAR), J. Anderson (IMAGE/NCAR), R. Ulrich (UCLA), and J. Boyden (UCLA) studied the response time of a flux-transport dynamo model to changes in meridional flow. They performed a series of dynamo simulations in which the meridional flow was changed for a range of intervals from every 2 months to every 5 years by a random amount. These simulations were run for the equivalent of about 25 sunspot cycles. The time history of meridional flow amplitude and the resulting cycle amplitudes for 1 year intervals are shown in Figure 1a and b. It can be seen that the amplitude and phase changes in the simulated cycles compared to the case with steady meridional flow can be quite significant. Dikpati et al. estimated the response time of the model to these changes in flow by correlating the flow variation input to the model with the cycle phase advancement rate in the simulation output. This correlation is shown in Figure 2, where it is seen that the correlation peaks around 8.4 months, and falls to almost zero around one year, as it should for flow speeds changing once per year. Therefore the time interval for adjustment of the meridional flow in the simulations of cycles 12-23 using sequential data assimilation should be longer than 8.4 months. It also needs to be much shorter than a sunspot cycle length to resolve the shape of a particular cycle in time. Time intervals of 1-2 years therefore appear to be best for the purpose of simulating shapes of particular cycles.

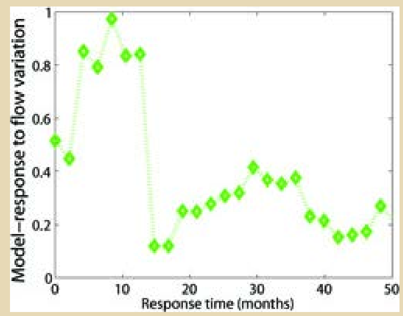

Figure 2: Correlation between flow variation and cycle response as a function of lag-time with respect to flow change.

High resolution figure

In the non-linear phase of a dynamo process, the back-reaction of the magnetic field upon the turbulent motion results in a decrease of the turbulence level and therefore in a suppression of both the magnetic field amplification (the alpha-quenching effect) and the turbulent magnetic diffusivity (the eta-quenching effect). While the former has been widely explored, the effects of eta-quenching in the magnetic field evolution have rarely been considered. Recently G. Guerrero (Univ. de Sao Paulo), M. Dikpati (HAO/NCAR) and E. de Gouveia Dal Pino (Univ. de Sao Paulo) (2009, ApJ, 701, 725) have investigated the role of the suppression of diffusivity in a flux-transport solar dynamo model that also includes a non-linear alpha-quenching term. The results indicate that, although for alpha-quenching the dependence of the magnetic field amplification with the quenching actor is nearly linear, the magnetic field response to eta-quenching is non-linear and spatially non-uniform. They found that the magnetic field can be locally amplified in this case, forming long-lived structures whose maximum amplitude can be up to ~2.5 times larger at the tachocline and up to ~2 times larger at the center of the convection zone than in models without quenching (see Figure 3). However, this amplification leads to unobservable effects and to a worse distribution of the magnetic field in the butterfly diagram. In this work, they also addressed the issue of whether the eta-quenching can cause a diffusion-dominated model to drift into an advection-dominated regime. It was found that models undergoing a large suppression of the turbulent magnetic diffusivity produce a strong segregation of magnetic fields that may lead to unsteady dynamo-oscillations, but an

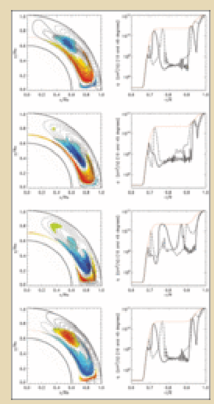

Figure 3: Left panel: Snapshots for four different times within a half-period of the relaxed model for a quenching magnetic field B_q = 10^3 Gauss. Right panel: Turbulent diffusivity without quenching (red dotted line), at latitude 10 degrees (continuous black line), and at 45 degrees (dashed blue line).

High resolution figure

initially diffusion-dominated model undergoing a small suppression in eta remains in the diffusion-dominated regime.

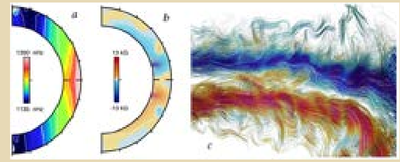

Figure 4: Rotational shear and toroidal magnetic fields in a global 3D dynamo simulation of a solar-type star rotating at three times the solar rate (from Brown et al. 2009). Panels (a) and (b) show the angular velocity and mean toroidal field averaged over longitude and time. Note the strong toroidal bands antisymmetric about the equator. Although these bands are highly organized, they are not enclosed by isolated flux surfaces. Rather, field lines thread throughout the convection zone as illustrated in the local volume visualization in panel (c). Red and blue lines denote positive and negative longitudinal magnetic flux and the view is radially outward from a vantage point under the convection zone and slightly north of the equator.

High resolution figure

As a follow-on of a keynote talk delivered at the CAWSES Symposium at Kyoto (2007), M. Dikpati was invited to write a review on the prospects for predictions of solar cycle features and long-term solar activity. The review was published by Japanese Terrapub, edited by T. Tsuda, R. Fujii, K. Shibata and M. A. Geller. This review focusses on how a predictive tool can be built from a flux-transport type dynamo model that operates with four major ingredients, the differential rotation (Omega effect), helical turbulence (alpha-effect), meridional circulation and turbulent diffusion. Demonstrating how meridional circulation and magnetic diffusivity together govern the memory of the Sun's past magnetic fields, certain average solar cycle properties, such as cycle-amplitude, north-south asymmetry and onset timing were predicted. Comparing the properties of the Oceanic conveyor-belt and that of the Sun's meridional circulation conveyor-belt, prospects for building more sophisticated data-assimilation scheme based on this class of solar dynamo models was demonstrated.

When the Sun was younger, it rotated faster. Observations of young solar-like stars reveal typical rotation rates an order of magnitude or more higher than the present Sun. Such young stars exhibit vigorous magnetic activity. In particular, rapid rotation promotes rotational shear and helicity, which in turn promotes the self-organization processes that are responsible for building stellar magnetic fields on large spatial scales. Similar self-organization processes also occur in the Sun, albeit in a relatively subdued manner. Together with colleagues at the University of Colorado, the Canadian Institute for Theoretical Physics (CITA) and CEA Saclay (France), Mark Miesch (HAO/NCAR) has been investigating the influence of rotation on solar and stellar dynamos using global-scale magnetohydrodynamic (MHD) simulations of turbulent convection. Rapid rotation promotes the generation of strong, organized bands of toroidal magnetic flux that, despite some theoretical expectations to the contrary, can persist amidst the turbulent convection zone for thousands of simulated days (see Figure 4). At more rapid rotation rates and lower magnetic dissipation, such dynamos can exhibit quasi-periodic polarity reversals and poleward-propagating torsional oscillations.

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Simulations and Observations of CMEs

Solar-driven space weather can have significantly adverse consequences for the Earth and near-Earth environment. Coronal mass ejections (CMEs) are the principal solar drivers of space weather. Through coronal observations and 3D magnetohydrodynamic simulations of the coronal magnetic field driven by the emergence of a twisted flux rope, HAO scientists have made significant advances in understanding the origin and dynamic evolution of CMEs and what makes a CME geoeffective.

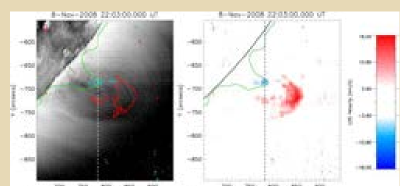

Figure 1. Observations of flows in a coronal prominence cavity. (a) Log intensity in Hinode/EIS Fe xii 19.5 nm. The green contour marks the edge of the prominence from SOHO/EIT 30.4 nm. The blue and red contours show �7 km/s line of sight (LOS) velocity. The vertical dashed line marks the raster step plotted in Figure 3. (b) LOS velocity in Fe XII 19.5 nm.

High resolution figure

The genesis of solar coronal mass ejections (CMEs) is both an intellectually intriguing, fundamental unsolved problem in plasma astrophysics, and a societally relevant subject critical to space weather prediction and mitigation. Dark coronal cavities surrounding cool, dense prominence material are observed within CMEs, but also as equilibrium states in the magnetically-dominated corona. Their plasma properties as observed in their quiescent phase provide clues to the nature of such equilibria and how they may ultimately be lost during CMEs. Sarah Gibson (HAO) is currently leading an International Space Science Institute (ISSI) International Team of 16 members to review existing prominence cavity research and to plan, obtain, and analyze new data to fill observational holes and motivate and constrain theoretical models. Graduate student Don Schmit of the University of Colorado, a member of this team and supervised by Gibson, has now published the first observational study of plasma flows in prominence cavities determined from EUV spectral diagnostics (see Figure 1). Gibson also worked with Graduate student J. Fuller of Cornell University on a study of 21 cavity systems observed in white light, which indicated that smaller cavities tend to have higher tops, relative to their widths, than larger ones. Indeed there seems to be an upper limit on cavity-top height, at

approximately 0.5 Rsun above the solar surface. This may be related to independently-established upper limits on prominence heights, and indicative of limits on the stability of pre- CME equilibrium states.

HAO researchers are also engaged in modeling the dynamic eruption of coronal streamers. Michiel Cottaar (visiting graduate student from Astronomical Institute Utrecht, the Netherlands) and Yuhong Fan (HAO) have examined the stability and dynamic evolution of a coronal helmet streamer containing an underlying twisted flux rope by performing global 2-D axisymmetric MHD simulations (Cottaar and Fan 2009, ApJ, 704, 576). By varying both the detached toroidal and poloidal fluxes in the underlying flux rope while fixing the normal flux distribution at the surface, they found that the transition from a stable to an eruptive state of the helmet takes place at a magnetic energy that is very close to the Aly open field energy. Furthermore, they found that the eruption does not occur at a single critical value of the total magnetic helicity, but depends on the profile of the underlying flux rope. Cases where the detached flux rope contains a higher amount of self helicity, i.e. higher internal twist or detached poloidal flux are found to become eruptive at a significantly lower total helcity. For the eruptive cases, the detached flux rope after emergence first rises quasi-statically due to a gradual opening of the field lines at the edge of the streamer and a slow reconnection below the flux rope, which continues to slowly increase the amount of the detached flux. This decreases the downward magnetic tension on the flux rope. The dynamic eruption is initiated when the magnetic pressure gradient no longer decreases fast enough to balance the decrease in the magnetic tension. Later rapid reconnections below the flux rope are important for accelerating the flux rope.

Yuhong Fan continues to carry out 3D MHD simulations of the evolution of the coronal magnetic field as a twisted magnetic flux rope emerges quasi-statically into a pre-existing coronal potential arcade field. By varying the amount of the twisted flux that is transported into the corona by the flux emergence, she has performed a sequence of simulations to study the conditions that lead to an eventual eruption of the flux rope as a CME. It is found that a critical condition for the onset of eruption is for the center of the flux rope to reach a critical height at which the external potential field strength P declines with height h at a sufficiently steep rate, with -dlnP/dlnh being higher than about 1.5, consistent with the onset of the torus instability of the anchored coronal flux rope. In several cases (see example in the attached movie), after the flux emergence is stopped, the flux rope first rises quasi-statically, with a sigmoid-shaped current sheet forming and with reconnections in the current sheet gradually adding twisted flux to the flux rope. The dynamic eruption of the flux rope takes place as the flux rope rises to the critical height given above. Further analysis of the simulations are being done to examine the evolution of the magnetic energy compared to the open field energy and the evolution of the magnetic helcity to examine how the eruptive conditions depend on these quantities.

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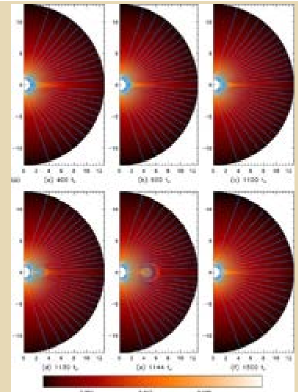

Figure 2: A simulation of the earlier quasistatic rise and the later loss of equilibrium of a coronal helmet streamer with its underlying flux rope being expelled in a CME-like eruption. The images show projected magnetic field lines in the meridional plane overlaid with density in log scale. One can see the 3-part density structure and the development of an intermediate MHD shock at the front during the eruption of the helmet.

High resolution figure

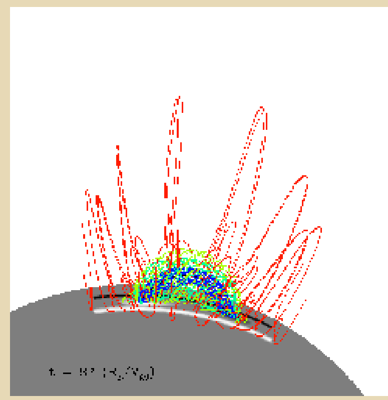

Figure 3: A 3D MHD simulation of the earlier quasi-static rise and the later dynamic eruption of a coronal flux rope confined by a potential arcade field. The eruption takes place as the center of the flux rope has risen to a critical height where the external potential magnetic field declines with height at a sufficiently rapid rate.

Play movie

Convection, Flux Tubes and Waves in the Solar Interior

The energy liberated through the nuclear burning of hydrogen in the core of the the Sun is transported outward by radiative diffusion for radii less than about 0.7 R_sun, and by convection within that portion of the interior located between 0.7 R_sun and the photosphere. Research on the structure and dynamics of this outer convective envelope, the nature of the interface between it and the underlying stably stratified radiative interior, and the hydrodynamical and magnetohydrodynamical (MHD) processes that take place within both the convective and radiative portions of the interior are essential to efforts to understand the Sun's magnetism and rotation. During

2009, HAO researchers made substantial progress in studies of the the nature and properties of the instabilities and waves that can exist in the the solar tachocline and radiative interior.

Global instabilities in the solar tachocline in 2D, quasi-3D shallow-water type models, and in 3D thin-shell models have been an active research area at HAO during the past decade. Extensive linear and some nonlinear studies of tachocline instabilities have been carried out using 2D and thin-shell 3D models. But the nonlinear evolution of shallow-water instabilities has not been studied yet. Given that employing a shallow-water system can help reduce the complexity of a full 3D MHD system without losing the basic physics behind the global dynamics of the fluid layer, Mausumi Dikpati has been studying the nonlinear evolution of this instability in the solar tachocline. The two-fold motivation of this study comes from the following:

1. A preliminary investigation by Dikpati and Gilman (2005, ApJ, 653, L193) in the linear regime has shown that the appearance of "active longitudes" at specified longitude locations on the Sun is most likely tied to the thickness profile of tachocline fluid layer containing toroidal magnetic fields. Therefore, the nonlinear evolution of such a fluid layer can simulate the time-evolution of active longitudes during an entire solar cycle or over several solar cycles.
2. Linear shallow-water models have shown that global, non-axisymmetric helical flow-fields can be generated in the solar tachocline, and hence can drive a dynamo without any mean-field approximations. Such a dynamo could be capable of explaining large-scale non-axisymmetry in the photosphere as well as coronal sector-boundary structure.

With these aims, Dikpati (2009, ApJ, in preparation) has been exploring the nonlinear evolution of shallow-water instabilities in the solar tachocline using a spectral transform method, in which the vector flow field and the scalar height field are respectively expanded in terms of vector and scalar harmonics in order to handle the pole problem. The results so far obtained for purely hydrodynamic calculations can be summarized as follows:

1. For high effective gravity of the system (G=10, where G is a measure of subadiabaticity of the system), a high-latitude prograde jet is formed (see frame (a) in Figure 1). For an initial perturbation of 50% of the reference state energy into the system, the jet amplitude stabilizes in a few months.
2. For low G (=0.5), along with high-latitude jet, a polar spin-up as well as some equatorial spin-up are seen to occur (see frame (b) of Figure 1).
3. While some tendency of jet formation was speculated from linear studies, a new feature of purely nonlinear origin is revealed in this study, namely the generation of gravity waves due to adjustment of geostrophic balance. The preliminary estimates show that the frequency of these gravity waves is high for high G. More detailed investigations are under progress.

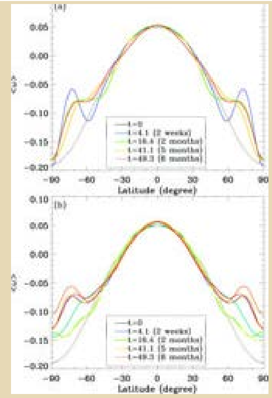

Figure 1. Evolution of the solar tachocline latitudinal differential rotation as a consequence of hydrodynamic shallow-water instabilities: (a) G=10; (b) G=0.5.

High resolution figure

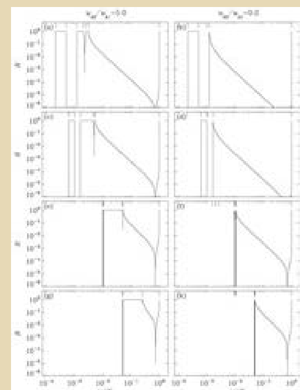

Figure 2: The reflection of MHD gravity waves in a medium with Alfven speed u_{A1} for z > 0 and u_{A2} for z < 0. The gravitational force acts in the negative z-direction. The left-hand (right-hand) panels pertain to wave propagation in a medium with u_{A2}/u_{A1}=5.0 (0.2). The reflection coefficient R, defined as the ratio of the vertical velocity amplitude of the reflected wave at z=0 to that of the wave incident there, is shown as a function of frequency for waves with lu_{A1}/N = 5 x 10^{-4} (panels [a] and [b]), 10^{-3} (panels [c] and [d]), 10^{-2} (panels [e] and [f]), and 5 x 10^{-2} (panels [g] and [h]), where l is the horizontal component of the wavevector and N is the buoyancy frequency.

High resolution figure

Internal gravity waves excited in the radiative interior by overshoot from the bottom of the convection zone can be influenced by rotation and by the strong toroidal magnetic field that is likely to be present in the solar tachocline. Using a simple Cartesian model, Tamara Rogers (Univ. of Arizona) and Keith MacGregor (HAO) have investigated 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. This interaction can prevent a portion of the downward traveling wave energy flux from reaching the deep solar interior. If a highly reflecting magnetized layer is located some distance below the convection zone base, a duct or wave guide can be set up, wherein vertical propagation is restricted by successive reflections at the upper and lower boundaries. The presence of both upward and downward traveling disturbances inside the duct leads to the existence of a set of horizontally propagating modes that have significantly enhanced amplitudes. The helical structure of these waves makes them capable of contributing to the production of an alpha effect in the layers just beneath the convection zone, and their propagation in a shear of sufficient strength could lead to instability, the result of wave growth due to over-reflection.

Rogers and MacGregor have also conducted more detailed numerical simulations of the interaction of internal gravity waves with a large-scale toroidal magnetic field inside the Sun. In these experiments, two inwardly propagating waves with opposite horizontal propagation directions (prograde and retrograde, respectively) were artificially driven at the base of the convection zone in a solar model. The computational domain (i.e., the solar radiative interior) contained a thin layer of toroidal magnetic field, located slightly below the convection zone. These calculations confirm results obtained from the simple model, namely that waves with frequencies comparable to the Alfven frequency in the layer are strongly reflected, a result with implications for the efficacy of waves as an angular momentum transport mechanism. Further detailed simulations are planned for the next year, in particular, to investigate the propagation and interaction of a spectrum of waves, generated by overshoot from the convection zone base.

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RT/MHD Modeling of the Solar Surface Layers

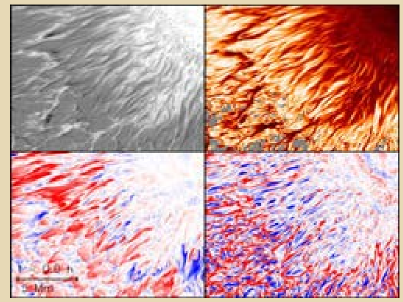

Figure 1. Numerical simulation of penumbral fine structure. The four panels present quantities in the photosphere showing the close relation between magnetic field and velocity structure in the transition from umbra toward penumbra. In each panel, the umbra is located in the top right corner. The quantities shown are: Top left: vertical magnetic field component (white: upward, black: downward); Top right: field inclination (dark red: vertical, bright yellow: horizontal); Bottom left: radial flow velocity (red: outflows, blue: inflows); Bottom right: vertical flow velocity (red: downflows, blue: upflows).

High resolution figure

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, because of lower temperatures, becomes partially ionized, requiring a more complicated equation of state. Also, the role of the magnetic field is changing: while the interior of the sun is dominated by the gas pressure, in or above the photosphere the magnetic pressure becomes the dominant contribution. Due to the rather short density scale height, the photosphere is a highly stratified medium in which convective motions easily steepen up to supersonic flows and shock waves. The combination of all these conditions make numerical modeling of the photosphere challenging, but also extremely interesting due to the strong interaction between convection, the magnetic field, and radiation, and the possibility for in depth comparison with high resolution observations.

Recent advances in supercomputing allowed scientists at HAO to perform the first comprehensive simulation of a pair of sunspots, in collaboration with researchers from the Max-Planck Institute for Solar system Research (MPS) in Germany. The MHD simulation with radiative transfer uses 1.8 billion grid points to be able to resolve sunspot fine structure at scales below 100 km, while the large scale extent of the sunspot pair is 100,000 km. For the first time, radiative MHD simulations present a unified magneto-convective model of sunspots including all aspects of sunspot fine structure, from umbral dots to penumbral filaments as well as large scale flows (the Evershed effect) in the outer penumbra. Numerical simulations of sunspots in large domains are also exploited to advance helioseismic inversion methods. Numerical models based on fully compressible MHD enable researchers to study the interaction of magneto-acoustic waves that are excited by convection with sunspots. Forward modeling of observable wave signatures in the photosphere of the Sun contributes to the testing and improvement of helioseismic inversion methods. This analysis is very timely due to the NASA SDO mission scheduled for launch in 2010 and is currently being carried out in collaboration with scientists from CoRA/MWRA. In collaboration with the Lockheed Martin Solar and Astrophysics Laboratory (LMSAL), the numerical sunspot model was also used to perform flux emergence simulations with radiative transfer on the scale of a small active region. For the first time it was possible to address processes responsible for the re-amplification of magnetic field in the near surface layers that ultimately lead to the formation of coherent sunspots.

In the near future, research will focus on simulations in larger computational domains at moderate resolution in order to address the long-term evolution as well as subsurface structure of sunspots. In addition, these simulations are also most useful for helioseismic forward modeling. We will continue working on flux emergence simulations in increasing domain sizes, with the ultimate goal of approaching the typical scale of active regions on the Sun. In parallel, we continue working in collaboration with the MPS and Kiepenheuer Institute for Solar Physics in Freiburg, Germany, on a more detailed analysis and comparison of sunspot simulations with high resolution observations. In addition to a more detailed characterization of the magneto-convective structure of the sunspot penumbra, we will also synthesize spectral line signatures for comparison with observations.

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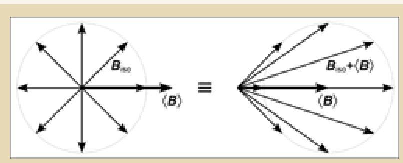
Fundamental physics of radiative processes



Almost everything we know about the Sun comes from our interpretation of its radiative output. The study of the intensity and polarization of the radiation that we receive from solar regions allows us to infer the thermodynamical and magnetic properties of the emitting plasma, if we are able to formulate adequate models of the origin and transport of polarized radiation in the solar atmosphere. In the deeper and denser layers of the

visible atmosphere (the photosphere), plasma collisions typically ensure that, at each point in the plasma, the ratio of radiation emissivity to absorptivity (the source function) is only determined by the local thermal properties of the plasma (local thermodynamic equilibrium, or LTE). Under these special conditions, the mechanisms for the production and transport of polarized radiation are very well understood, and reliable models have been available for at least half a century.

As we move outward in the solar atmosphere (the chromosphere and corona), the plasma density rapidly decreases, while at the same time, the radiation becomes increasingly anisotropic. Both conditions determine significant departures from LTE, as the atomic equilibrium is now driven mainly by optical pumping by the underlying photospheric radiation. These are also the regions of the solar atmosphere where the topology of the magnetic fields that permeate the heliosphere - finally interacting with the Earth's magnetosphere - takes shape. So the development of adequate models of polarized radiative transfer in these regions, in order to determine the correct magnetic boundary conditions of the heliosphere, is of primary importance for our understanding of solar drivers of Space Weather.

As part of the past year's work, HAO researchers engaged in a series of numerical simulations of spectro-polarimetric signatures from spectral lines formed in scattering media, and in the presence of magnetic fields with an unresolved, complex topology that can be described as a quasi-chaotic distribution of magnetic fields of various strengths and non-zero spatial average. As a simplyfing modeling assumption, the specific case of a deterministic field (matching the observed average magnetic field strength) superimposed with a completely isotropic distribution of a given strength was considered (see Figure 1). This study was motivated by recent spectro-polarimetric observations of an active region filament in the He I line at 1083 nm, which showed a significant suppression of the scattering-induced polarization component of the signals, with respect to the predictions of current models of line formation in filaments. The idea of the action of a quasi-chaotic distribution of magnetic fields was suggested by the many examples of the intricate and fast-evolving filamentary structure of prominence plasmas seen in the high-resolution images and movies of solar prominences taken by the Solar Optical Telescope (SOT) on board the Hinode spacecraft. The adopted model of quasi-chaotic magnetic field was successful in reproducing the observations of that active region filament (see Figure 2), suggesting that the anomalous depolarization of the observed signals could indeed be caused by the action of a turbulent and unresolved magnetic field in the filament's plasma.

Figure 1: Schematic model for a quasi-chaotic distribution of magnetic fields with non-zero spatial average. This is obtained by superimposing a perfectly isotropic distribution of magnetic fields, of a given strength B_iso, with a deterministic magnetic field with strength determined by the inversion of spectro-polarimetric observations.

High resolution figure

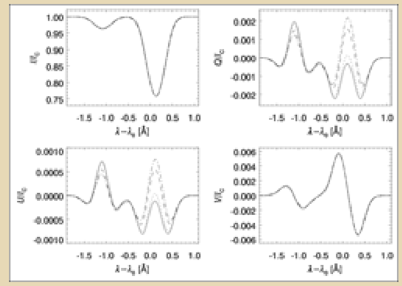


Figure 2: Examples of Stokes profiles of the He I line at 1083 nm observed on the disk, formed in a scattering medium in the presence of a nearly horizontal magnetic field of 700 G, plus a completely isotropic field of various strengths: 0 G (continuous curve), 200 G (dotted curve), 500 G (dashed curve), 1000 G (dashed-dotted curve). The polarization signals obtained for isotropic field strengths above 500 G are consistent with those recently observed in an active region filament.

High resolution figure

For next year, understanding of scattering polarization will be further advances by resuming a long-term effort towards the derivation of a higher-order master equation for the description of atom + radiation evolution. The goal is to arrive at a self-consistent treatment of partial redistribution of photon frequency in the polarized scattering of radiation from complex atoms. This work is carried out in collaboration with colleagues at the University of Florence, Italy, and at the Instituto de Astrofisica de Canarias, Spain. In particular, the partial results on generalized redistribution functions that have been obtained during the course of this work will be applied to some spectral lines relevant for magnetic field diagnostics of the solar chromosphere (such as, the Ca II H and K lines, the Mg I b1 and b2 lines, and the Na I D1 and D2 lines).

HAO researchers will also continue their efforts on the implementation of the HANLE codes for the modeling and inversion of scattering polarization in the chromosphere and corona within the framework of the Community Spectro-polarimetric Analysis Center. This effort is particularly relevant at this time, after the recent deployment of HAO's Prominence Magnetometer, which will soon initiate quarterly campaigns of observations of solar prominences in the two He I chromospheric lines at 587.6 and 1083.0 nm. The HANLE codes are instrumental for the modeling and interpretation of this type of observation.

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MHD Physics of the Solar Corona

The solar corona, heated by various mechanisms to million-degree temperatures, is fully ionized. Embedded with a magnetic field of about 10 Gauss at the coronal base, this atmosphere is an excellent conductor of both heat and electric current. Outward thermal conduction of heat, aided by MHD and plasma waves, drives the outer corona to expand continuously into the solar wind, filling interplanetary space. High electrical conductivity enables the magnetic fields to store significant amounts of energy which is released through the resistive dissipation of thin sheets of electric current.

This MHD process heats the corona ubiquitously and produces the impulsive flares, but we still have much to learn about its basic physical nature. The corona is not static, of course (de Toma et al. 2008). Its magnetic field changes in time, reversing its global polarity once every 11 years in concert with the dynamo in the solar interior. Thus, the dynamo rejuvenates the corona in each cycle, producing flares and sending daily coronal mass ejections into the more slowly varying solar wind. This is the dynamical origin of space weather. The NCAR program described below investigates the basic MHD of the corona as an essential component of the national space-weather research.

Under coronal conditions of extremely high electrical conductivity, magnetic fields evolve with no change in their field topologies except when the ordinarily weak effect of electrical resistivity is enormously amplified via the spontaneous formation of current sheets in topologically complex fields, as described by the theory of Parker (1994); see also Casini, Manso Sainz & Low (2009). Plasma parcels embedding distinct magnetic flux systems cannot mix freely during evolution, and current sheets would develop as tangential field discontinuities at the boundaries between the flux systems. This nonlinear physical process is three-dimensional (3D) in nature and is formidable to treat, but new insights have been obtained by investigating the topologically untwisted magnetic fields defined by Low (2006a, b). Ase Marit Janse (ASP, Oslo University) & B. C. Low (HAO) presented three classes of explicit demonstrations of current-sheet formation in these mathematically simpler magnetic fields (Janse & Low 2009a, b, Low & Janse 2009). The general result obtained is that a coronal tube of magnetic flux anchored to the heavy coronal base may form current sheets extensively within the tube as it changes its shape and volume in quasi-static evolution with its surrounding magnetic field and atmosphere. These current sheets become so intense that they dissipate resistively resulting in magnetic reconnection. Thus, the coronal fields are able to change their topologies with ease in spite of, or, alternatively, because of the high electrical conductivity. Heating, both in the quiescent and explosive forms, is thus a natural consequence of field evolution. The above works explain, in particular, the macroscopic sizes of hard X-ray footprints commonly observed in solar flares, in terms of the dense formation of current sheets suggested by the demonstrations. These works have raised new questions on field topology and MHD ideas at the fundamental level that are being investigated by Janse, Low and Eugene Parker (University of Chicago).

The formation of current sheets is also investigated by numerical time-dependent MHD simulations in 3D, guided by the basic physics emerging from the theory development (Janse, Low & Parker 2009). A standard computational approach cannot treat current sheets developing as singularities in a 3D magnetic field at the precision required by the theory. An ongoing simulation project led by Piotr Smolarkiewicz (MMM/IMAGe) and Low is based on describing magnetic field evolution directly in terms of its flux surfaces as potential sites for magnetic singularities, based on the theory in Low (2006a). Joined by Ramit Bhattacharyya (ASP), a proof of concept investigation based on this novel approach has been completed, directly demonstrating such singularities by the graphical displays of the breakup of the computed flux surfaces (Bhattacharyya, Low & Smolarkiewicz 2009). This precision approach, implemented with the multi-dimensional positive-definite advection transport algorithm (MPDATA) of Smolarkiewicz (2000), has opened the door for investigating current-sheet formation, a basic process that eventually needs to be incorporated into the MHD simulation models in solar and space-weather research.

Natasha Flyer (IMAGe), Bengt Fornberg (University of Colorado), Ken Miller (Wichita State University) and Low continue with their investigation of turbulently-relaxed force-free magnetic fields as long-lived coronal structures (Miller et al. 2009). Their 2D numerical solver for constructing the magnetic flux surface as a free-boundary separating such a force-free field from its surrounding potential field is being extended to 3D. This mathematically non-trivial development is one of the steps to realistic 3D modeling of observed coronal structures.

Flyer, Mei Zhang (National Astronomical Observatory, Beijing and NCAR Affiliate Scientist) and Low continue with their theoretical study of magnetic helicity accumulation in an open hydromagnetic atmosphere (Zhang & Flyer 2008). The approximate conservation of magnetic helicity under conditions of high electrical conductivity distinguishes flares from coronal mass ejections as the two principal eruptive means of releasing stored magnetic energy. The former are releases of energy by current sheets and magnetic reconnection, a resistively dissipative process that nevertheless conserves helicity. The part of the stored magnetic energy trapped by helicity conservation, against dissipative release during a flare, is released ideally in a coronal mass ejection.

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Structure and evolution of clear and cloudy atmospheric boundary layers

Work has continued on analysis of the chemical behavior of dimethyl sulfide (DMS) and SO2, as well as scalar variance budgets in the marine boundary layer (MBL) using data from the Pacific Atmospheric Sulfur Experiment (PASE) using the NCAR C-130 aircraft in the tropical marine boundary layer in collaboration with scientists at the University of California, Davis. This effort has resulted in a submitted paper on the DMS budget in PASE. Figure 1 shows vertical profiles illustrating the thermodynamic structure and typical DMS variation with height in the boundary layer and the overlying buffer layer (BuL) from one of the PASE flights. Another paper is nearing completion on the SO2 budget in PASE, which we plan to finish during the upcoming year.

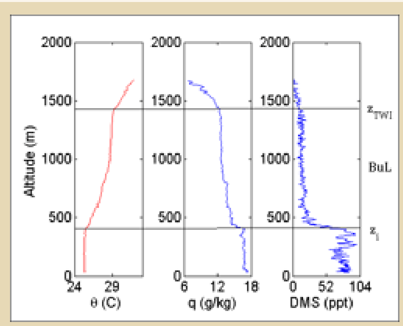

Figure: Boundary-layer structure observed During PASE. z_i is the mean height of the

This past year, a study of vertical velocity w spectra in the convective planetary boundary (CBL) using Doppler lidar data collected during the

Lidars in Flat Terrain (LIFT) experiment over flat farmland in central Illinois during summer 1996 was completed and published. This is a continuation of previous analyses that dealt with the 2-point turbulence statistics of w. The NOAA High Resolution Doppler Lidar (HRDL) was pointed straight up for over 100 hrs, providing 11 different cases of a midday convective boundary layer. This takes advantage of the lidar's capability to obtain range-resolved radial measurements, from which a two-dimensional field of w can be obtained by assuming that the field of turbulence is "frozen" as it advects past the lidar. Measurements of w were obtained from a height of z 390 m above the surface to near the CBL top with an unprecedented vertical resolution of 30 m. Considerable day-to-day variability was found in the spectral shape, as shown in the figure, and previous models of the w spectra were not particularly good at describing the observations. Some of this variability was found to be linked to mean CBL structure, including wind speed, shear across the CBL top, and processes at, and just above the capping inversion. Work has continued over the past year on analysis and interpretation of profiles of higher-order moments of w, from LIFT, including variance, skewness and kurtosis, which are being compared with large-eddy simulation (LES) results. Such comparisons provide a test of the ability of LES to accurately simulate CBL structure. We plan to finish this work during the upcoming year.

weak MBL inversion and z_{TWI} denotes the stronger trade wind inversion aloft. Horizontal axes are potential temperature, water vapor, and DMS respectively

High resolution figure

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Atmosphere / ocean interactions

Air-sea interaction occurs over a wide spectrum of scales ranging from millimeters (spray droplets and air bubbles) to hundreds of kilometers (synoptic scale storms) and even larger (global climate). A goal of marine surface layer research is to identify and quantify coupling mechanisms that connect the atmospheric and oceanic boundary layers (the ABL and OBL) and surface waves. Some of the specific problems of interest in the ABL include the effects of wave age, swell, surface roughness, and wind-wave misalignment. In the OBL, waves induce Langmuir circulations and break which generate mean currents and turbulence. Wave influences on the OBL are of particular importance under high wind conditions. Turbulence resolving simulations and in particular large-eddy simulation (LES) and its ability to perform systematic process studies plays an important role in air-sea interaction research. LES has provided new insights into the couplings between imposed waves and turbulence.

In the past year our air-sea interaction research was directed towards developing LES models of the marine atmospheric and oceanic boundary layers applicable to high wind regimes. Our LES model of the high wind OBL is driven by time varying winds, surface scalar fluxes, and wave fields characteristic of Hurricane Frances. Frances, a large category 4 hurricane, was one of the most heavily studied storms in the Coupled Boundary Layer Air-Sea Transfer (CBLAST) program. Our process studies examine the impact of resonant and anti-resonant winds and wave-current interactions on cooling of the OBL. The amounts of cooling produced by different combinations of these processes are illustrated in Figure (BB). For the high wind atmospheric boundary layer, we adapted our massively parallel LES code to accommodate a general 3D time varying lower surface. The code is capable of simulating boundary-layer turbulence in and around hilly topography and above moving ocean waves. These boundary-layer codes are being used to help interpret two future Office of Naval Research field campaigns: the High-Resolution Air-Sea Interaction experiment which will be carried out off the California coast in Spring 2010 and the Impact of Typhoons on the Western Pacific Ocean study to be carried out in Fall 2010. Future plans include extensive validation of these models and comparison with field and laboratory observations.

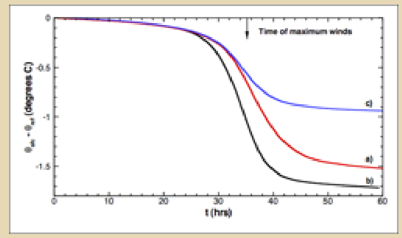

Figure: Variation of sea surface temperature for three different LES of a high wind (hurricane) OBL driven by time varying winds and cooling similar to Hurricane Frances. a) resonant side of storm track and no wave effects; b) resonant side of storm track with simple model of the wave Stokes drift; and c) non-resonant side of storm track and no wave effects. The additional cooling in b) is a consequence of enhanced entrainment induced by Langmuir circulations.

High resolution figure

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Numerical simulation of turbulence

Large-Eddy Simulation (LES) has been widely used to examine turbulence in the PBL, however most LES applications have been limited to PBLs over idealized terrain and meteorological conditions. To extend the LES applications to real-world PBLs, we simulated two complex PBL regimes: (1) PBL under a deep convection system and (2) PBL over a ridge-valley surface.

(1) PBL under a deep convection:

As part of the research funded by the NSF Center for Multiscale Modeling for Atmospheric Processes (CMMAP), we performed a large-domain LES of a tropical deep convection system over a domain of about 205 km x 205 km x 27 km with a grid mesh of 100 m x 100 m in the horizontal and 50-150 m in

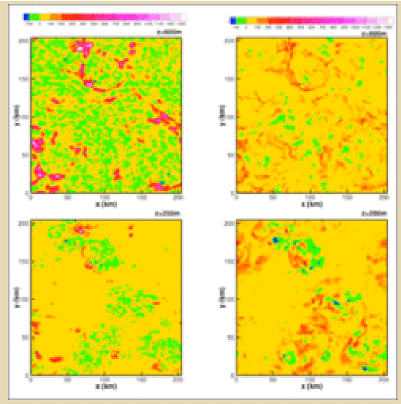

Figure: Horizontal distributions of the LES-retrieved SFS fluxes with a filter width of 4 km (left panels) and the K-modeled fluxes (right panels) of water vapor at (a) z = 600 m (top) and (b) z = 200 m (bottom).

High resolution figure

the vertical. This simulation thus resolves not only a deep convection system, but also energy-containing individual clouds and turbulent eddies, and can be used as benchmark to study the scale interaction between cloud-system and small convection (including turbulence) scales. We applied a Gaussian filter with various filter scales to separate the LES flow into the filter-scale (FS, cloud-system scales) and the subfilter-scale (SFS, small convection and turbulence scales) and also to retrieve the SFS fluxes. These FS and SFS fields can be referred to as the resolvable and subgrid-scale (SGS) fields, respectively, in typical CRMs. We used this information to test a simple SGS K-model commonly used in CRMs. The figure compares the spatial distributions of the retrieved SFS fluxes and the K-model predicted SGS fluxes. The differences between the right and left panels of Fig. 1 reveal the deficiencies of the K model. In the near future, we will analyze the flow fields to find variables that are responsible for the deficiencies and then to improve the existing K model.

(2) PBL over a ridge-valley surface:

Collaborating with Sapienza University (Rome, Italy), we investigated the thermally driven circulation and turbulence over a ridge-valley surface by performing a WRF-LES.The model was designed with a symmetrical geometry, i.e., a periodic ridge-slope-valley surface in x and uniform in y. The anabatic turbulent flow was generated by imposing a time varying surface temperature and geostrophic wind along the valley. The presence of the orography introduced numerous complexities both in the mean and turbulence features, which differ significantly from the idealized PBL. We highlighted the different structure of the PBL at various regions of the domain by presenting the first- and second-moment statistics and the TKE budgets.

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Convection organization: Observational analysis and resolved simulations

The propensity for deep, moist convection to organize and project onto larger spatial and temporal scales requires numerical simulations spanning convection-resolving scales to continental scales. Furthermore, simulation studies must be closely constrained by observational analysis of the organizing properties of convection. Prediction of convection, and the response of the synoptic-scale and planetary-scale flow is vital for increasing our ability to anticipate significant weather events and for proper statistical representation of convection is also vital for credible climate simulations.

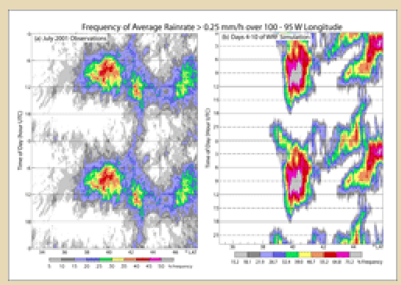

Figure: Time versus latitude plots of the frequency of rainfall averaged longitudinally from 100-95W exceeding 0.25 mm for (a) July 2001; and (b) 10-day ARW simulation forced on the lateral boundaries by only the mean diurnal variation for July 2001.

High resolution figure

Last year, ESSL scientists participated in the Second Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX2). Thermodynamic soundings were collected every 15-30 minutes as a squall line passed over a mobile rawinsonde site. Preliminary analysis shows that the cold pool was 3.6 km deep only 16 km behind the surface gust front, revealing that cold pools in organized continental convection may be much deeper and stronger than suggested by previous studies. Real-time WRF forecasts of convection were also conducted in support of the VORTEX2 program. The highlight was an accurate simulation of a derecho that produced widespread damaging winds over a long swath in the central U.S. WRF predicted the formation of a warm-core mesoscale convective vortex (MCV) with hurricane-force winds. Analysis of data from the Terrain-induced Mesoscale Rainfall Experiment (TiMREX) suggested in strong west-southwest flow or in weak flow, rainfall was more likely over the mountains, whereas with more southerly flow a coastal front developed yielding flooding coastal rains.

Analysis of WRF ARW simulations of propagating convection over North Africa continued, from which it appeared that long streaks tended to suppress convection on subsequent days by limiting convective susceptibility to the west of the Ethiopian Highlands. In a separate study, a 10-day WRF simulation employing only monthly mean diurnal forcing on the lateral boundaries realistically simulated the observed monthly mean diurnal and latitudinal variation of rainfall over the

continental United States (see figure). These simulations were then used to diagnose the combined, three-dimensional effects of the mountain-plains solenoid and the nocturnal low-level jet on the diurnal cycle of warm-season convective precipitation. Shorter-term (0-48 h) Simulations of cases from the Bow Echo and MCV Experiment (BAMEX) showed that deep, long-lived MCVs formed by a superposition of a vortex at the north end of the convective line and a mid-tropospheric vortex. Strengthening of the low-level circulation occurred after maturation of the parent mesoscale convective system, as the troposphere was moistened, downdrafts suppressed and the convergent flow in the boundary layer was evident.

Work in the coming year will focus on further analysis of VORTEX2 and TiMREX data, as well as using WRF simulations to understand the transition from surface-based convection to convection rooted in air above the boundary layer, mainly nocturnal convection.

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Hurricane research

The prediction of hurricanes (at many time ranges) requires a basic understanding of the interaction of convection and rotational circulations in a marine environment. Processes such as turbulence, air-sea interaction, cloud physics and dynamics (especially rapid intensity change and genesis) are central to hurricane research. Modeling and observations are being conducted in MMM in each of these areas.

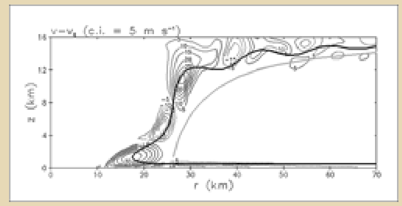

Figure: Shown is a comparison of an actual airflow trajectory in a simulated hurricane (black) with the trajectory assumed in the potential intensity theory (grey). The center of the hurricane is at r=0. Contours show the difference between actual flow and balanced flow, and demonstrated that flow can oscillate between super-gradient and sub-gradient.

High resolution figure

A study was undertaken to determine why simulated hurricanes are sometimes stronger that a theoretical upper limit. The theory, referred to as potential intensity (PI), is based on several assumptions, most of which were determined to be accurate. However, one assumption in the PI theory -- the assumption of dynamically balanced flow -- is violated in the eyewalls of hurricanes (Fig. X). By extending PI theory to include this effect, the new study showed that 50% of the intensity of strong hurricanes could be attributed to unbalanced flow effects.

Analysis of a high resolution (LES) simulation of an idealized hurricane has shown that small-scale turbulence in the eye and eyewall primarily acts to weaken hurricanes. The transition to turbulence seems to occur for grid spacing around 100 m. Recent work has quantified the effect of eddies to reduce the intensity of the symmetric vortex. Results from LES modeling can be used to determine turbulence settings for lower-resolution simulations and for axisymmetric models.

An idealized-simulation study of subtropical cyclones was performed using WRF. Subtropical cyclones have elements of both tropical and extratropical cyclones. The study defined subtropical cyclones dynamically as those with a dominant contribution from condensation heating, but still an important role for baroclinic waves to organize convection. Such waves were found to grow on an unstable subtropical jet.

In FY10, MMM scientists will participate in the PRE-Depression Investigation of Cloud Systems in the Tropics (PREDICT), which will utilize the NCAR G-V based in St. Croix, U.S. Virgin Islands to study tropical and subtropical waves in attempt to observe key factors distinguishing waves that develop into tropical cyclones from those that do not. The project is collaboration with scientists from NOAA (through their Intensity Forecast Experiment, IFEX) and NASA (through their Genesis and Rapid Intensification Processes, GRIP project). PREDICT will take place August 15-September 30 and involves investigators at 8 universities.

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Land atmosphere/coupling

Much of our knowledge of land-atmosphere coupling stems from research that has largely held one or the other constant; i.e. atmospheric response to fixed surface forcing, or surface/vegetation response to fixed atmospheric demand. During the last year, we have focused on developing further capability to investigate fully coupled land-atmosphere interactions. On the atmospheric side, turbulence is at the heart of this coupling as it responds to and evolves with the land surface occur through complex processes. On the land-surface side, soils and vegetation control the exchange of trace gases as they respond to atmospheric demand.

To address the complex interactions between vegetation, soils, and the turbulent atmosphere, the single ‘big-leaf’ vegetation representation in the NOAH land surface model has been extended vertically so that canopy-induced sources/sinks of trace gases is now a function of the spatial variation

of radiation availability/absorption, atmospheric temperature, moisture, and wind speed. Data from the Canopy Horizontal Array Turbulence Study (CHATS) served as the basis for initial testing the model (See Graphic 1). This land-surface model is designed so that it is relatively simple. It only requires ten parameters describing the canopy's characteristics (e.g., height, density, type, leaf width/length, scattering/absorption coefficients). When coupled to NCAR's large-eddy simulation (LES) code, it is also designed to be driven by and to force rapidly fluctuating atmospheric turbulence. This new land-surface model therefore permits investigations of the coupled response between plant physiology, radiation absorption, soil properties and availability, and atmospheric turbulence at scales ranging from the leaf level (centimeter to meter scale for a leaf or clumps of leaves) to the planetary boundary layer (kilometer scale).

Figure: The time evolution of shaded and sunlit leaf-temperature profiles (left panel, green and blue lines, respectively) predicted by the multi-layer canopy version of the NOAH land surface model as driven by atmospheric conditions measured during Days 140-141 of the Canopy Horizontal Array Turbulence Study that took place during the Spring of 2007 in Dixon, California. In the left panel, the red line depicts observed 5-minute averaged air temperature and in the right-panel the blue line depicts observed 5-minute mean wind speeds from CHATS. The incoming solar radiation (red line, right panel) at the top of the canopy (z/h=1) was also measured during CHATS, but the model predicts the within-canopy profile.

High resolution animation

The near-term scientific objectives are to use this model to provide a time-dependent, spatially varying canopy-induced and land-surface induced source/sink distributions for canopy-chemistry-turbulence studies to evaluate current methods used to estimate biogenic sources from ecosystem-scale fluxes. Future investigations will also examine flow separation induced by vegetation in the lee of low orography and the impact that trace-gas accumulations in the separated region have on canopy-induced sources/sinks and on ecosystem averaged trace-gas fluxes. Since NOAH is the primary land-surface model in NCAR's Weather Research and Forecast model (WRF), we are also actively working to incorporate an appropriate parameterization for the unresolved atmospheric roughness sublayer turbulence to permit full multi-layer canopy coupling in weather and regional climate studies.

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Instrument and experimental meteorology

During FY2009, MMM continued to work on the analysis of data from the MMM-led field program the Ice in Clouds Experiment-Layer Clouds. In an article that appeared in Nature Geosciences and led by Kerri Pratt, a graduate student at UCSD, we used aircraft- aerosol time-of-flight spectrometry during ICE-L to directly measure the chemistry of individual cloud ice-crystal residues (obtained after evaporation of the ice), which were sampled at high altitude. The field program found that biological particles and mineral dust comprised most of the ice-crystal residues: mineral dust accounted for about 50% of the residues and biological particles for about 33%. Along with concurrent measurements of cloud ice-crystal and ice-nuclei concentrations, these observations suggested that certain biological particles initiated ice formation in the sampled clouds.

Figure: Top: Image of hole punch and canal clouds captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite at 19:05 GMT on 29 January 2007 (Image courtesy of NASA Earth Observatory and specifically Jeff Schmaltz). State boundaries are shown. Bottom: Pictures taken from near New Orleans at 21:10 to 21:17 GMT on 29 January 2007, looking NW towards Shreveport, LA. Photos courtesy of Jafvis. This figure is presented in the article by Heymsfield et al., Bulletin of the American Meteorological Society, in press.

High resolution image

In an entirely fortuitous situation during ICE-T, the primary sampling aircraft, the NCAR C130 flew through snow from a "hole punch" cloud that was created by two commercial turboprop aircraft that had departed along a standard flight departure route from Denver International Airport and ascended into a supercooled altocumulus cloud. In an article in press in the Bulletin of the American Meteorological Society and led by (Heymsfield et al. 2009), this cloud feature was documented from in-situ measurements for the first time. An unprecedented data set combining the C130 measurements from microphysical probes with remote sensing measurements from cloud radar and lidar, as well as ground-based NOAA and CSU radars, is used to describe the radar/lidar properties of a hole punch cloud and channel and the ensuing ice microphysical properties and structure of the ice column that subsequently developed. Ice particle production by commercial turboprop aircraft climbing through clouds much warmer than the regions where contrails are produced is suggested as a inadvertent cloud seeding under some conditions. Most surprisingly, these authors found that jet aircraft can produce hole punch clouds when flying through altocumulus with supercooled droplets at heights lower than their normal cruise altitudes where contrails can form (See Figure). They suggested that commercial aircraft can generate ice and affect the clouds at temperatures as much as 30°C warmer than the –40°C contrail formation threshold temperature. Analysis of the ICE-L data is continuing.

In FY10, the PMG Group will be leading an effort to study ice nucleation processes active in tropical maritime clouds. Drawing upon the results of the successful Ice in Clouds-Layer (ICE-L) Clouds field campaign, they will be

planning the next phase of a study of ice processes acting in clouds called the Ice in Clouds Experiment (ICE) tropical (T) which will address the following objectives:

1. Attempt to reproduce the observed glaciation of maritime cumulus with top temperatures warmer than -10C.

2. Determine if primary ice nucleation can explain the onset and glaciations of maritime cumuli.

3. Determine whether secondary ice formation processes are critical to the glaciation of cumulus. If so what concentration of primary IN are sufficient to trigger them and how does the process work?

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Director's Message

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Imperatives

Research Catalog

ESSL LAR 2009: IMPERATIVE II

Provide capabilities for more accurate prediction and attribution of changes in climate, severe weather, air quality, and solar output, and the impacts of such changes on ecosystems and human well-being

A. Produce experimental high-resolution climate forecasts for the next few decades, with companion measures of uncertainty, and work with collaborators to use these for investigating regional-scale climate impacts

1. Climate and tropical cyclones - MMM
2. Decadal prediction, predictability and modes of variability - CGD
3. Predication Across Scales - MMM/CGD

B. Conduct research and develop models to improve the accuracy and utility of forecasts of high-impact weather, focused on hurricane landfall and intensity, severe thunderstorms, and other extreme events

1. Landfall impacts of hurricanes - MMM
2. U.S. Weather Research Program/Short Term Explicity Prediction Program (USWRP/STEP) - MMM

C. Use models and observations to more accurately identify the natural and anthropogenic processes driving atmospheric changes as well as related societal and environmental vulnerabilities, impacts, and feedbacks

1. Bioemissions and photochemical processing - ACD
2. Emission inventories and application - ACD
3. Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) contributions - ACD
4. Polar Climate - CGD
5. Climate change - probabilistic climate change, and solar forcing of climate - CGD
6. Long-term climate change in the thermosphere - HAO

D. Develop new techniques for predicting changes in air quality and their impacts on ecosystems and human health

1. Globalization of air quality and intercontinental transport - ACD
2. Model for Ozone And Related chemical Tracers (MOZART): Global chemistry-transport modeling - ACD
3. UTLS dynamics, trends, and composition - ACD
4. Stratospheric ozone recovery - ACD
5. Tropospheric Ultraviolet and Visible (TUV) - Radiation Model - ACD
6. Master mechanism - ACD

E. Analyze and predict the Sun's variable magnetic, radiative, and particulate outputs and their impacts on the terrestrial environment

1. Solar cycle prediction - HAO

F. Collect critical measurements needed to improve our understanding of physical processes and test and improve models and their predictions of the atmosphere and the Sun

1. Megacities Impacts on Regional And Global Environments/Megacity Initiative: Local and Global Research Observatories (MIRAGE/MILAGRO) - ACD
2. OASIS - ACD
3. Texas air quality study - ACD
4. High Resolution Dynamics Limb Sounder (HIRDLS) recovery and application - ACD
5. The Flow of Energy through the Climate System - CGD

6. Spectro-polarimetric studies of magnetic fields - HAO
7. Analysis of data from Hinode and STEREO - HAO
8. Sunrise balloon mission - HAO
9. Development of instrumentation for SDO - HAO
10. Analysis of data from TIMED and COSMIC - HAO
11. Severe atmosphere convection - MMM

G. Develop a comprehensive model of interactive processes throughout the Earth's atmosphere-ionosphere-magnetosphere systems, analyze how these are affected by solar variability, and begin prediction of space weather

1. Chemistry and dynamics of the middle and upper atmosphere - ACD
2. Upper atmosphere community models - HAO
3. Space weather: model development and data analysis - HAO

Climate and tropical cyclones

The Year of Tropical Convection (YOTC) project, which is coordinated with the World Climate Research Programme (WCRP) and the World Weather Research Programme's THORPEX seamless prediction initiative, centers on the three strategic elements summarized in the accompanying figure. These objectives focus on multi-scale convective phenomena that are central issues in global weather and climate prediction: MJO and convectively-coupled waves, intraseasonal variability of the monsoons, easterly waves and tropical cyclones, tropical-extratropical interaction, and the diurnal cycle. The YOTC Project Office based at NCAR is supported jointly by NSF, NOAA and NASA. The web site www.ucar.edu/yotc contains information on meetings, outreach, science, and implementation. Sessions were convened at the fall 2008 and spring 2009 AGU meetings of the American Geophysical Union and the 2009 annual meeting of the American Meteorological Society. The YOTC project was presented at the 3rd Joint Scientific Committee for the WMO, the Third THORPEX Science Symposium, 13th Session of the Working Group on Coupled Modeling (WGCM), and numerous other venues. Papers on YOTC and seamless prediction were contained in a Compendium circulated at the World Climate Conference -3 (WCC-3). Global high-resolution prediction analyses, forecasts, and special diagnostics from the prediction systems of ECMWF T799 (25km), the NASA Global Modeling and Assimilation Office GEOS-5 (¼ degree), and NCEP (40km) global models are being archived for the period May 2008-April 2010. Key multi-sensor satellite measurements have been identified and NASA has provided funding for developing the Goddard-based *Giovanni* satellite dissemination and analysis system for research purposes. Examples of YOTC's outreach activities include:

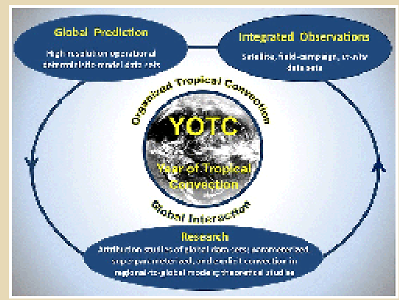

Figure: YOTC strategic objectives: tropical convection, multi-scale organization of precipitation systems, and interactions with the global circulation consisting of three primary elements: i) complete global analyses, forecasts and special diagnostics from ECMWF, NASA GEOS-5, and NCEP deterministic global prediction systems; ii) multi-sensor satellite data with emphasis onatmospheric profiling measurements; iii) research involving high-resolution operational prediction systems, advanced research models, and mathematical theory.

High resolution image

1. Experiments with climate models run in weather mode based on 5-day initialized forecasts and addressing critical issues in weather and climate prediction in collaboration the WCRP and Commission for Atmospheric Sciences (CAS) Working Group on Numerical Experimentation (WGNE).
2. Regional-to-global cloud-system resolving modeling experiments involving selected meteorological events.
3. Intra-seasonal multi-model 20-year hindcast experiments collaborative with the CLIVAR Asian-Australian Monsoon Panel (AAMP) and the Asian Monsoon Years (AMY).
4. Extension of the GEWEX Cloud System Study (GCSS) Pacific Cross-section Intercomparison (GPCI) simulation experiments through July 2008.

Priorities for 2010 include: i) moving forward with the above research objectives; ii) engaging the Asian and Deep Tropics communities in YOTC; iii) planning the international YOTC Research Workshop; iv) fostering financial support for the research phase of YOTC.

The YOTC project is supported by NSF, NASA, NOAA, WCRP and WWRP-THORPEX.

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Decadal Prediction, Predictability and Modes of Variability

Overview

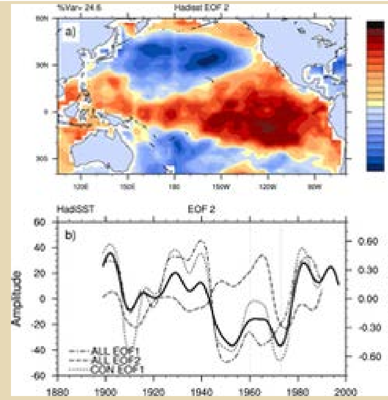

Figure Caption: Time series (bottom panel) of observed amplitudes (solid) of the IPO (top panel) showing the mid-1970s climate shift. Remaining curves are amplitudes of structures representative of intrinsic (dashed) and forced (dashed & dot-dashed) variability suggesting the shift corresponds to a transition to a situation where intrinsic variability became relatively less important.

High resolution figure

Interest in the prospects for decadal prediction has been spurred by the advent of new oceanic observing systems, by the development of new assimilation tools for the ocean, and by a strong emphasis on decadal time scale predictions in the upcoming IPCC Fifth Assessment Report. This interest has encouraged ESSL researchers to continue to expand their research in decadal variability, prediction and predictability. Much of this work has focused on prominent intrinsic modes of the system, which many scientists believe are likely to have above average predictability.

Recent Accomplishments

Intrinsic Variability and Climate Change

It is important to gain an understanding of the relative contributions of internally generated and externally forced decadal timescale climate fluctuations to provide insight into the problems involved with the newly emerging activity of decadal prediction. For example, a significant shift from cooler to warmer tropical Pacific sea surface temperatures (SSTs), part of a pattern of basin-wide SST anomalies involved with a transition to the positive phase of the Interdecadal Pacific Oscillation (IPO), occurred in the mid-1970s with effects that extended globally. One view is that this change was a product of internally-generated decadal variability. However, during the mid-1970s there was also a significant increase of global temperature and changes to a number of other quantities that have been associated with changes in external forcings, particularly greenhouse gases. ESSL scientists analyzed observations, an unforced control run from a global coupled climate model, and selectively forced 20th century simulations to show that the observed 1970s climate shift had a contribution from changes in external forcing superimposed on what was likely an inherent decadal fluctuation of the Pacific climate system. Thus this inherent decadal variability delayed what likely would have been a forced climate shift in the 1960s from a negative to positive phase of the IPO (figure below).

The relative importance of forced and intrinsic variability was also considered with a 40-member ensemble of CCSM3 forced with the SRES A1B greenhouse gas and ozone recovery scenarios. Analysis was performed to see how internal variability leads to uncertainty in the projected climate change. An example of such analysis is given in the figure below, which shows the ensemble mean sea-level pressure (SLP) trends during DJF (December, January, February) and JJA (June, July, August) (contours) and the minimum number of ensemble members needed for the ensemble-mean signal to be detected with 95% confidence. The results show that there is more uncertainty in the extra-tropical atmospheric circulation changes compared to those in the tropics, with only a few ensemble members needed in the tropics compared to 6-12 in the extratropics. This has implications for the decadal predictability of the circulation trends and their associated impacts on temperature and precipitation. Much of the uncertainty is due to internal atmospheric processes associated with "weather noise" (not shown) that is inherently unpredictable on long time scales.

Atlantic Variability

The question of the sensitivity of Atlantic decadal modes of variability to forcing and initial state specification has been approached by examining the sensitivity to surface boundary conditions of model simulations of the Atlantic Meridional Overturning Circulation (AMOC). This was accomplished by examining a suite of historically-forced (1948-2007) ocean-only and coupled ocean-ice experiments which differ only in their surface freshwater forcing and sea ice treatments. For each model configuration, four realizations, each utilizing a different surface salinity restoring timescale, were compared. Common AMOC variations were ascribed to invariant forcing terms, while the differences in ocean circulation associated with changes in uncertain boundary conditions were used to discriminate between robust and spurious AMOC variability.

AMOC sensitivity to the choice of initial conditions was also examined in preparation for future projection experiments using CCSM4. For the IPCC Fifth Assessment Report hindcast experiments were conducted which examined the possibility of using ocean initial conditions either from analyzed ocean states or ocean alone states produced using estimates of observed forcing. In these hindcasts these options have demonstrated a modicum of skill although model drift has limited predictive skill to a few years even for AMOC decadal modes of variability.

North Pacific Predictability

Any efforts to benefit from knowledge of the current state of the climate system when making future projections will be limited by the climate system's inherent sensitivity to small perturbations in the initial state. To quantify these limits in the North Pacific, 40 member ensembles of CCSM3 SRES A1b experiments, including the one discussed above, were utilized. The large ensemble size enabled predictability to be assessed as a function of geographical position and to be measured in terms of relative entropy, a natural measure of the information content of a forecast. As indicated in the figure, it was found that on a basin-wide basis, initial condition uncertainty limits the useful influence of the initial state to about a decade. And it becomes less important than the growth of GHGs after about eight years. These limits have strong geographical dependence; some regions of the North Pacific retain predictability for as much as three times longer than other regions. The leading pattern of subsurface temperature variability in this model is the Pacific Decadal Oscillation.

Interestingly, its predictability is not particularly long. If, however, one takes into account that it is one component of an eastward propagating phenomenon, then its predictability extends to about a decade for typical events.

2010 and Beyond

An ambitious set of decadal climate prediction experiments will be performed and analyzed for assessment in the IPCC AR5.

Determination of the dynamical processes underlying the forced atmospheric circulation changes in global change scenario experiments will be a priority.

21st century CCSM ocean hindcast ensembles, which are strongly constrained by ocean observations using Data Assimilation Research Testbed (DART) algorithms, are being produced. Analyses of the assimilated ensemble predictions will compare the AMOC strength and variability obtained in these ensemble initial states with those studied in 2009 and will compare results from fully coupled projection experiments that use the different initializations. The ensemble capability inherent in DART will also be exploited to analyze atmospheric variations co-variate with the AMOC.

Approaches developed for assessing decadal predictability of the North Pacific will be applied to other basins. And as a means of considering many different initial states rather than just the few that can be investigated using ensemble techniques, approaches will be developed that exploit information in long model control runs. These include the fitting of stochastic models and employment of strategies that exploit analogues.

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Prediction Across Scales

Overview

The Prediction Across Scales initiative is a collaborative effort between CGD and MMM to coordinate research and system development activities across weather and climate scales. Recent major advances in petascale computing coupled with rapid advances in scientific understanding are enabling progress in simulating a wide range of physical and dynamical phenomena with associated physical, biological and chemical feedbacks that collectively cross the traditional weather-climate divide. Such simulations and predictions are essential to a society that is becoming much more sophisticated in its requirements for weather, air quality and climate predictions and that is able to make useful economic and social use of such improvements. Moreover, fundamental barriers to advancing such prediction on time scales from days to years, as well as long-standing systematic errors in weather and climate models, are partly attributable to our limited understanding and capability to simulate the complex, multiscale interactions intrinsic to atmospheric and oceanic fluid motions. The scientific and societal questions and issues to be addressed are many. A limited sample includes better understanding of

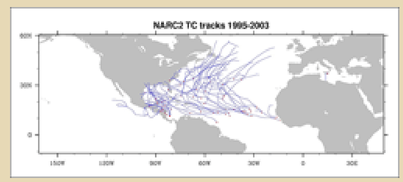

Figure: Tropical cyclone tracks from NARC II current climate simulation (North Atlantic tracks only). Red dots indicate genesis points.

High resolution image

- The water cycle and its predictability, particularly the limitations of available water and the impacts on food production;
- The limits of weather, air quality and climate predictability including the impacts of mega-cities and the stressed Earth's capacity to sustain quality of life;
- The interaction of hydrological, chemical and biogeochemical cycles and their feedback on weather/climate processes;
- The mechanisms by which solar variations influence the chemistry and dynamics of the upper atmosphere, and how these effects are manifested in the lower atmosphere;
- The interactions between climate change, ENSO and other natural modes of variability, including changes to the behavior of phenomena like hurricanes; and
- The mechanisms of abrupt climate change and potential tipping points.

The enabling tool for much of this research will be a community Nested Regional Climate Model (NRCM). The result of this ambitious effort to combine high resolution regional atmosphere and ocean models with a state-of-the-science climate model will be fundamental progress on the understanding and prediction of regional climate variability and change. In particular, embedding Advanced Research WRF (ARW) and a Regional Ocean Model System (ROMS) within CCSM will allow scientists to resolve processes that occur at the regional scale, as well as the influence of those processes on the large-scale climate, thereby improving the fidelity of climate change simulations and their utility for local and regional planning.

Recent Accomplishments

As a first step toward the development of NRCM, NCAR and community scientists have continued analyzing a recently completed 1995-2005 simulation of the tropical circulation with the NRCM configured in a channel mode at 36 km resolution using NCEP/NCAR reanalysis data on the poleward boundaries and specified surface conditions. In addition,

several high resolution two-way interactive simulations inside the channel model were completed, including high resolution nested domains over the Maritime Continent and the North Atlantic. Several papers featuring results from these simulations are in press.
With the support of CISL, two sets of climate change experiments over the North American region began in FY09. The primary aims for these experiments were water resource management in the Intermountain West and tropical cycle (TC) variations in tropical North Atlantic. The first set (referred as NARC I) was directly forced by outputs from CCSM-3 IPCC Fourth Assessment Report (AR4) scenario (A1B and A2) simulations. The results from NARC I showed a severe bias in that the large-scale flow from CCSM-3 produced anomalously large vertical wind shear which precluded the formation of TCs in the tropical North Atlantic. A second set of simulations (NARC II) was thus forced by bias-corrected CCSM data. In this run, TCs form throughout the tropical North Atlantic and their spatial distribution was remarkably similar to observations. The annual cycle of TC is also well captured. More comprehensive analysis of the NARC II experiment will take place through FY10.

FY 10

Work will continue on the nesting of ROMS within CCSM and fully coupling in a 2-way manner the NRCM to CAM and ROMS, and the completion and analysis of NARC experiments. In particular, research during FY2010 will have a number of overarching objectives:

- Oceanic:
    - Investigate the atmosphere-ocean coupling that emerges from a more accurate treatment of regional physical scales in a global climate model and the implications for downscaled regional projections of future climate; and,
    - Study the physics, biogeochemistry and ecosystems of major eastern boundary upwelling systems;
- Expand and continue development of down- and up-scaling capabilities utilizing the NRCM and CCSM;
- Continue Analysis of NARC2 simulations to include:
    - Conclusion of the study on Gulf of Mexico hurricanes in collaboration with DOE, the offshore energy industry and Georgia Tech;
    - Collaboration with the Caribbean Institute for Meteorology & Hydrology on Caribbean rainfall and hurricane activity; and,
    - Analysis of detailed changes in precipitation and snowpack over the Intermountain West region.

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Landfall impacts of hurricanes

Background

Research and applications work within ESSL and in collaboration with our colleagues in RAL and CISL, the Willis Research Network, Albany SUNY, FSU, and RSMAS has led to improvements in hurricane intensity prediction, prediction of impacts of landfalling storms, and studies of communication of hurricane information to the public.

Progress made in FY09

In collaboration with colleagues at CISL real-time hurricane and retrospective forecasts Atlantic tropical cyclones were conducted with an improved version of the Advanced Hurricane-research WRF (AHW) model initialized by an ensemble Kalman filter (from the data assimilation research testbed, DART). Retrospective simulations conducted as part of the NOAA Hurricane Forecast Improvement Project (HFIP) showed that the high-resolution version of AHW (as fine as 1.3 km horizontal grid spacing) produced statistically improved intensity prediction compared to forecasts on a 12-km grid. Real-time AHW forecasts, collected into a mesoscale ensemble by Florida State University, predicted the evolution weak tropical storms were better than operational models owing to higher resolution and improved initialization. A similar cycling assimilation system has been run for the period of the T-PARC field campaign. Data are currently being analyzed with particular emphasis on typhoons Sinlaku and Jangmi.

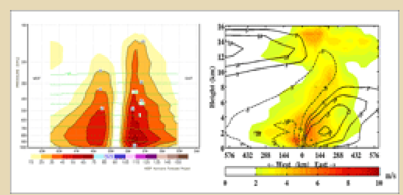

Figure: Vertical cross sections showing north-south wind component from HWRF (left, color-filled, units are knots) and EnKF initial condition for AHW (right, contours) units are m/s. Also shown at left are contours of temperature (10-degree interval). Color-filled field at right is the ensemble standard deviation of north-south wind component (m/s). Valid time is 06 UTC 2 September, 2009. Note the tilt of the vortex with height in the EnKF initial condition at right. This forced convection to occur to the right of the vortex, rather than in the center of the vortex, and this inhibited intensification.

High resolution image

In collaboration with RAL/ISSE, MMM researchers developed, implemented, and analyzed data from an interview-based study of Texas coastal residents following Hurricane Ike. A manuscript on the findings, which examine interviewees' perceptions of hurricane risk, protective decision making, and opinions of hurricane forecasts, has been submitted to the new AMS journal Weather, Climate, and Society. MMM researchers, as part of a multi-year NSF/NOAA-

funded project on Communicating Hurricane Information, conducted observations and interviews with NHC and NWS forecasters, broadcast meteorologists, and emergency managers in Miami, Florida, focusing on the processes by which hurricane risk messages are developed, the resulting content, and channels used to communicate about hurricane risk.

A tropical cyclone damage index has been developed in collaboration with the reinsurance industry. The index uses intensity, size and translation speed as inputs and outputs a single number that provide information on the likely damage sustained in 1993 USD. This index has been coded to run in parallel to the real-time hurricane forecasts with plans to apply it to the regional and global climate simulations.

In FY10, participation in HFIP will continue with real-time and retrospective simulations seeking the minimum computational requirements for significant improvements in intensity prediction. Societal research will also continue where results from the interviews will be used in FY10 to design a survey examining how at-risk coastal residents, including more vulnerable populations, comprehend and react hurricane warning messages communicated in different ways.

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U.S. Weather Research Program / Short Term Explicit Prediction Program (USWRP / STEP)

The ShortTerm Explicit Prediction (STEP) Program (http://www.mmm.ucar.edu/STEP) is a multi-NCAR Laboratory activity to improve the short-term forecasting of high-impact weather such as severe thunderstorms and heavy rainfall. The program includes research into basic understanding of high-impact weather systems, development of forecast techniques, real-time testing of forecast systems, improving our ability to observe the four-dimensional structure of the atmosphere, enhancing data assimilation capabilities, forecast verification, and interaction with users of forecasts. The basic goal is to improve forecasts of convective-scale phenomena on time scales that are quasi-deterministic (0-12 h or so). Short-term forecast skill depends upon advanced initialization strategies, physical parameterizations and the coupling between the two. This collaborative effort incorporates national and international scientists, engineers, and operational personnel from universities, government institutions and the private sector.

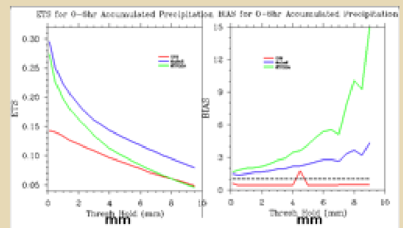

Figure: ETS (left panel) and BIAS (right panel) of 6-hour accumulated precipitation with respect to precipitation amount for the period of June 10-16, 2002. Red: GFS initialization; green: ARW forecast without radar data; blue: ARW forecast with radar data.

High resolution image

The primary activity for STEP this year was the continued collaborative effort on the IHOP retrospective study that started in 2008. MMM scientists evaluated the sensitivity of convective forecast skill and depiction of convective structure to varying treatments of physical processes, finding the largest sensitivity for variations in boundary-layer parameterizations. Preliminary results of data assimilation research indicate that when radar observations are assimilated through either the 3DVAR or a 3DVAR/nudging hybrid technique, the forecast skill, evaluated over a 1 week period (see Figure) is improved significantly with respect to simulations initialized directly from operational model analyses. Further comparison of data assimilation strategies revealed robust results from ensemble data assimilation and from four-dimensional variational assimilation (4D-VAR) compared to the use of 3D-VAR for convective scales. Diagnostic studies of WRF forecasts showed how, despite large areas of negligible convective inhibition, the initiation of deep convection was confined to regions with organized vertical motions and/or horizontal advections. Thermodynamic destabilization prior to afternoon CI is generally more gradual than that in advance of the mature evening mesoscale convective systems (MCSs) that may engender abrupt lifting along their surface outflows.

In FY09, the STEP scientists also participated in two field programs: TiMREX and VORTEX2. TiMREX post-experiment data analysis was conducted focusing on heavy rainfall induced by a lower-tropospheric mesoscale convective vortex (MCV) and understanding why some rainfall events are focused near the coastal Plain of Taiwan while others occur mainly over its mountains. One of STEP scientists played a key role in VORTEX2 planning and field execution, collecting valuable datasets for the study of supercell storms and tornados.

A workshop was conducted in January 2009 to report on the final results for each project and to discuss collaborative publications and future themes for STEP. In the coming year, a number of publications will be written to summarize the results of the IHOP retrospective study. The research emphasis will be on orographic precipitation and elevated convection. TiMREX data and BAMEX data will be the common datasets for the collaborative study. The convective scale data assimilation systems will be further developed and evaluated through retrospective study using data in the Rocky Mountain front-range region collected by the FRONT network.

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Bioemissions and photochemical processing

Chemicals produced by the biosphere include volatile compounds that are emitted into the air where they can have a substantial impact on the chemistry of the atmosphere. These biogenic gases are dominated by

volatile organic compounds (VOCs) both in total mass and number of compounds. The important role of biogenic VOCs in controlling global oxidant (e.g., OH and ozone) distributions has been demonstrated using global models while regional air quality models have shown that it is necessary to included biogenic VOC emissions in modeling efforts to develop regional ozone pollution control strategies. ESSL scientists are investigating the processes controlling biogenic emissions and their role in tropospheric photochemistry and are developing numerical schemes for including this information in regional and global earth system models.

Tropical landscapes are thought to be responsible for about 80% of global biogenic VOC emissions and yet are among the least understood. Global chemistry and transport models often perform poorly when using the biogenic VOC emission rates recommended by current emission models. This could be due to uncertainties in emissions but could also be a result of inaccurate characterization of boundary layer meteorology and/or chemistry. ESSL scientists have participated in recent tropical forest studies in central Amazonia (AMAZE) and in the south-east Asian tropical forests of Borneo (OP3) along with an international team of scientists that included Scot Martin (Harvard University), Jose Jimenez (U. Colorado) and Tony Prenni (Colorado State University). FY2009 analyses of these observations by ESSL scientists show the production of certain OVOCs (e.g. hydroxyacetone) from isoprene photo-oxidation in the lower atmosphere is significantly underpredicted by standard chemistry schemes. The triangular plot shown in Figure 1 summarizes findings from five field campaigns, including the AMAZE study, conducted near isoprene emission sources. Concentrations from these datasets, which are representative for typical local noontime conditions, were normalized by the sum of isoprene, MVK, MAC and hydroxyacetone in order to quantitatively compare their relative ratios. The color coded triangular symbols represent a chemical trajectory along which the relative ratios would evolve. The color coding indicates photochemical age (time exposure to OH). Measured distributions from all field observations, in particular the AMAZE dataset, show that hydroxyacetone mixing ratios are significantly higher than what would be expected from the standard chemical schemes. The discrepancy becomes larger for data collected closer to the source (recent supply of isoprene). The only way to reconcile such fast production of hydroxyacetone is to include additional production paths from isoprene.

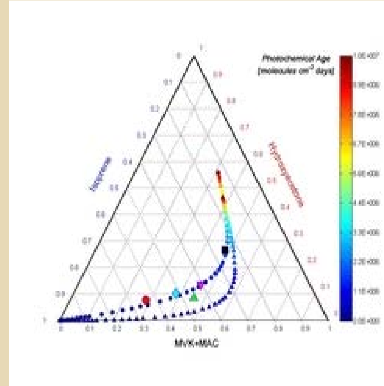

Figure 1. Triangular correlation plot between isoprene, MVK+MAC and hydroxyacetone mixing ratios normalized by the sum of isoprene, MVK, MAC and hydroxyacetone. Modelled concentrations are color coded by photochemical age. Triangles represent the standard scheme (no fast production). Circles show a case that includes fast photochemical production of hydroxyacetone. Field datasets are depicted by symbols as following: red circle (AMAZE, 2008), blue diamond (LBA-Claire, 1999), green triangle (CELTIC 2003), magenta triangle (ICARTT, 2004,) and black square (Blodgett Forest, 2003). Both chemical trajectories end at the steady state limit, typically reached after 10^7 molecules cm-3 days of OH exposure. This figure is presented in the article by Karl et al. in Atmos. Chem. Phys., 9, 7753-7767, 2009.

High resolution figure

ESSL scientists are conducting multi-year measurements (FY2008- FY2012) to investigate biogenic emissions and photochemical processing at the ESSL Manitou Forest Observatory. Figure 2 presents the diurnal variations of ambient concentrations of methyl butenol (MBO), monoterpenes (MT), acetone (m/z 59+) and glycolaldehyde+acetic acid (m/z 61+), averaged over a three week summer period. FY09 analyses of these data by ESSL scientists show a clear anti-correlation in the diurnal variations of MBO and MT, the two major BVOC emitted by the ecosystem. The light dependent emission behavior of MBO leads to maximum mixing ratios during the day despite dilution into a deeper boundary layer. On the other hand, the lower boundary layer depth during the night seems to be the main controlling factor of the diurnal variation of MT concentrations, with maximal mixing ratios occurring at night despite lower emissions resulting from cooler temperatures. The diurnal variation of the oxidation products such as acetone, possibly contributed by direct emissions, and glycolaldehyde + acetic acid is more complex due to photochemical production during daytime and variations of the boundary layer height throughout the day.

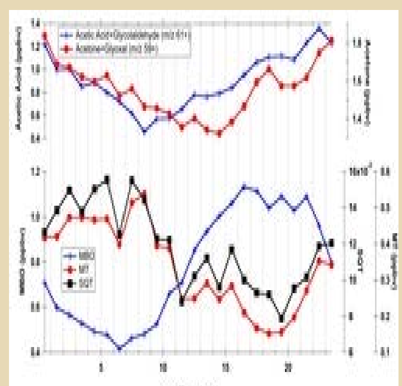

Figure 2. Averaged diurnal variations of biogenic VOC and their oxidation products for three weeks in summer at the ESSL Manitou Forest Observatory. This figure is presented in the article by Kim et al. in Atmos. Chem. Phys. Discuss., 9, 20819-20852, 2009.

High resolution figure

FY2010 work will continue laboratory and field investigations of factors affecting biogenic emissions and their impact on oxidants. This work was funded by NSF/NCAR and EPA.

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Emission inventories and application

Trace gas and aerosol emissions into the atmosphere are the major drivers of the chemical composition of the atmosphere. There is widespread concern

about the effect of human activities on these emissions and their impact on atmospheric chemical composition. Changes in human activities are the underlying cause of the current increase in pollutant levels on regional and global scales. In some cases, changes in trace gas emissions are due to obvious pollutant sources including many technological sources. Other sources, including biomass burning and biogenic, have a natural component but are strongly influenced by humans. In order to understand these increases and to predict future changes, ESSL scientists are quantifying emissions from various sources and improving our understanding of the natural and human influenced processes that control emissions.

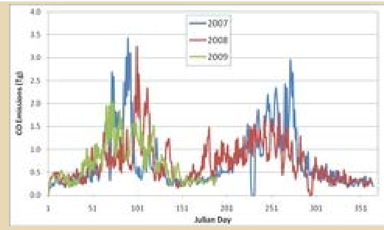

Figure: Daily global CO emissions from fires for January 2007 until July 2009 estimated with the newly developed global fire emissions model.

High resolution figure

ESSL scientists have been continuing the development of the 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. It is driven by landcover, weather, and atmospheric chemical composition information. MEGAN is a global model with a base spatial resolution of ~ 1 km. A stand-alone version of MEGAN is now available on the NCAR community data portal during the past year and has already been downloaded by > 200 users from more than 20 countries. MEGAN has also been incorporated as an on-line component of several regional and global models including MOZART, CCSM-CLM, GEOS-CHEM and WRF-CHEM. As part of the effort to integrate MEGAN with WRF-CHEM, a preprocessor for MEGAN inputs has been developed, which will enable users to have more flexibility when applying the model. Continued development of MEGAN has resulted in a version that includes a detailed canopy environment model that will enable more realistic estimates of the response to landcover and climate change.

ESSL scientists have also continued to improve a North American wildfire emission model. The model estimates daily emissions from fires for all of North America at a 1km resolution. More recently, ACD scientists teamed with NASA and University colleagues to expand the model to estimate global emissions of carbon dioxide, carbon monoxide, particles, and other emissions from biomass burning. These estimates have been used for model simulations of the U.S., South America, Europe, and India.

FY2010 work will include continued improvements of MEGAN and the fire emissions model and enhanced support for the communities using these models. In addition, efforts will be focused on evaluating the model results and quantifying model uncertainties. The emission models will be used in regional chemical transport modeling studies to investigate the radiative impact of aerosols from fires and biogenic sources, to study the interactions between direct particulate fire emissions and secondary organic aerosol formation, and to evaluate observations from various field studies from around the globe. Other work will focus on development of a model to estimate emissions from trash burning in developing countries. This work is funded by NSF/NCAR and EPA.

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Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) contributions

ESSL scientists are participating in the Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS), a new 10 year land-atmosphere project of the International Geosphere-Biosphere Programme (IGBP). The goal of iLEAPS is to understand how interacting physical, chemical, and biological processes transport and transform energy and matter through the land-atmosphere interface. The project is designed to study interactions and feedbacks on scales from molecules to the entire globe, and from minutes to centuries, both past and future. The project brings together multi- and cross-disciplinary scientists to collaborate, distribute ideas and results rapidly, and increase scientific relations with developing countries. The iLEAPS International Project Office is based at the University of Helsinki in Finland and promotes international research projects studying essential phenomena related to global climate change.

iLEAPS Logo

High resolution figure

In FY2009 ESSL scientist Alex Guenther was elected to the iLEAPS Scientific Steering Committee. ESSL scientists also participated in the iLEAPS sponsored workshop on " Induced BVOC emissions: Processes and feedback mechanisms from cells to atmosphere" in Taagepera, Estonia and the iLEAPS scientific conference in Melbourne, Australia. ESSL scientists will continue to contribute to iLEAPS activities in FY10 and will propose several ESSL led projects for sponsorship by iLEAPS. This work is funded by NSF/NCAR.

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The impacts of climate and weather on society and ecosystems: Polar climate

Overview

Over the past several decades, Arctic sea ice extent has been steadily shrinking. Associated with this is an observed amplification of Arctic warming relative to the rest of the world. Observed sea ice extent in September 2007 smashed the previous record low. Climate models project that sea ice decline will continue into the foreseeable future, with the possibility of summer ice-free conditions being reached later this century. This projected ice loss is often punctuated with instances of rapid change. Considerable effort is underway to examine these observed and projected changes in the sea ice system and their consequences for the climate and ecological systems.

Along with sea ice loss, there are strong indications of high latitude terrestrial change. Thawing of permafrost is likely to induce a number of feedbacks to the hydrologic and carbon cycles of the Arctic system. Of particular concern, especially from a global perspective, is how permafrost thaw will affect the carbon balance in the Arctic. Greenland ice sheet loss has accelerated with potential implications for ocean meridional overturning circulation and sea level. Projected changes in snow cover over land have important climate effects.

Finally, while changes in high northern latitudes are considerable, many aspects of the Antarctic climate have remained more stable. There are numerous and varied reasons for this different behavior in the southern high latitudes, including changes in the atmospheric circulation and ocean heat uptake that appear to mute an anthropogenic warming signal. However, recent work suggests a larger anthropogenic signal than previously appreciated. Additionally, changes are projected for the future with potential implications for southern ocean ecosystems. Overall, the interactions and importance of numerous processes for the future Antarctic climate remain unclear.

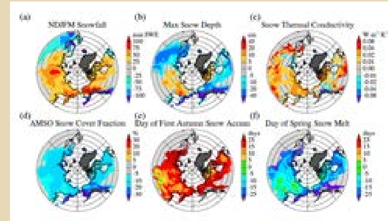

Figure Caption: Projected changes (2080-2099 minus 1950-1969) in climatological snow-related properties calculated from a single CCSM3 20th and 21st century (SRES A1B) integration. (a) Winter (Nov to Mar; NDJFM) snowfall in snow water equivalent; (b) annual maximum snow depth; (c) winter snow thermal conductivity; (d) annual mean snow cover fraction; (e) day of year when autumn snow accumulation reaches 10cm, grid cells with <90-day or >350-day snow season in either 1950-1969 or 2080-2099 are masked out in light grey; (f) day of year when spring snow melt brings snow depth below 10cm, masking as in (e). Dark grey in all maps indicates grid box is at least partly composed of glacier land cover type with perennial snow cover.

High resolution figure

Recent Accomplishments

In 2009, we made substantial progress on a variety of research topics, ranging from an evaluation of the Arctic hydroclimatology in coupled models, an assessment of cloud-sea ice interactions, a better understanding of Arctic and Antarctic changes on paleo-climate timescales, and the role of sea ice loss for Arctic and Antarctic ecosystems. We also continue to evaluate the role of changes in freshwater forcing on the meridional overturning circulation (MOC) and associated impacts on climate. In addition, we have continued to augment CCSM to improve the representation of cold region processes and to include new processes such as aerosol deposition onto snow and ice.

2010 and Beyond

CCSM experiments exhibiting periods of abrupt sea ice loss and rapid permafrost thaw raise the question as to whether or not sea ice or permafrost loss exhibit characteristics of a so-called tipping point in the climate system. Experiments are underway to investigate the role of physical climate feedbacks on rapid sea ice change and to assess the stability of seasonally ice free conditions. Associated with this are studies that assess changing Arctic ocean circulation and freshwater pathways, and the potential implications for polar climate feedbacks. Experiments are also planned to evaluate whether permafrost is sustainable or not once the ground has reached a thermal state in which talik, a perpetually unfrozen layer between seasonally frozen ground above and permafrost below, has formed.

Work is underway to incorporate a dynamic wetland model that is capable of simulating the anticipated changes in wetland distribution associated with permafrost thaw induced soil subsidence. Additional efforts will focus on an integration of the CLM organic soil representation with the prognostic soil carbon calculated in the CLM carbon cycle model. We also intend to evaluate how a conversion of tundra to woody arctic shrubland will affect the carbon cycle and surface energy budgets, with an emphasis on the relative importance on these budgets.

We also plan continued evaluation of the climate response to Arctic sea ice loss, with a particular emphasis on the seasonal atmospheric, oceanic, and terrestrial response. The primary goal is to investigate the mechanisms underlying the seasonal response of the climate system to Arctic sea ice loss within the context of anthropogenic climate change. Additional studies on the marine ecosystem response to a changing sea ice melt season length are also planned. A study on the repercussions of seasonal sea ice change for sea bird populations is also underway.

As Arctic sea ice continues to retreat, issues of marine access have become increasingly important. Studies are underway to investigate a number of scientific issues related to this. In particular, we are currently assessing the predictability of Arctic sea ice cover on seasonal to interannual timescales in the context of a rapidly changing Arctic environment. Additionally, the climate implications of increased black carbon (soot) deposition on the Arctic sea ice and snow cover from increased Arctic shipping will be investigated using climate model integrations.

Work is underway to elucidate the relative roles of radiative forcing and internal climate variability in shaping observed Antarctic climate change. We are using an extensive database of instrumental and proxy records to characterize the natural climate variability of the Antarctic over the past ~250 years, providing a long context for the changes that are occurring today. We will evaluate existing and new atmospheric model experiments, forced with the observed history of

tropical and/or global sea surface temperatures, with and without changes in direct atmospheric radiative forcing, for the period 1870-present. A particular interest is to understand the dynamical processes responsible for tropical-Antarctic climate connections, including the roles of El Nino-Southern Oscillation (ENSO) and the Southern Hemisphere Annular Mode (SAM).

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The impacts of climate and weather on society and ecosystems: Climate change - probabilistic climate change, and solar forcing of climate

Overview

NCAR was one of the first centers to study anthropogenic climate change with global coupled climate models starting in the late-1970s. Consequently, the earliest climate change experiments done at that time were pioneer projects at a national and international level. Few groups were doing climate change modeling as it was considered to be a sidelight to other more highly regarded modeling problems. NCAR climate change modeling (funded by DOE and NSF) was prominent in the DOE State-of-the-Art climate change assessments in the late 1980s, and in the first IPCC assessment in 1990 and the 1992 IPCC update since only four groups in the world (including NCAR) had functioning global coupled climate models that were being used for climate change projections.

Since then, climate change modeling has become a very prominent activity at NCAR, most recently through the Community Climate System Model (CCSM) effort, and is now a headline activity for NCAR. As climate change modeling evolves to include more complexity, we have formulated a first generation earth system model with a coupled carbon-nitrogen cycle model as a standard part of the CCSM for the first time. This crosses division boundaries in ESSL and requires close cooperation with the other science divisions since the earth system model version of CCSM will soon include not only the basic atmosphere-ocean-land surface-sea ice global coupled model and the newly coupled carbon-nitrogen cycle model, but also components of chemistry, aerosols, and dynamic vegetation.

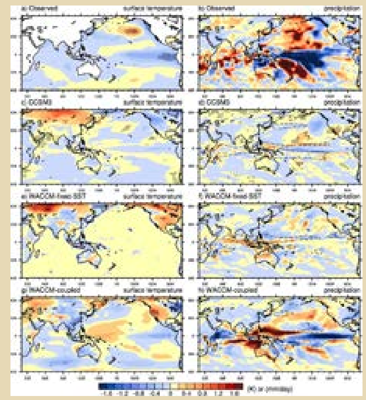

Figure Caption: Composite averages for DJF for peak solar years, a) observed SSTs for 11 peak solar years (2), °C, b) same as (a) except for precipitation for three available peak solar years, mm day^{-1}; c) same as (a) except for CCSM3 average of five ensemble members for 20th century climate, °C, d) same as (c) except for precipitation; mm day^{-1}; e) same as (a) except for WACCM with specified non-varying SSTs, 10 peak solar years; f) same as (e) except for precipitation (mm day^{-1}); g) same as (a) except for WACCM coupled to the dynamical ocean, land, and sea ice components of CCSM3, 11 peak solar years, °C; h) same as (g) except for precipitation (mm day^{-1}). Stippling indicates significance at the 10% level, and dashed lines indicate position of climatological precipitation maxima..

High resolution figure

Recent Accomplishments

ESSL scientists and collaborators have been involved with research that has directly influenced and characterized national and international climate science research. For example, decadal variability from external sources such as the sun has been examined recently. One of the mysteries regarding the earth's climate system response to variations in solar output has been how the relatively small fluctuations of the 11-year solar cycle can produce the magnitude of the observed climate signals in the tropical Pacific associated with such solar fluctuations. Two mechanisms, the top-down stratospheric response of ozone to fluctuations of shortwave solar forcing, and the bottom-up coupled ocean-atmosphere surface response, are included in versions of three global climate models: CCSM, the Whole-Atmosphere Community Climate Model (WACCM) run with specified Sea Surface Temperatures (SSTs), and WACCM coupled into CCSM with either mechanism acting alone or both together. We show that the two mechanisms act together to enhance the climatological off-equatorial tropical precipitation maxima in the Pacific, lower the eastern equatorial Pacific SSTs during peaks in the 11-year solar cycle, and reduce low latitude clouds to amplify the solar forcing at the surface (Fig. 1).

2010 and Beyond

Future research priorities in climate change modeling include further studies of extremes especially with regards to changes in daily temperature records, decadal prediction experiments for short term climate change, and new mitigation scenarios used to simulate longer-term future climate change to quantify questions involved with climate change mitigation/adaptation.

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Climate Change in the Thermosphere and the Effects of Solar Minimum

The thermosphere-ionosphere system goes through cyclical changes in temperature and density driven by the Sun's 11-year activity cycle, heating and expanding at solar maximum, cooling and contracting at solar minimum. Superimposed on these changes is a slow secular decrease in temperature and density driven by anthropogenic changes in greenhouse gases,

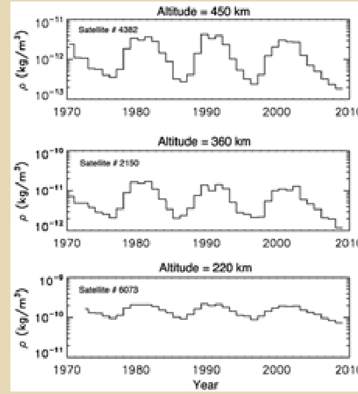

Figure 1. Annual averages of thermospheric density at three different heights, derived from long term tracking data of satellites in elliptical orbits with perigees at the indicated altitudes. The first three solar minima are similar, except for the small but steady decline in density due to increasing greenhouse gases. In 2008, the density is much lower than previous minima. According to solar measurements and model results, this additional change is due to unusually low levels of solar ultraviolet and X-ray emissions during the extraordinarily long, deep, and quiet solar minimum between solar cycles 23 and 24.

High resolution figure

especially CO_2. These gases can increase temperature in the lower atmosphere due to their ability to absorb infrared radiation, but also affect the upper atmosphere through radiational cooling. Since the prediction by Roble and Dickinson in 1989 that a consequence of increasing CO_2 levels would be to decrease the temperature of the upper atmosphere, NCAR researchers have been studying this effect and its consequences for the near-Earth space environment.

Detection of the gradual changes occurring in the thermosphere due to increasing greenhouse gases is difficult due to the extremely large solar-cycle variation. Studies of density changes by observing the effect of atmospheric drag on satellite orbits have revealed that thermospheric density is systematically decreasing by several percent per decade near 400 km altitude, in general agreement with model predictions. The secular change under solar minimum and solar maximum conditions is variable, with larger trends at solar minimum and smaller change during solar maximum. Measurement and modeling of the larger solar minimum effect has been based in part on the assumption that solar ultraviolet and X-ray irradiance return to characteristic levels at each solar minimum. However, Solar activity during the solar minimum period from mid-2007 to mid-2009 was unusually low, including ultraviolet irradiance, solar wind parameters, and the interplanetary magnetic field. NCAR researchers at the High Altitude Observatory, working with colleagues at the University of Colorado (Tom Woods), the Naval Research Laboratory (John Emmert) and at the NASA Langley Research Center (Marty Mlynczak), are investigating the question of whether the terrestrial response to this solar minimum is significantly different from previous solar minima.

Thermospheric density data from atmospheric drag on satellites, infrared cooling rate data and solar irradiance observations by the TIMED mission, and model simulations using the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM), are employed to evaluate how much of the current phenomenon is attributable to solar variation, and how much to anthropogenic sources. Figure 1 shows annual average changes in thermospheric density at three different heights, derived from long term tracking data of satellites in elliptical orbits. For the first three solar minima (during ~1975, ~1985, and ~1996) the small but steady decline in density due to increasing greenhouse gases is evident, but in 2008, the density is much lower than previous minima. Preliminary model results show that this change, about 30% at the higher altitudes, is commensurate with the lower-than-usual solar ultraviolet and X-ray irradiance levels. However, this also shows that we cannot generally assume solar minima to be alike, and thus the quantification of anthropogenic thermospheric cooling becomes more complicated, and requires high-accuracy, on-going measurements of the upper atmosphere energy balance.

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Globalization of air quality and intercontinental transport

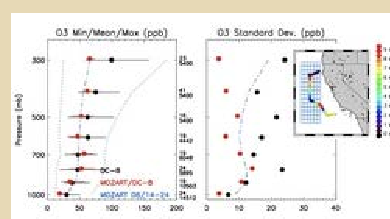

Figure 1: Left-hand side: Minimum, mean and maximum ozone profiles averaged over 100 mbar altitude bins during the ARCTAS/CARB flight on 22 June 2008. Observed (black) and modeled (red) aircraft data, as well as statistics of modeled ozone distribution for 14-24 June 2008 over the region shown in the map (blue). Right-hand side: Corresponding standard deviation over the 100 mbar altitude bins.

Over the recent years, Air Quality, once thought of as a purely local problem, has been recognized as being a much more complex issue. We now know that atmospheric pollutants have often long-distance impacts on regional and continental scales and up to hemispheric and global scales. Thus it is important to understand the impacts of long-range transport (LRT) of pollution on the local atmospheric composition, its controlling factors and variability. Following selected highlights of recent studies in this research field.

Variability in emissions versus variability in meteorology and transport

The transport of pollution across the Pacific has been analyzed for 2000-2006. The tools included in this study include multi-year satellite retrievals of CO from the Measurements of Pollution in the Troposphere (MOPITT) instrument, aircraft measurements taken during the Intercontinental Chemical Transport Experiment Part B (INTEX-B) experiment in spring 2006 as well as accompanying model simulations with the global chemistry transport model MOZART-4. Model tracers for CO are used to examine the contributions of different source regions and source types to pollution levels over the Pacific. Additional modelling studies were performed to separate the impacts of inter-annual variability in meteorology and dynamics from

changes in source strength.

Interannual variability in the tropospheric CO burden over the Pacific and the U.S. as estimated from the MOPITT data range up to 7% and a somewhat smaller estimate (5%) is derived from the model. When keeping the emissions in the model constant between years, the year-to-year changes are reduced to (2%), but show that in addition to changes in emissions, variable meteorological conditions also impact transpacific pollution transport. We estimate that about 1/3 of the variability in the tropospheric CO loading over the contiguous US is explained by changes in emissions and about 2/3 by changes in meteorology and transport. Biomass burning sources are found to be a larger driver for inter-annual variability in the CO loading compared to fossil and biofuel sources or photochemical CO production even though their absolute contributions are smaller.

This work is published in Atmos. Chem. Phys. Discuss., 9, 17817-17849, 2009.

This work was funded by NASA and NSF.

High resolution figure

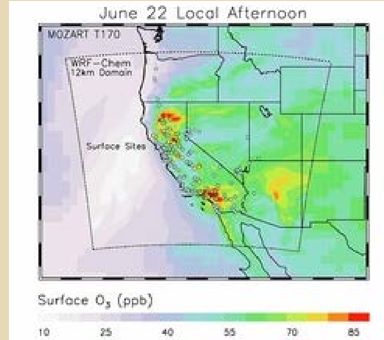

Figure 2: Afternoon surface ozone from MOZART-4 (colored grid in large domain), WRf-Chem (filled contours in smaller domain) and surface sites (filled circles); 22 June 2008.

High resolution figure

Chemical Boundary Conditions for Regional Modeling

In order to take long-range transport into consideration in regional chemistry transport modeling, it is necessary to specify the time-varying concentration fields of long-lived (time scales of hours or larger) species throughout the simulation period at the lateral and upper boundaries of the regional domain. While, until recently, most regional chemical modeling at the most considered only climatological boundary conditions for key chemical species, it is now being recognized that the inflow into a region can be highly variable in time and space and might have significant impact even on surface concentrations.

The high variability of inflow into a region is demonstrated in Figure 1. During the ARCTAS/CARB campaign in June 2008, the DC-8 performed a "boundary conditions" flight to gain information about inflow of trace gases and particles into the U.S. West Coast. The graph shows statistics of the observed ozone profile during the particular flight leg and illustrates how well the observations are simulated by the MOZART-4 model. Statistics from MOZART-4 modeled ozone fields taken over a larger region and a 10-day period are also included to put the observations into a larger perspective. Ozone concentrations in the mid-troposphere cover a wide range from about 20-100 ppb with standard deviations on the order of about 10 ppb in the model and nearly twice as high in the observations.

To consider the influence of pollution inflow and also allow for investigating the characteristics of this influence, we have developed a software package that takes output from either MOZART-4 or the CAM-Chem model and creates time- and space-varying chemical boundary conditions for real-time and archived MOZART-4 simulations. A further step was taken to increase the chemical compatibility between the chemical boundary conditions and the regional model by adding the MOZART-4 gas phase chemical mechanism to WRF-Chem. This package will be released in WRF-Chem V3.2 in spring 2010. An example of the different scales that can be jointly analyzed with this setup is given in Figure 2.

This work was funded by NASA and NSF.

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MOZART in the analysis of tropospheric observations

Ozone Budget over the Contiguous U.S.

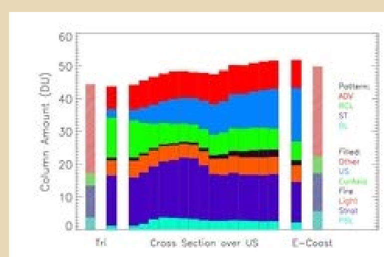

Figure 1: Changes in the ozone budget across the contiguous US for MOZART-4 tracers (filled) and the laminae analysis terms (pattern; BL (boundary layer ozone), ST (stratospheric ozone), RCL (regional convection & lightning), ADV (background ozone)). The cross section over the US is derived by averaging the MOZART-4 budget for 1 July-15 August over the latitude range

The origin of ozone over the summertime contiguous US during summer 2004 was examined using the Intercontinental Transport Experiment Part A (INTEX-A) ozonesonde network (IONS-04) over North America together with simulations from the global chemistry transport model MOZART-4. We included synthetic tracers in the model that keep track of the ozone produced from selected NOx sources (stratosphere, lightning, anthropogenic and biomass burning sources in Eurasia and the contiguous US, and North American boreal fires). This "model budget" is evaluated against results from a "laminar identification method (LID)", a more empirical approach to extracting information about contributions from ozone transported down from the stratosphere, advection and convection from the ozonesonde data.

Both methods give comparable results for the contribution from stratospheric ozone, an average over all sites of 20±7% for the LID budget and of 26±6% for the model budget (the standard deviation gives the variability over the IONS sites). These results point towards the important contribution of downward transport of ozone from the stratosphere in assessing tropospheric ozone. The contributions for the other tracers are 25±9% for

US sources, 13±5% for Eurasian sources, 3±2% for boreal fires and 10±2% from lightning. In the boundary layer the dominant contribution generally comes from local (US) sources. Eurasian sources can add up to 8% on average for some sites, lightning up to 4%, and North American boreal fires up to 10%.

This work is published in J. Geophys. Res., 113, D23306, doi:10.1029/2008JD010190. This work was funded by NASA and NSF.

30-50N for each longitude bin between 125 W and 70W. Separate bars on the left show the average budget for Trinidad Head, separate bars on the right show the budget averaged over the East Coast sites (Be, Wa, Na, Ya, Sa, RB).

High resolution figure

ARCTAS

Chemical forecasts from MOZART-4 were used to assist in flight planning of the NASA airborne experiment ARCTAS (Arctic Research of the Composition of the Troposphere from Aircraft and Satellites), which took place April-July 2008, based in Alaska and Canada. Following the experiment, MOZART-4 is being used to interpret the observations and provide context for the experiment. CO emissions from various regions and source types are “tagged” in the model to keep track of the source contributions in various regions. The CO concentrations in the Arctic during April 2008 are dominated by anthropogenic emissions, particularly from China, with lesser amounts from Europe and North America. Biomass burning in Siberia began earlier in the Spring than typical years, influencing the composition of the Arctic in April.

This work was funded by NASA and NSF. This work will be published in FY10.

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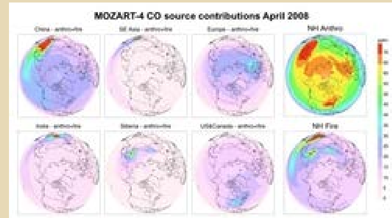

Figure 2: CO source contributions determined by tagging CO emissions in MOZART-4. Tropospheric column averages of anthropogenic and fire emissions for different regions (left 6 panels) and for total Northern Hemisphere sources of anthropogenic and Fire emissions (right 2 panels).

High resolution figure

UTLS Dynamics, Trends, and Composition

Chemical structure of the tropopause

Measurements from the NCAR GV START08 field campaign (April-June 2008) have been used to quantify chemical structure of the UTLS and tropopause region, and these data have been used to examine the performance of chemistry-climate models. To facilitate comparisons between models and observations, NCAR scientists performed a specific WACCM run nudged by observed meteorological analyses, which produces a reasonable representation of the START08 time period. Detailed studies are ongoing, for example using tracer-tracer correlations to examine the transport and mixing in the tropopause region. Figure 1 shows a comparison of ozone (O3) – carbon monoxide (CO) correlations from one START08 flight and the corresponding WACCM results, showing very reasonable agreement of model and observations. Similar analyses are underway using all START08 flights and different chemical tracers. Figure 2 gives an example of observed and modeled correlations with ozone and CO versus CFC-12. Since the START08 tracers span a wide range of chemical lifetimes, the comparison will provide key indicators of how well the chemistry and dynamics are represented in the model.

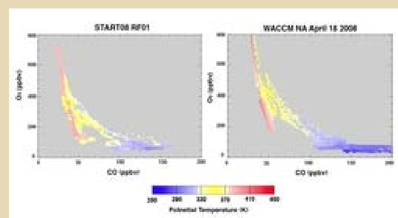

Figure 1. O3-CO correlation from START08 flight RF01 (April 18, 2009) and WACCM model. Color shadings are used to indicate the potential temperature ranges represented in the tracer space. RF01 is a research flight that targeted regions of tropospheric air mass intrusions into the lower stratosphere. The intruding air mass is identified in the O3-CO tracer-tracer space to be around the lower end of the “red” branch, associated with potential temperature greater than 370 K.

High resolution figure

Transport and chemistry of the Asian monsoon anticyclone

Satellite observations of tropospheric pollutants show persistent maxima over the Asian monsoon anticyclone in the UTLS during Northern Hemisphere summer, associated with transport of near-surface air in deep convection and confinement by the strong anticyclonic circulation. ACD scientists used carbon monoxide (CO) measurements from the Microwave Limb Sounder (MLS) onboard NASA Aura satellite and global chemistry model (MOZART-4) to explore transport pathways in the Asian summer monsoon anticyclone. The MOZART-4 CO shows good agreement with the MLS observations at 100 hPa (~16 km), for both daily data (Figure 3) and seasonal variability. The model is furthermore used to quantify transport pathways in the monsoon, showing that the main source region for pollution in the anticyclone is India and Southeast China, via deep convection associated with the monsoon. Vertical profiles of cloud fraction from the CloudSat satellite show that convection over the Tibetan Plateau has little contribution to the monsoon maximum. Ongoing research is aimed at quantifying the influence of the Asian monsoon to transport to the stratosphere.

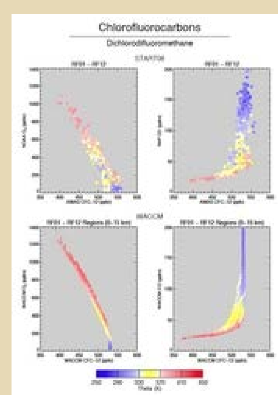

Figure 2. Correlation of CFC-12 with ozone (left) and CO (right) for the START08 flight 1-

HIRDLS cloud measurements

ACD scientists led validation and analysis efforts for measurements of cirrus clouds from HIRDLS satellite data. Quantifying cirrus structure and variability from observations is important for understanding UTLS water vapor budgets and radiative feedbacks. HIRDLS measurements were combined with CALIPSO satellite lidar data to quantify the frequency of occurrence, geospatial distributions, vertical, and horizontal structure of cirrus in the upper troposphere. Since these experiments are able to observe thin cirrus layers in greater detail than previous satellite experiments, new information on laminar cirrus is now possible; one new finding demonstrates that isolated laminar cirrus is most prevalent away from the equator during NH winter, as shown in Figure 4.

Multi-model assessment of the UTLS

ACD Scientists have led efforts to evalutate the performance of 18 coupled Chemistry Climate Models (CCMs) in the Tropical Tropopause Layer (TTL). Several aspects of model behavior are analyzed, including climatology of the cold point tropopause, TTL transport transit times and long-term trends. Figure 5 shows a comparison of seasonal variations in tropical cold point temperature from models and observations, revealing reasonable agreement in the amplitude of the seasonal cycle, but substantial mean biases among models. These are in turn reflected in the amount of water vapor entering the stratosphere in the respective models, and result in important biases in water vapor climatologies (which influence stratospheric chemistry and radiative balances). This work is one component of a community-wide evaluation of chemistry-climate models, termed CCMVal (Chemistry Climate Model Validation).

Processes regulating short-lived species in the tropical tropopause layer

A one-dimensional model of vertical transport in the tropical tropopause layer (TTL) has been developed. The model uses vertical advection, a convective source and a chemical sink to simulate the profiles of very short lived substances (VSLS) in the TTL. The model simulates evanescent profiles of short lived hydrocarbon species observed by satellite, and is also used to simulate short lived bromine species. Tracers with chemical lifetimes of 25 days or longer have significant concentrations in the stratosphere and vertical advection is critical. Convection is important up to its peak altitude, nearly 19km. Convection dominates the distribution of species with lifetimes less than 25 days. The annual cycle of species with lifetimes longer than 25 days is governed primarily by the variations of vertical velocity, not convection. This is particularly true for carbon monoxide, where a seasonal cycle in the lower stratosphere of the right phase is produced without variations in tropospheric emissions. An analysis of critical short lived bromine species (CH_2Br_2 and $CHBr_3$) indicates that substantial amounts of these tracers may get advected into the lower stratosphere as source gases at 18km, and are estimated to contribute 2.8 pptv (1.1–4.1) to stratospheric bromine.

ENSO influence on the tropical lower stratosphere

Analyses of WACCM model simulations forced by historical sea-surface temperature variations show that tropospheric El Nino – Southern Oscillation (ENSO) events are linked to coherent variations of zonal mean temperature and ozone in the tropical lower stratosphere, tied to fluctuations in tropical upwelling. ENSO temperature variations in the lower stratosphere are out of phase with tropospheric variations, i.e. stratospheric cooling associated with ENSO 'warm events', as shown in Figure 7a. Very similar results are found in analysis of observational data (Figure 7b). The coherent temperature and ozone signals are evidence that ENSO modulates upwelling in the tropical lower stratosphere.

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12 (top) and corresponding WACCM results (bottom).

High resolution figure

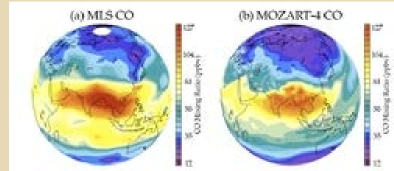

Figure 3. Synoptic map of carbon monoxide (CO) at 100 hPa obtained from (a) Microwave Limb Sounder (MLS) and (b) MOZART-4 global chemistry transport model for 14 June 2005. The CO enhancement over the Asian monsoon anticyclone is well reproduced in the model (from Park et al., 2009).

High resolution figure

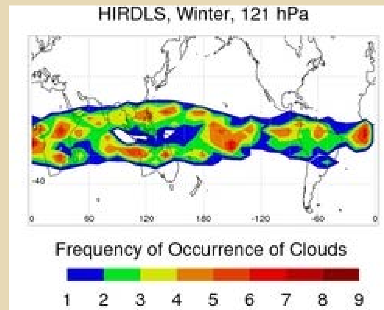

Figure 4. Frequency of occurrence of isolated cirrus at 121 hPa during winter (December 2006 – February 2007) derived from HIRDLS satellite measurements. Over the maritime continent, cirrus layers are present away from the region of frequent deep convection over the equator.

High resolution figure

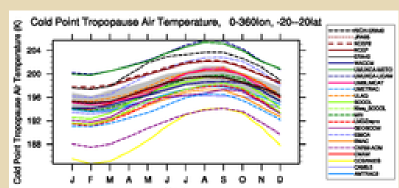

Figure 5: Annual cycle of tropical (20S-20N) cold point tropopause temperature from models and observations. Observations are from the period 1980-1999. Gray shaded region is 2σ variability from ERA40 analyzes.

High resolution figure

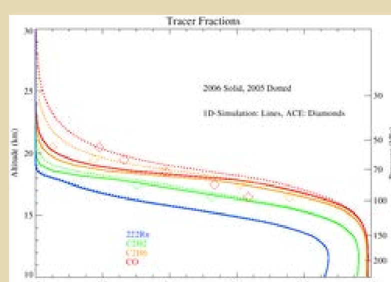

Figure 6: Annual mean normalized mixing

ratios of CO(red), C2H6 (orange), C2H2 (green)and radon(222Rn: blue) in the TTL from the idealized transport model. Solid lines represent runs with 2006 winds, dotted lines 2005 winds. ACE satellite observations (normalized) shown as diamonds.

High resolution figure

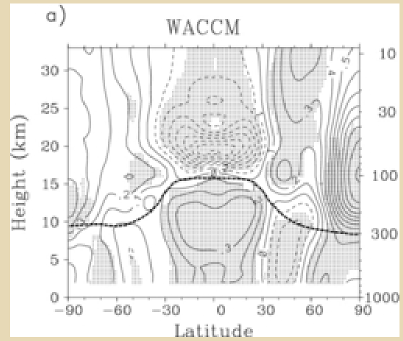

Figure 7a.

High resolution figure

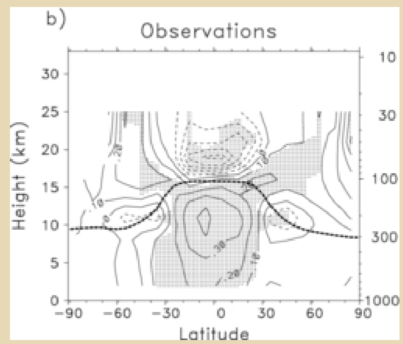

Figure 7b.

Figure 7. Meridional structure of the zonal mean temperature response to El Nino Southern Oscillation (ENSO) climate variations in WACCM simulations (a) and observations based on radiosondes (b). Contours show the regression of temperature onto a proxy for ENSO variability (the Multivariate ENSO Index, MEI), based on a multiple linear regression analysis over 1960-2005. Units are degrees K per standardized MEI index. Note the out of phase variations in the tropics above and below the tropopause (indicated by the dark dashed line), for both the model and observations. From Randel et al, 2009.

High resolution figure

WACCM (Stratospheric ozone recovery)

The coupling of stratospheric chemistry models with climate models has lead to the development of a new generations of model designated as Chemistry-Climate models (CCMs). Periodic assessment exercises organized by the UNEP/WMO Scientific Assessments of Ozone Depletion use these CCMs to address current understanding of observed historical ozone and temperature trends and projections of these trends into the future. However, in previous assessments, there has been insufficient time to evaluate CCM performance thoroughly while preparing the Ozone Assessment. For this reason, SPARC has established the Chemistry-Climate Model Validation Activity (CCMVal) for

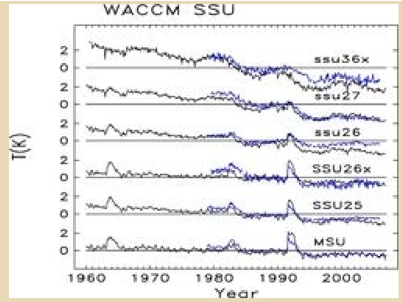

Figure 1. Comparison of global stratospheric temperature trends between WACCM (black) and observations (blue). Results from the WACCM simulation are consistent with the CCMVal REFB1 scenario.

High resolution figure

coupled chemistry-climate models. The goal of CCMVal is to improve understanding of Chemistry-Climate Models (CCMs) and their underlying GCMs (General Circulation Models) through process-oriented evaluation, along with discussion and coordinated analysis of science results.

For the 2010 Ozone Assessment, SPARC CCMVal is preparing a Report on the Evaluation of chemistry Climate Models that will be completed in time for the assessment. This report will consist of two major parts. Part A will evaluate how well the CCMs perform in process-oriented evaluation in four major areas (radiation, dynamical, transport, and stratospheric chemistry). Part B will examine the coupled ozone-climate response to natural and anthropogenic forcing. ACD scientists have played a major role in defining model scenarios, defining diagnostics, analyzing model results, and leading sections of this report. NCAR WACCM3 has also been used in support of this effort. One example on how well the WACCM model represents the observed temperature trend is shown in Figure 1. This figure shows the historical time-series of the observations and model. Throughout the altitude range covered by the observations (100 hPa to 1 hPa), the model does an excellent job of representing the historical temperature trend. This good agreement to the historical record gives one confidence that the model will accurately represent future evolution of temperature under future climate change forcings.

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Tropospheric Ultraviolet-Visible (TUV) model

The Tropospheric Ultraviolet-Visible (TUV) model was upgraded to include several molecules including chlorine monoxide and dimethylnitrosoamine, and updates were made to the absorption cross section and quantum yield data for several other photolysis reactions. The implementation of the TUV model was also updated in the WRF-Chem model. In a collaboration by ACD (Madronich) with researchers from Colorado State U. (C. Corr, S. Kreidenweis and J. Slusser) and NASA (N. Krotkov and B. Holben), the model was used to interpret direct/diffuse ratio measurements at ultraviolet wavelengths, determined during the 2006 MIRAGE field campaign in Mexico City. The results show that aerosols have a strong and as yet unexplained absorption at these wavelengths and therefore cause a significant slowing of photochemical processes in the urban boundary layer.

The TUV model also participated in an international intercomparison of photolysis models, PhotoComp2008 under the auspices of the SPARC CCM validation activity. Results from all participating models are still being analyzed.

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Organic Chemistry of the Atmosphere

ACD scientists (Madronich, Lee-Taylor) are collaborating with U. of Paris researchers (Prof. Bernard Aumont and his group) to develop the most comprehensive chemical mechanism for the evolution of organic gases and particles (aerosol) in the atmosphere. The chemical mechanism, named Generator of Explicit Chemistry and Kinetics of Organics in the Atmosphere (GECKO-A), combines critically evaluated data bases of reactions and rate constants measured in laboratories with computer-generated values based on structure-activity relations. In the last year we have focused on simulations of measurements obtained during the 2006 ACD-led MIRAGE field campaign in Mexico City. The simulations are initialized with measured values of about 50 different hydrocarbons as well as nitrogen oxides and meteorological parameters. This initial mixture proliferated photochemically into ca. 200,000 intermediate species participating in ca. 1.2 million reactions. Two-day integration of this complex mixture resulted in simulated oxidants (esp. ozone and hydroxyl radicals) in good agreement with observations. Many of the intermediate organics were found to have low vapor pressures and therefore condensed to form secondary organic aerosols (SOA). While the predicted amounts of SOA are still lower than observed, fair agreement was found for the oxygen/carbon ratio of the particulate matter.

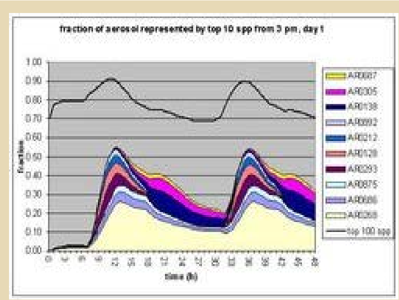

Figure 1: Fraction of aerosol mass represented by the most abundant species. Colored areas give contribution of the top 10 individual species. Solid black line gives cumulative contribution of the top 100 species. Legend shows GECKO-A chemical code names; structures for three typical molecules are given in Figure 2.

High resolution figure

The major precursors for the simulated SOA were identified as 1,2,4 trimethyl benzene and m-xylene, with only minor contributions from non-aromatic compounds (see Figure 1). This identification has important implications for regulatory strategies aimed at reducing the atmospheric amounts of SOA and therefore ameliorate the health impacts of these particles. For the first time, we also identified the major chemical constituents of the organic particles (see Figure 2), thus allowing targeting of specific chemicals for measurement by newly developed instrumentation such as proton-transfer reaction mass spectrometry (PTR-MS) or gas-chromatography coupled with mass spectrometry(GC-MS).

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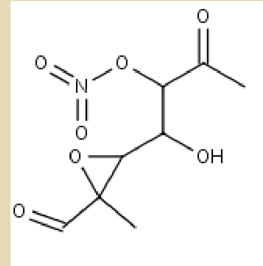
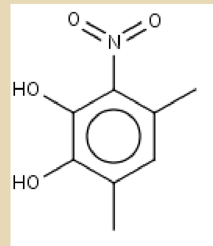
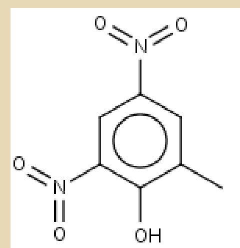


GECKO-A code name: AR0268.
2,3-epoxy-4-hydroxy-5-nitrooxy-6-oxo-heptanal.
Produced from the oxidation of m-xylene.



GECKO-A code name: AR0293.
3,5-dimethyl-6-nitro-catechol.
Produced from m-xylene.



GECKO-A code name: AR0138.
2-methyl-4,6-dinitro-cresol.
Produced from toluene oxidation.

Figure 2: Typical major organic molecular species predicted to be present in the particle phase of Mexico City.

Solar Cycle Prediction

HAO researchers have made significant contributions to the development of the Babcock-Leighton flux-transport model of the solar dynamo. In this model, buoyant loops of toroidal magnetic field rise through the convection zone, are twisted by the Coriolis force to acquire a poloidal component, and emerge at the photosphere to form bipolar magnetic regions. The emerged poloidal fields are advected to the poles by the meridional circulation in the convection zone, where they are subducted to the tachocline, and sheared by differential rotation to produce a toroidal field that is transported equatorward by the return flow at the radiative-convective interface. HAO scientists have had remarkable success in applying this basic model to the problem of simulating and predicting solar cycle amplitudes. Mausumi Dikpati (HAO), Peter Gilman (HAO), and Jeffrey Anderson (IMAGE) are currently extending this work, developing a solar cycle simulation and prediction scheme that uses sequential data assimilation to incorporate past data for surface magnetic fields and time variations in meridional circulation. The goal of this work is to be able to simulate and predict simultaneously the amplitude, duration and even the shape of each cycle.

Figure 1. A flow-diagram for sequential data-assimilation algorithm.

High resolution figure

In the very first flux-transport dynamo-based simulation and prediction

scheme (Dikpati,2004; Dikpati, deToma and Gilman, 2006; Dikpati and Gilman, 2006), a very simplified "data-nudging" technique was used to forecast the cycle amplitude only. In that calculation, the variations in cycle-length from cycle to cycle were not included; instead, all cycles were considered to be of the same length. This was done in order to avoid non-physical mismatches between the intrinsic dynamo period and the variation in cycle period contained in the surface magnetic data from past cycles used to force the model. The surface magnetic data was stretched or compressed in time so that all cycle periods in the observed data equaled the intrinsic period of the dynamo. This implied that the model could not be used for predicting future cycle periods.

Using a sequential data-assimilation technique, the model simulations will be done in a sequence of steps, with an initial meridional flow guided by surface velocity observations. At specified time intervals the simulation of the first cycle will be compared with surface magnetic observations of that cycle. The difference between the observed and simulated cycle will be used to adjust the meridional flow for the next time interval of simulation. This adjustment will be repeated in regular intervals until the cycle is complete. The whole cycle simulation will be recorded and compared to the corresponding observations. The flow chart shown in the accompanying Figure graphically depicts the sequence of steps. This process will then be repeated using slightly changed initial meridional flow, until a whole ensemble of simulations is generated. To set the time interval for the sequence of simulations it is necessary to estimate the response time of the model to a change in meridional flow. Preliminary calculations indicate this interval is about eight months. The time-interval for updating the meridional flow should be longer than this response time.

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Megacities Impacts on Regional And Global Environments / Megacity Initiative: Local and Global Research Observatories (MIRAGE/MILAGRO)

MIRAGE is an NCAR Strategic Initiative designed to improve the understanding, numerical modeling, and predictability of the chemical and physical processes that occur when urban plumes are dispersed over larger geographic regions. Future urbanization of the global atmosphere could have wide-ranging consequences for human health and cultivated and natural ecosystems, visibility degradation, weather modification, changes in radiative forcing, and tropospheric oxidation (self-cleaning) capacity.

ACD scientists continued the analysis, interpretation, and modeling of the measurements from the 2006 MIRAGE/MILAGRO field campaign in and near Mexico City. Many of these results have been published as part of a special issue of the journal *Atmospheric Chemistry and Physics*. Highlights include measurement and modeling of the chemical evolution of hydrocarbons and ozone on the urban and regional scales, assessment of the contribution of biomass burning to air quality, emissions and transport of primary aerosols, nucleation of nanoparticles, formation of secondary organic aerosols, and estimation of aerosol optical properties at ultraviolet wavelengths. Aircraft-based measurements allowed studies of the polluted outflow as the urban plume ages photochemically. Figure 1 shows measurements of ozone (O_3), carbon monoxide (CO) and benzene obtained initially near Mexico City (blue points, 18 March, G-1 aircraft), and in the same airmass a day later (red points, 19 March, C-130 aircraft). Trajectories and balloon releases indicate that the same air mass was sampled by the two aircraft. Benzene and CO have a long chemical lifetime, so their concentrations are determined by dilution of the plume with background air. On the other hand, photochemical ozone production along the plume is evident from the steeper O_3 vs. CO correlation in the more aged air. Figure 2 shows that the regional O_3 production results from the reactivity of OH with CO and oxygenated volatile organic compounds (OVOCs), in contrast to the urban O_3 production for which hydrocarbons are more important. Detection of OVOCs has only recently become possible, through the development of advanced chemical instrumentation such as ACD’s GC-MS and PTR-MS systems.

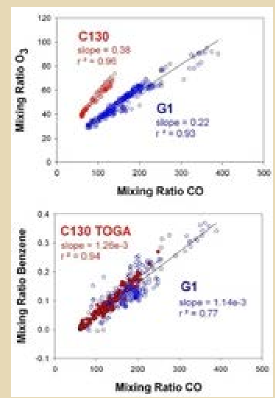

Figure 1: Correlations of ozone (O_3, top panel) and benzene (bottom panel) with carbon monoxide (CO), measured near Mexico City (blue points) on 18 March by the G-1 aircraft, and several hundred km downwind (red points) on 19 March by the C-130 aircraft. Photochemical ozone production along the plume is evident from the steeper O_3 vs. CO correlation in the more aged air.

High resolution figure

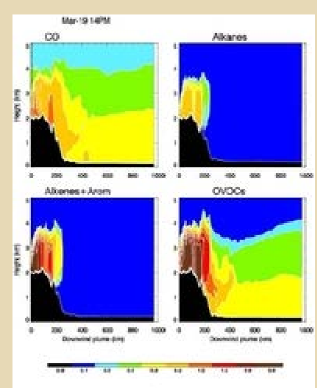

Figure 2: Contribution of carbon-containing compounds to the regional OH reactivity downwind of Mexico City, calculated with the

ACD scientists also contributed to scientific advances in another megacity: Shanghai, China. The WRF-Chem model has been ported (by X. Tie and colleagues at the Shanghai Meteorological Bureau) over the highly industrialized and heavily populated Yangtze River Delta region. Preliminary evaluation of the model is underway using measurements obtained during September 2009 at three locations (urban, remote, and industrial) in and near Shanghai. ACD researchers participated with measurements of nitrogen oxides, ozone, and hydrocarbons at the three locations, as well as capacity building via intercomparisons with measurements made by local researchers.

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WRF-Chem model. Carbon monoxide (CO) and oxygenated volatile organic compounds (OVOCs) dominate downwind, while hydrocarbons (alkanes, alkenes, and aromatics) are important in the urban atmosphere.

High resolution figure

Ocean - Atmosphere - Sea Ice – Snowpack (OASIS)

The OASIS field campaign, successfully carried out in Barrow AK from early March to mid-April, 2009, 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.

NCAR scientists were heavily involved in the planning and coordination of the gas/aerosol portion of the campaign, and successfully deployed ten instruments (or instrument suites) which formed the backbone for the gas-phase study and provided the characterization of the ambient aerosol. Gas-phase measurements were mostly made from two trailers located to the east of the Barrow Arctic Research Center site (see photos below), itself located NE of the city of Barrow. Aerosol measurements were made from an adjacent building (not shown). With the prevailing wind from the NE, this setup meant that sampling was mostly of air masses arriving at the site from the Arctic Ocean with minimal interference from local pollution.

As is detailed in Table 1 below, gas/aerosol measurements made at the site included O3, NOx, NOy, PAN, HONO, OH, H2SO4, HO2 and RO2, members of the ClOx, BrOx and Hg families, CH4, CH2O, VOCs (including oxygenates and halogenates), as well as OH reactivity, aerosol physical-chemical properties, actinic flux and a suite of meteorological measurements. The more stable species (O3, NO, NO2, PAN, Hg, CH4, CH2O and VOCs) were measured from various heights on a tower (3, 6, and 20 ft) and on a tethered balloon (150, 300 and 450 ft), so that gradients and fluxes to/from the surface could be determined for these species. Measurements of snowpack chemical, physical and optical properties were provided by groups from UC-Davis, LGGE (Grenoble, France), Villanova University and Royal Holloway, University of London.

Preliminary data from the campaign have recently been submitted to a common database, and are currently under analysis by OASIS investigators. Further coordinated and integrated analysis will result from discussions and presentations to take place at an OASIS data workshop (to be hosted by UC-Davis, Dec. 2009), as well as at a special session at the upcoming Fall AGU (San Francisco, Dec. 2009). A preliminary look at the data reveals that ozone depletion events (ODEs) were common throughout the campaign, see Figure 1, with sub-ppb ozone levels being observed in some cases.

Further analysis of the integrated data is expected to shed new light on numerous aspects of the complex boundary layer chemistry occurring in polar regions, including (but not limited to):

1. The behavior of HOx species (OH, OH reactivity, HO2 and RO2) in and out of ODEs;
2. The behavior, partitioning and impact of the ClOx and BrOx families under conditions of varying ozone;
3. An indication of the level and impact of iodine compounds on the ozone depletion chemistry;
4. A quantification of the emissions of OVOCs / halogenated VOCs from the local snowpack, and impacts of these emissions on the oxidizing capacity of the boundary layer; and
5. An improved understanding of the budget of PAN in this region of the

High resolution figure

Photos 1 and 2: Site of the OASIS field experiment, NE of the city of Barrow, AK. Photos show research trailers from which the majority of the gas-phase measurements were made. Photo on left also shows the tethered balloon (operated by Detlev Helmig and Patrick Boylan, University of Colorado), from which gradients of some species were measured.

High resolution figure

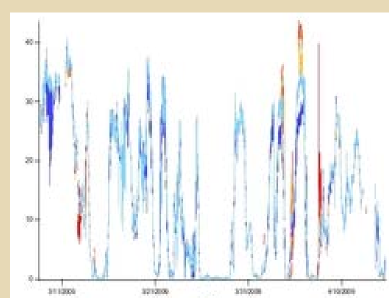

Figure 1: Preliminary O3 data (CARI group, NCAR) for the entire OASIS campaign. Blue colors indicate measurements made at various heights on the tower, red/orange colors indicate measurements made from the tethered balloon. Boundary layer structure (as indicated by different levels of O3 at tower heights compared with balloon heights) is evident, for example, on April 5 and April 7.

atmosphere.

High resolution figure

Table 1: Gas-phase and aerosol measurement techniques successfully deployed at the OASIS field site.

Instrument / Technique	**PI (NCAR unless otherwise noted)**	**Other Investigators (NCAR unless otherwise noted)**	**Compounds / Parameters Measured**
Actinic Flux	Sam Hall	Kirk Ullmann	Photolysis rates for photo-active species.
IR Laser Absorption	Alan Fried	Petter Weibring Jim Walega	Formaldehyde (CH_2O), Methane
Trace Organic Gas Analyzer (Fast GC-MS)	Eric Apel	Alan Hills, Becky Hornbrook Dan Riemer (U. Miami)	VOCs, including oxygenated and halogenated species
PAN Thermal-Decomposition CIMS	Wengang Zheng Frank Flocke		PAN [$CH_3C(O)OONO_2$] and analogs (e.g, PPN, PBN, etc.)
NO_x, NO_y, O_3 Chemiluminescence	Andy Weinheimer Frank Flocke	David Knapp, Denise Montzka, Steve Gabbard	NO, NO_2, NO_y, O_3
CIMS, OH	Lee Mauldin	Ed Kosciuch, Josh McGrath (U. Colorado)	OH, H_2SO_4, MSA
CIMS, OH Reactivity	Lee Mauldin	Ed Kosciuch, Josh McGrath (U. Colorado)	OH Reactivity
CIMS, HO_2/RO_2	Chris Cantrell	Becky Hornbrook	HO_2, RO_2 radicals
Aerosol physical and chemical properties, various instruments	Jim Smith	Steve Sjostedt, Jon Abbatt (U. Toronto)	Aerosol number concentration, size distribution, hygroscopicity, volatility, bulk composition
Cartridge samples, GC-MS analysis	Alex Guenther	Jim Greenberg Andy Turnipseed	Alkyl halides
3D anemometer	Alex Guenther	Jim Greenberg Andy Turnipseed	Turbulence, vertical wind
PTR-MS / VOC measurements	Steve Sjostedt, Jon Abbatt (U. Toronto)		Oxygenated VOCs
CIMS – inorganic	Greg Huey	Dave Tanner	BrO, HCl, Br , Cl , BrCl, HOBr

halogens	(Georgia Tech)	(Ga. Tech) Jin Liao (Ga. Tech)	2 2
Hg CVAFS instrumentation	Sandy Steffen, Jan Bottenheim, Ralf Staebler (all Environ. Canada)	Stoyka Netcheva, Patrick Lee (Both Env. Canada)	Gas-phase Hg, reactive gas-phase Hg, particulate Hg
Tethered Balloon system	Detlev Helmig	Patrick Boylan	Gradients of stable species (see text)
O_3 chemiluminescence	Detlev Helmig	Patrick Boylan	O_3 flux
Various meteorological instrumentation (e.g., Sodar, anemometers)	Ralf Staebler (Env. Canada)	J. Bottenheim, S. Netcheva, P. Lee (Env. Canada)	Various meteorological parameters, boundary layer characterization
Chemical Conversion - GC	Paul Shepson (Purdue University)	Chelsea Thompson, Adam Keil (Purdue University)	ClO, BrO
LOPAP - HONO	Jorg Kleffman, Guillermo Villena (both U. Wuppertal)	Peter Wiesen (Wuppertal)	HONO
DOAS	Udo Friess, Holger Sihler (U. Heidelberg)		BrO, NO_2

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High Resolution Dynamics Limb Sounder (HIRDLS) recovery and application

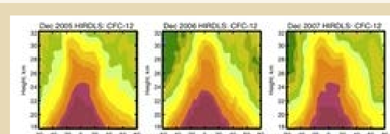

Figure 1. HIRDLS V4 monthly zonal mean cross sections of CFC12 for 3 Decembers, showing the effects of the QBO in the tropical stratosphere above 25 km. Data for September also show striking indications of

The High Resolution Dynamics Limb Sounder (HIRDLS) is a 21 channel infrared limb scanning radiometer, jointly developed by ACD, the University of Colorado, and the Physics Department of Oxford University. It is designed to make observations of temperature, ozone, water vapor and 8 other trace species, as well as PSC's, aerosols and cirrus clouds, from the upper troposphere to the mesosphere, with higher vertical resolution than has previously been available from space observations. NASA funded the U.S. share of the HIRDLS development. When HIRDLS was launched on the Aura spacecraft in July 2004, a thin plastic film from inside HIRDLS came loose and obstructed most of the instrument's aperture, limiting the view to the atmosphere to a small fraction of the width of the optical beam. As described

previously, the HIRDLS team, led by John Gille, the U.S. PI, and John Barnett (Oxford), the U.K. PI, showed that there was useful information in the signals. This required the development of 4 major adaptations and corrections to the measured signals. The first two, revising the calibration and removing the spurious oscillations (due to mechanical oscillations of the plastic), were described previously.

the Southern Hemisphere surf zones.

High resolution figure

The next steps in correcting the measured signals to make them as close as possible to the expected radiances were to finalize the amount of correction needed to account for the partial viewing area, to further refine the pointing, and to improve the estimation and removal of the signal coming from the obstruction. These, plus better cloud location and a number of smaller corrections and improvements have been incorporated in the operational processing code. The resulting version will be finalized at the beginning of the next reporting period, and used to process the entire mission. After validation, it is anticipated that these data, designated internally as v4.06.32, will be released to the community at the end of the year as Version 5 (V5). These data, like the earlier V4, include profiles of CFC 11, CFC12, (see Figure 1) and aerosol extinction, as well as temperature and ozone that have improved accuracy and fewer data spikes, while continuing the 1 km vertical resolution and ability to resolve atmospheric features with small vertical scales described previously.

A key method for determining these corrections is to have the spacecraft pitch by 5.25°, so that HIRDLS looks above the atmosphere and measures signals only from the plastic film. The initial development of these algorithms was described previously, but work continued to refine subtraction of the signal added by the plastic film. The latter continues to be the biggest difficulty at this time, and a new approach, which appears to be a significant improvement, is now in advanced development, although not yet ready for operational use.

The team contributed to the Aura mission proposal for extension beyond the nominal 5-year lifetime. This was highly successful, and resulted in extension of the mission for another 2 to 4 years, with some additional resources. The NCAR HIRDLS team hosted members of the core Oxford team for a 3-day meeting in July to review data improvements and discuss future plans.

As mentioned last year, the chopper ceased operating on 17 March 2008. Considerable effort has gone into attempting to restart the chopper, so far without success. Several more radical approaches are now being developed. In the next year the correction algorithms will be refined to allow the recovery of additional species such as water vapor and methane. Emphasis will be on improved estimation of the signal from the plastic, including allowances for the variation of the latter with time over the whole mission, and on possible improvements in the retrieval algorithm itself. In parallel, emphasis will be placed on the use of the released data for scientific studies, especially of UT/LS processes and strat-trop exchange, but broadening to many other areas.

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The Flow of Energy through the Climate System

Overview

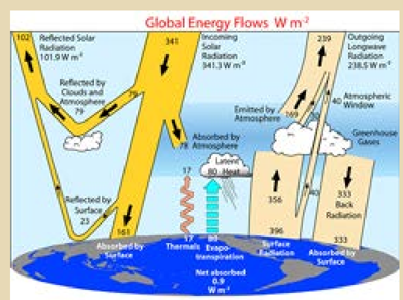

Figure Caption: From Trenberth et al. (2009) shows the estimated global mean energy flows for the 2000 to 2005 time frame.

High resolution figure

Understanding and tracking the changes in the flow of energy through the climate system as the climate changes are important for assessments of what is happening to the climate and what the prospects are in the future. The present-day climate is changing mainly in response to human-induced changes in the composition of the atmosphere as increases in greenhouse gases promote warming, while changes in aerosols can increase or diminish this warming regionally depending on the nature of the aerosols and their interactions with clouds. Human activities also contribute directly to local warming through burning of fossil fuels, thereby adding heat. Radiative forcing occurs from increases in greenhouse gases but once aerosol cooling is factored in, the total net anthropogenic radiative forcing is estimated by the Intergovernmental Panel on Climate Change (IPCC) to be about 1.6 W m^{-2}. The actual imbalance at the top-of-atmosphere (TOA) increases when water vapor and ice-albedo feedbacks are included but is reduced by negative feedbacks; by increasing temperatures, outgoing longwave radiation (OLR) is increased as partial compensation. Hence the total is estimated to be about 0.9 W m-2 owing to the other responses of the climate system (Figure). Unfortunately, these values are small enough to yet be directly measured from space, but their consequences can be seen and measured, at least in principle.

Current global analyses of the atmosphere and the ocean contain spurious variability on decadal time scales that arises from inadequacies and changes in the observing system. A holistic integrated approach that brings all information to bear can provide constraints on what is happening and where the main weaknesses are in the observing system.

Recent accomplishments

A focused activity in the Climate Analysis Section of CGD continues to update and extend previous analyses of the energy and moisture budgets in light of the new CERES (Clouds and the Earth's Radiant Energy System) top-of-atmosphere (TOA) radiation and several reanalyses, including the European Centre for Medium-Range Weather Forecasts (ECMWF)

ERA-40, ERA-interim, the Japanese 25-year Reanalysis JRA-25, and the new NASA reanalyses (MERRA). Estimates of the atmospheric energy storage and transport, and estimates of the surface energy budget have been derived using many different datasets, including all the available reanalyses. These, combined with estimates of ocean heat content from several ocean datasets have contributed to an unprecedented analysis of the flow and storage of energy in the climate system and have contributed greatly to a quantification of existing uncertainties. These observationally based estimates are being used to evaluate reanalyses and global climate models from the AR4 CMIP3 (Coupled Model Intercomparison Project) archive, and reveal problems with the archive, problems with models, and insights into climate sensitivity. For instance, climate models typically have too much downward longwave radiation which is compensated by too much evaporation and precipitation. All atmospheric and climate models have too much radiation coming into the southern oceans, owing to too few clouds, with consequences for poleward heat transports and storm tracks in the southern hemisphere that are linked to climate sensitivity.

In a series of papers, this work has examined the trends, variability, mean and annual cycle of energy flowing through the climate system, and its storage, release, and transport in the atmosphere, ocean, and land surface as estimated with recent observations using the latest datasets. The current imbalance in radiation at the top-of-atmosphere owing to human-induced increases in greenhouse gases means that the atmosphere, land and ocean are warming up, and ice is melting, leading to a rise in sea level. A discussion of our ability to track these changes with current observations and analyses reveals problems after about 2003, where a key question is "where has global warming gone?"

2009 and beyond

Research continues in examining climate models and how they equilibrate to warming and how the energy budgets change over time. Particular questions relate to what happened to energy flows and storage during the 2007-2009 La Niña and how these change in the El Niño that has begun in June 2009.

Trenberth, K. E., J. T. Fasullo, and J. Kiehl, 2009: Earth's global energy budget. Bull. Amer. Meteor. Soc., 90, No. 3, 311-324, doi: 10.1175/2008BAMS2634.1.

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Spectro-polarimetric studies of magnetic fields in the lower solar atmosphere

The Lower Solar Atmosphere (LSA) section studies the evolution of the solar magnetic field and its interactions with the plasma from its emergence through the photosphere up to the chromosphere. The magnetic flux rises from the interior due to buoyancy and becomes directly measurable at the photospheric level by means of spectro-polarimetric observations. In this layer, the dynamical state of emerging magnetic flux is dominated by convective plasma motion, and the field is forced to follow these flows. As the field moves upwards into the upper photosphere and lower chromosphere, a transition to a completely different physical regime occurs, one in which magnetic forces take over and dominate the dynamics. Understanding the implications of this transition is the main challenge of the LSA section, which is heavily driven by observations of the polarimetric signatures imprinted by magnetic fields on photospheric and chromospheric spectral lines.

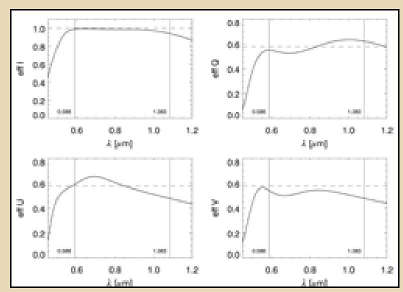

Figure: Polarization modulation efficiencies for the four Stokes parameters, I, Q, U, and V, from the design of the ProMag modulator. This modulator is based on two fast-switching FLCs and one fixed retarder. The configuration of these three optical elements was optimized to attain the highest possible efficiencies in the spectral range delimited by the two vertical lines (corresponding to the wavelengths of the two chromospheric He I lines at 587.6 and 1083.0 nm). The horizontal dashed lines show the maximum efficiencies attainable simultaneously by an optimal modulator over a modulation cycle.

High resolution figure

A significant achievement for the past year was to provide the solar community with new diagnostic tools to study the magnetism of solar prominences. This is an essential preliminary step towards the development of capabilities that are relevant for forecasting Space Weather, because of the strong correlation between prominence eruptions and coronal mass ejections. HAO has approached this challenge with a multi-faceted effort, encompassing the theoretical MHD modeling of prominence plasmas, the study of polarized line formation in magnetized media, the development of inversion tools for spectro-polarimetric observations of chromospheric spectral lines, and, finally, the design and construction of instrumentation dedicated to such spectro-polarimetric observations. The main involvement of the LSA section in this effort over the past year was in the creation of the first inversion code for scattering polarization in multiple lines, and in the successful deployment of the Prominence Magnetometer (ProMag) at the Evans Solar Facility (ESF) of the National Solar Observatory at Sacramento Peak (Sunspot, NM). The work on ProMag was particularly significant, since it involved a complete re-design of the polarimeter modulation stage to ensure that high polarization-modulation efficiencies could be attained at all wavelengths of interest for prominence observations. This has led to the development of a new paradigm for the design and optimization of polarization modulators, and to the successful construction of the first poly-chromatic modulator based on fast-switching ferro-electric liquid crystals (FLCs), with polarixation efficiencies better than 45% between 550 nm and 1.1 micron. Figure 1 shows the efficiency plots derived from the ProMag design. Preliminary calibration data at 588 nm taken at the ESF during the deployment run of August, 2009 have confirmed that the design specifications are met by the ProMag modulator.

For next year, we expect to begin regular quarterly observations of solar prominences with ProMag, and to apply our multi-line scattering polarization inversion code to those observations. LSA scientists will also be heavily involved in the definition and design of the Visible Spectro-Polarimeter (ViSP) for the Advanced Technology Solar Telescope (ATST). The expertise in the design of poly-chromatic polarization modulators, acquired during the ProMag effort, will be a valuable asset for this new instrument project, which is expected to be funded at the end of FY10.

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Analysis of Data from Hinode

During FY2009, HAO/NCAR continued its substantial involvement in the joint Japan/US/UK Hinode space mission, which entered its third year of operations as of October 2008. HAO/NCAR has been involved in this mission since its inception, and collaborated with the Lockheed Martin Solar and Astrophysics Laboratory to develop the focal plane instrumentation for this, the largest telescope to observe the Sun from Earth orbit. The ongoing NCAR involvement in Hinode was underscored at the beginning of FY2009 when HAO/NCAR hosted the Second Hinode Science Meeting at the Center Green Campus from 29 September – 3 October 2008. This highly successful meeting saw participation of over 200 scientists. HAO/NCAR has taken the lead editorship for publication of the proceedings, which will appear in print in late 2009.

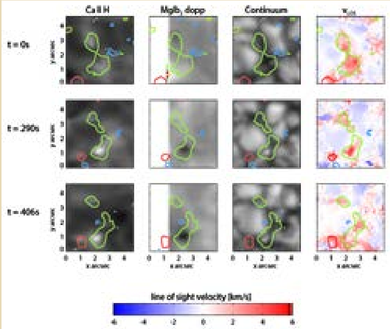

Figure 1. An example of a convective collapse event associated with downflows throughout the photosphere is shown. This figure shows only a tiny segment of the solar disk — just a few granules across — measuring 3500 km on a side. Time progresses downwards, and the columns show (from left to right) the intensity in the chromospheric Ca II H-line, the Dopplergram in the upper photospheric Mg I line, the continuum intensity (showing the pattern of solar granulation), and the photospheric line-of-sight velocity. Black corresponds to downflows in the Mg I Dopplergram, and positive (red) Doppler velocities correspond to down flows. Green (red) contours indicate the location of line-of-sight flux directed toward (away from) the observer, and blue contours indicate regions of horizontal magnetic field. Strong downflows are seen to occur first in the lower photosphere (right column), then progress to the upper photosphere (second column), at which time a brightening is revealed both in the photospheric continuum image (third column) and in the chromosphere (left column). This event, and 49 others like it, confirm the hypothesis of convective collapse as the mechanism for creation of small-scale kilogauss magnetic flux concentrations in the solar photosphere.

High resolution figure

HAO scientists continue to collaborate with colleagues from the US, Japan, and Europe for analysis and interpretation of Hinode data. This collaboration is exemplified by the work of a Ph.D student Catherine Fischer at the Utrecht University, The Netherlands as illustrated in the accompanying Figure. Several decades ago it was discovered that the Sun is able to intensify magnetic fields in the solar photosphere to strengths in excess of 1000 Gauss, and concentrate these fields into tiny, isolated "flux tubes". In 1978, E. N. Parker postulated that this concentration might proceed via a "convective collapse" process, whereby downward convecting motions in the magnetic field do not heat as rapidly as their superadiabatic surroundings, leading to an acceleration of the flow, relative evacuation of the magnetized downflow, then compression of the magnetic fields to a smaller volume. Prior to the availability of very high resolution, high precision polarimetric measurements provided by Hinode, observations only hinted at this process. Using the Spectro–Polarimeter, Narrow Band Filter, and Broadband Filter instruments on Hinode, Fischer was able to follow the evolution of 49 events that demonstrate the validity of the convective collapse phenomenon (see Figure 1). She demonstrated that the convective collapse motions persist throughout the photosphere, and are accompanied by brightening in the chromospheric layers.

Additional scientific accomplishments by HAO/NCAR scientists involving Hinode data during FY2009 include: the first measurement and successful interpretation of scattering polarization in spectral lines arising in the photosphere observed at the extreme limb of the Sun, investigation of the process of cancellation of magnetic flux at small scales in the solar photosphere, determination of the process by which the magnetic flux of an active region disperses and decays, and the details by which waves propagate in and around magnetic flux concentrations in the photosphere.

HAO/NCAR continues to provide service to the community through maintenance of the data processing pipeline for the Hinode Spectro-Polarimeter data. Data reduction procedures were developed under the NCAR Community Spectro-Polarimetric Analysis Center Strategic Initiative, and comprise routine calibration and processing of the data, as well as application of the MERLIN inversion procedure to extract measures of the magnetic field vector. During FY2009, this extensive data processing was brought up-to-date, and significant efforts continue at HAO/NCAR to maintain the high quality of these data products provided to the community.

Finally, HAO/NCAR scientists continue to participate in the development of Hinode observing programs and the execution of those programs, both for internal research and as a service to the community. HAO staff travel either to Palo Alto, California or to Japan in order to serve as a "Chief Observer" for the Solar Optical Telescope on Hinode.

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Development of a Coronal Solar Magnetism Observatory

The Sunrise balloon mission produced the highest resolution images ever taken of the Sun, including images at ultraviolet wavelengths that are not observable from the ground. These im-ages elucidate the complex physical processes taking place within the Sun that affect its radiative output and magnetic field, controlling its impact on the Earth. The gondola technology and solar pointing system developed by NCAR demonstrated that high altitude balloon missions fill a val-uable role by supplementing large ground based solar observatories and complex space missions, both costing hundreds of millions of dollars more than comparable balloon missions. Engineers and scientists in the High Altitude Observatory and the Earth Observing Laboratory, working with several international partner institutions and with the NASA Columbia Scientific Balloon Facility, collaborated on a complex development effort, test flight at Fort Sumner, New Mexico, in 2007, science flight at Kiruna, Sweden, in 2009, and recovery near Resolute Bay, Canada. Su-nrise is one of the largest balloon gondolas ever flown, supporting a 1-meter telescope with ex-tremely precise pointing requirements, and its success was a significant accomplishment for NCAR, NASA, and the international partners.

Figure 1. Engineering drawing of the HMI Instrument. Light enters through the primary lens at the lower left and is imaged on the CCD cameras (light green, upper left).

High resolution figure

The Sunrise flight was the culmination of a very challenging, complex, seven-year international collaboration that included the Max Planck Institute for Solar System Research, the Kiepenheuer Institute for Solar Physics, the Instituto de Astrofisica de Canarias, the Lockheed-Martin Solar and Astrophysics Lab, the Swedish Space Corporation, the NASA Columbia Scientific Balloon Facility, and NCAR. The engineering effort included design, construction, and flight of a 1-meter telescope, spectroscopic and photometric optical instrumentation, and a large gondola system. The programmatic and technical complexity of the effort was in many ways comparable to development of a spacecraft system, but with a much smaller budget.

The science goals of the mission are to study the solar magnetic field, to investigate photospheric and chromospheric phenomena, to resolve time dependent characteristics of magneto-convective patterns, to analyze small scale interaction of convective flows and the magnetic field, and to test the predictions of magnetohydrodynamic models. Studying these effects help answer the following questions:

1. How is the magnetic field brought to and removed from the solar surface?
2. How does the magnetic field transport energy and momentum to the outer at-mosphere?
3. What are the origin and the properties of the intermittent magnetic structure in the photosphere?
4. What is the underlying physics of the solar UV irradiance variability?
5. What is the physical nature of the solar chromosphere, and how is it heated?

The NCAR gondola system includes a support structure for the telescope, instruments, elec-tronics, and communications equipment. It supplies power, thermal protection, and, above all, provides high accuracy pointing. It consists of thousands of individual parts which when assem-bled stands 22 feet tall, weighs 3200 pounds, and produces 1300 Watts of continuous power. It is required to autonomously point approximately 4500 pounds of equipment to better than ±20 arc-seconds accuracy while operating in the upper stratosphere at 30 to 35 km altitude. The individual parts are controlled to acceptable temperature ranges while ascending through air as cold as -45°C, and then thermally stabilized while subjected to a near-vacuum environment and intense solar ultraviolet radiation. The gondola components need to survive up to ten times Earth's gravity force, generated during parachute deployment, and to protect both the telescope and the data storage system upon landing.

The pointing system consists of three pointing sensors specially designed by the NCAR team and one fine azimuth-elevation sensor supplied by NASA/GSFC. Three motorized pointing devices, consisting of coarse and fine azimuth drives and an elevation drive, steer the telescope by commands issued from an environmentally-controlled on-board computer. This computer also communicates with the ground station. The multi-threaded software is autonomous, capable of switching between multiple pointing servo loops, and runs a ground support user interface, providing quick look data while writing all the data to on-board storage media. Numerous technical innovations were required to make the system work: the NCAR-designed pointing sensors, servo control systems and complex custom software; a gondola structural design which was light yet strong enough to protect the delicate telescope and data system upon landing; a highly optimized and automated pointing control software system; lithium-ion batteries which worked flawlessly during flight, and innovative thermal insulation. Sunrise is the first balloon mission to qualify and successfully use lithium-ion batteries, and, based their success, NASA is planning to use this technology on future missions. The Prodex thermal insulation, which had never been used before on a scientific balloon, significantly simplified the installation of thermal blankets over large sur-face areas. Other innovations were improvisational, including the use of a theater lamp to test the gondola pointing systems indoors. All of these systems have advanced the technology of scientific ballooning, and will help design and conduct future balloon missions.

The NCAR team accomplished a tremendous amount engineering work leading up to the science flight in June 2009: the

gondola was rebuilt after the October 2007 test flight; 20 electronics boxes with numerous upgrades were reconfigured and tested; sensors were rebuilt and redesigned; over 50 electronics cables were re-built and tested; a new battery vendor was found and the new batteries were analyzed, tested and packaged; thermal designs were analyzed and implemented; lightweight solar arrays were procured; servos were developed and tuned, and a tremendous amount of software was written and tested in order to develop the automated pointing system. The ground testing, shipping and integration logistics were equally daunting. The team rose to the challenge, and found solutions for difficult problems. All of the international team’s mechanical and electrical components and software fit perfectly together the very first time during integration at the launch site at Esrange, near Kiruna, Sweden. The first compatibility test on the launch pad went perfectly. The launch occurred one week later, on 8 June 2009, and the science flight provided six days of high-quality solar observations. Recovery of the gondola and payload was supported in the field by EOL personnel, and although the gondola sustained significant damage on impact, it protected the telescope, instruments, and data storage, which were all recovered in excellent condition.

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Development of instrumentation for the Solar Dynamics Observatory (SDO)

The Helioseismic and Magnetic Imager (HMI) is one of the primary instruments to be flown on board NASA's Solar Dynamics Observatory spacecraft which will launch in February 2010. The HMI will record images of the Sun with 4096 by 4096 pixel detectors in wavelengths around the Fe spectrum line at 617.3 nm in various polarization states. These will allow us to construct images of the velocity and magnetic field over the entire solar surface with a spatial resolution of 1 arcsecond at a cadence of 90 seconds. The instrument development is led by researchers at Stanford University and the instrument is being constructed at Lockheed. The construction phase was completed in 2008 and the instrument is now ready for launch. Our role at HAO is to assist with the calibration of the instrument and to develop tools to convert the observations into physical parameters, such as the magnetic field strength and orientation. One challenging aspect will be to analyze the enormous volume of data in real time. We have developed a computer code called VFISV (Very Fast Inversion of the Stokes Vector) which can determine magnetic field parameters from polarization measurements significantly faster than any previous code. The code is available for use by the community through the NCAR-sponsored Community Spectro-Polarimetric Analysis Center (CSAC). (Make link to CSAC) In 2009, we incorporated this code into the HMI processing pipeline. In 2010, we will participate in the flight commissioning of the HMI instrument and in the instrument calibration. Following the six-month commissioning period, data from the instrument will be made freely available in near-real time to the international research community.

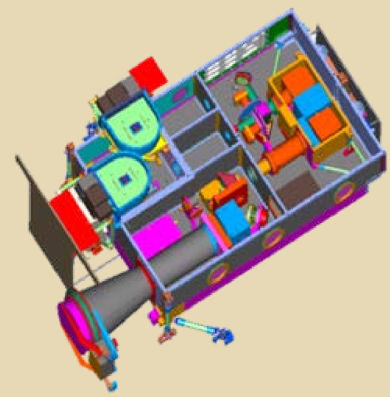

Figure 1. Engineering drawing of the HMI Instrument. Light enters through the primary lens at the lower left and is imaged on the CCD cameras (light green, upper left).

High resolution figure

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Analysis of data from TIMED and COSMIC Missions

NCAR researchers at the High Altitude Observatory continued to work with NASA, University, and International colleagues on analysis and modeling of data from two important space flight projects, the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) and the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) mission.

TIMED has tracked the response of the Earth's upper atmosphere to varying solar conditions from solar maximum in 2002 to the very long and deep solar minimum period of 2007-2009. Data from the Solar EUV Experiment (SEE) and the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument over the history of the mission are shown in Figure 1. Two spectral ranges of solar input, the soft X-ray or XUV emissions from 1 to 27 nm, and the extreme-ultraviolet or EUV range from 27 to 10^5 nm, are shown. This energy is removed by emissions from the thermosphere, primarily from CO_2 at 15 microns and from nitric oxide (NO) at 5.3 microns, as measured by SABER. CO_2 cooling responds slightly to the solar cycle, but NO cooling dramatically decreases, by almost an order of magnitude, as solar activity declines, and effect sometimes known as the "thermospheric thermostat."

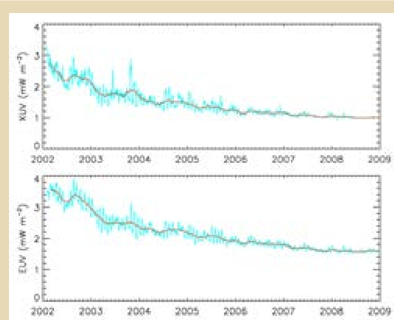

Figure 1. Solar ultraviolet measurements by the TIMED/SEE instrument integrated over the XUV (1 to 27 nm) and EUV (27 to 10^5 nm) bands.

High resolution figure

In addition to the multi-year changes, geomagnetic activity frequently

exhibits multi-day periodicity, driven by modulations in the solar wind speed and interplanetary magnetic field magnitude. Terrestrial responses to this multi-day periodicity have been observed in thermospheric neutral density, NO cooling, and ionospheric total electron content. Using a 3D upper atmospheric general circulation model, researchers at the High Altitude Observatory (Liying Qian and Stan Solomon) worked with Marty Mlynczak of NASA Langley Research Center to model this multi-day periodicity. NO cooling rates were simulated using the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM), and compared with NO cooling rates measured by the SABER instrument. Frequency analysis shows that the unusual nine-day periodicities during 2005, driven by high-speed streams in the solar wind, appear as regular features in the NO cooling rates, due to fluctuations in the NO density driven by auroral activity. The nine-day periodicities continued in 2006 but seven-day periodicities also contributed. These are both harmonics of the 27-day solar rotation period, related to the configuration of equatorial coronal holes during the descent to solar minimum.

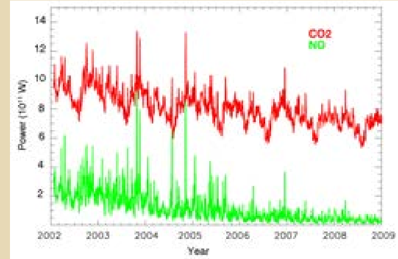

Figure 2. Thermospheric infrared emissions from CO_2 at 15 microns and NO at 5.3 microns, measured by the TIMED/SABER instrument.

High resolution figure

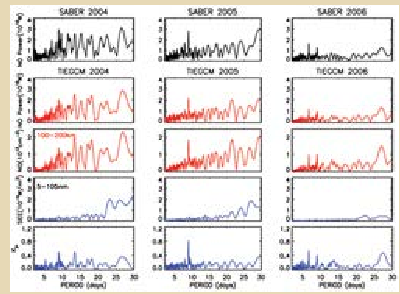

Figure 3. Periodogram (2–30 day) of TIMED/SABER measured NO cooling power, TIE-GCM simulated NO cooling power and NO column number density (100–200 km), TIMED/SEE integrated EUV flux (5–10^5 nm), and K_p index, for 2004, 2005, and 2006. TIMED/SEE measurements are used as solar input for the model while K_p index is used to parameterize geomagnetic forcing (hemispheric power and cross-tail potential). Model input: blue; Model results: red; Data: black.

High resolution figure

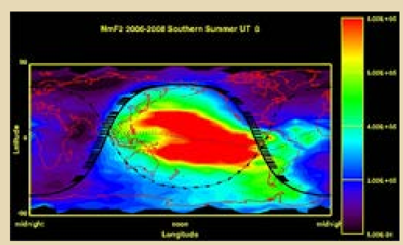

Figure 4. Global plot of N_mF_2 for 0000 UT. This plot is a median plot of N_mF_2 for the periods from October 15 to February 15 during 2006–2008. The color scale is saturated at 8 x10^5 electrons cm^{-3}. The hatched line represents the terminator, the dashed line the magnetic conjugate locations of the terminator in the other hemisphere, and the dotted line represents the magnetic equator.

High resolution figure

The COSMIC mission is best-known for its comprehensive global measurements of tropospheric parameters, but it also performs valuable measurements of the ionosphere. COSMIC observations have revealed that unusual summer conditions near Antarctica known as the Weddell Sea Anomaly (WSA) is a wide-spread feature of the mid-latitude ionosphere and has a weaker northern-hemisphere counterpart. In research submitted to the Journal of Geophysical Research, Alan Burns, Stan Solomon, Wenbin Wang and Art Richmond of the NCAR High Altitude Observatory worked with Chris Rocken and Bill Kuo of the UCAR COSMIC team, Charles Lin of National Cheng-Kung University, Taiwan, and Geonhwa Jee of the Korea Polar Research Institute to understand this phenomenon and to place it in the wider context of a general phenomenon that occurs near dusk. The WSA is a condition in the austral summer where peak electron densities in the F_2 region of the ionosphere (near 300 km altitude) are greater over the Weddell Sea at night than they are in the daytime. The terminator and the magnetically conjugate points for the terminator in the other hemisphere were plotted over global maps of COSMIC peak electron density (N_mF_2) and height of that peak (h_mF_2) for two months on either side of the December and June solstices, from 2006 to 2008. These plots showed that, in the late afternoon when the terminator and conjugate terminator are sufficiently separated in local time, there were distinct enhancements of N_mF_2 and increases in h_mF_2 as soon as the conjugate footprint of the field line on the winter terminator is seen at middle latitudes in the summer hemisphere. This effect is most pronounced where the WSA is formed, but it also occurs across the South Pacific Ocean in the southern summer, and across much of the North Atlantic Ocean, Siberia and Kamchatka during the northern summer. An h_mF_2 increase occurs between the two terminators even at locations where there is no increase in N_mF_2. A similar, but reversed, effect occurs in h_mF_2 near dawn. The N_mF_2 enhancement starts at the poleward boundary of the equatorial anomaly and occurs further from it at later local times. This behavior is inconsistent with neutral wind or downward precipitation explanations of the phenomenon, but is consistent with the behavior expected from a poleward ion drift occurring in the evening.

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Severe atmosphere convection

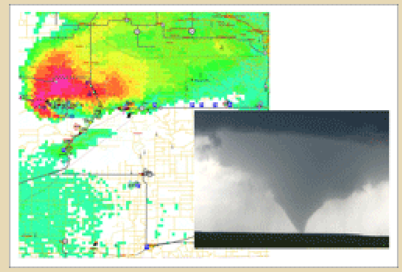

Figure: VORTEX2 deployment around the Goshen County, Wyoming tornadic supercell thunderstorm, as viewed in real time on the Situational Awareness for Severe Storm Intercept display at 2209 UTC 5 June 2009. Instrument locations, city and town names, roads, and reflectivity from the KCYS radar (shading) are shown. (image provided by Rasmussen Systems and NCAR EOL). Photo at right (provided by David Dowell) shows the Goshen County, Wyoming tornado intercepted by VORTEX2 on 5 June 2009.

High resolution image

Severe convective weather, including tornadoes, other severe winds, hail, and lightning, impacts life and property throughout the world. In the United States, severe convective weather results in over a hundred deaths every year. ESSL scientists study the processes by which thunderstorms produce severe weather with the goal of understanding and better predicting their occurrence.

ESSL scientists have been collaborating with other scientists at NCAR, NOAA, universities, and private companies in the Verification of the Origins of Rotation in Tornadoes Experiment 2 (VORTEX2). This field experiment in the US Great Plains is investigating tornadogenesis, near-ground winds in tornadoes, relationships between tornadic storms and their environments, and numerical weather prediction of supercells and tornadoes. ESSL scientists have played key roles in the planning of VORTEX2, and they went to the field 10 May - 13 June 2009 for the first year of the field experiment.

In a fully mobile mode of operations, VORTEX2 fielded approximately 40 vehicles in 2009, with instruments that included mobile radars, mobile mesonets, a deployable surface observing network, sounding systems, tornado probes, photogrammetry cameras, and disdrometers. VORTEX2 intercepted supercell thunderstorms on 9 different days during 2009. The primary 2009 case for tornadogenesis studies is the 5 June 2009 Goshen County, Wyoming tornadic storm (See Figure). The Goshen County tornado lasted approximately 30 minutes and was rated EF2, with estimated near-ground wind speeds of 130 mph. Detailed VORTEX2 data collection began 20 minutes before the tornado formed and continued throughout the life cycle of the tornado.
ESSL scientists will return to the field for the second year of the VORTEX2 field experiment 1 May - 15 June 2010. In the meantime, they are working with other VORTEX2 scientists to analyze data that were collected during the first year and to prepare for the field deployment in year two.

In addition to going to the field, ESSL scientists are supporting VORTEX2 and participating in the NOAA Hazardous Weather Testbed Spring Experiment (described elsewhere in the Lab Annual Report) through real-time high-resolution WRF numerical weather prediction. ESSL scientists produced WRF forecasts twice daily on a 3-km grid capable of producing convective storms explicitly. On many days of VORTEX2 operations, the explicit forecasts of supercell thunderstorms were accurate enough and had sufficient lead time to provide useful guidance to the mobile teams that were selecting target areas and planning instrument deployments.

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WACCM (Chemistry and dynamics of the middle atmosphere)

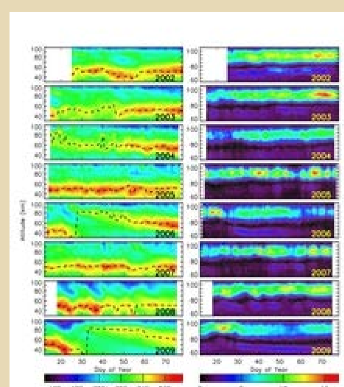

Figure 1. SABER observations for days 12-78 during the north-facing yaw period of the

Atomic oxygen is the most abundant reactive trace species in the mesosphere. Although various techniques have been developed to observe it, comprehensive measurements are still rare and have many uncertainties. For the first time, it is possible to determine the global distribution of O during both day and night. ACD scientists have used observations by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite to determine atomic oxygen mixing ratio for a multi-year period from January 2002 through September 2009. The day and night retrievals of O use different techniques and independent measurements but show excellent agreement, giving confidence to the retrieved concentrations. Even though the photochemical lifetime of O is long, this species has a large diurnal variability in the equatorial region due to transport by the vertical winds of the diurnal tide. The observations indicate a large diurnal variation in O, ranging from a factor of two to more than a factor of ten. The relative magnitude varies with season (larger near the equinoxes) and with altitude (largest near 85 km).

years 2002 to 2009, averaged over 70°-83°N. Left panels are night temperature (K) for the altitude range 30-100 km; the dashed black line gives the altitude of the stratopause. Right panels are night ozone (ppmv) for the altitude range 60-105 km.

High resolution figure

In another study, ACD scientists analyzed observations from SABER and found mesospheric ozone was significantly perturbed during the northern hemisphere winters of 2004, 2006, and 2009. SABER measures temperature and ozone through the middle atmosphere from 20 to above 100 km. The SABER measurements in NH winter (mid-January through mid-March) capture the evolution of ozone and temperature during recent unusual winters (Figure 1). It is now well documented that the altitude of the temperature maximum (stratopause) was elevated for significant periods in 2004, 2006, and 2009. SABER provides the first evidence that mesospheric ozone was also significantly perturbed in these periods. The altitudes of the ozone secondary maximum (~90-95 km), the minimum (~80 km) and the tertiary maximum (~72 km) were all lower by 3-5 km during the three anomalous winters. The ozone amount at the secondary maximum was lower. The ozone anomalies indicate enhanced downward motion and are consistent with observations of unusual profiles of trace species made by a variety of instruments.

One further study used a modified version of WACCM including parameterized polar mesospheric clouds (PMCs) to investigate long-term variability in these clouds that occur around 80 km in altitude. It is clear from observational record that PMCs exhibit long-term variability, and it is reasonable to assume that this variability is the result of changes in the background mesopause environment. Factors responsible for these changes include variations in solar irradiance over the 11-year sunspot cycle and trends in mesopause composition and temperature caused by increasing anthropogenic emissions in the troposphere. Simulations were performed with WACCM driven with observed changes in the surface composition and solar spectral irradiance. Using multiple-linear regression analysis of WACCM PMC albedos, ACD scientists calculate that in the northern hemisphere there was an increase of between 19% and 39% over the last 30 years, and that albedos can be reduced by up to 55% during solar maximum relative to solar minimum. Both responses increase with increasing latitude. In the southern hemisphere the solar response is similar to that in the northern hemisphere, but we find no long-term trend. Good agreement is found between WACCM and PMC observations made by the Solar Backscattered Ultraviolet (SBUV) satellite instrument.

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Upper atmosphere community models

HAO scientists have developed a suite of upper-atmospheric models, in collaboration with scientific visitors and scientists at universities, government labs, and other organizations. These models are made available for use by the community, typically through collaborations between HAO scientists and scientists in the community. A central model is the Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM) and simplified variants of it http://www.hao.ucar.edu/modeling/tgcm/ . The TIME-GCM simulates the three-dimensional, time-dependent global dynamics, chemistry, energetics, and electrodynamics of the mesosphere, thermosphere, and ionosphere, for given inputs representing solar, magnetospheric, and lower-atmospheric effects. Other HAO models with extensive use by the community are the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) http://www.hao.ucar.edu/modeling/amie/AMIE_head.php procedure for synthesizing high-latitude observations of ionospheric electric fields and currents, the Global-Scale Wave Model (GSWM) http://www.hao.ucar.edu/modeling/gswm/gswm.html for calculating atmospheric tides and planetary waves from the ground through the thermosphere, and the GLOW model for calculating the effects of solar ultraviolet and X-rays as well as energetic particles. These models are used to understand the processes affecting the dynamical, electrodynamical, thermodynamical, and chemical conditions in the Earth's upper atmosphere, its response to the Sun's variable radiative, particulate and magnetic emissions, and its coupling to the lower atmosphere and the magnetosphere.

The models have been continually upgraded through improvements to atmospheric tidal forcing, auroral precipitation, and coupling with magnetospheric electrodynamics. In collaboration with the University of Colorado, the Global Ionosphere Plasmasphere (GIP) model has been coupled with the TIE-GCM, to allow replacement of the TIE-GCM imposed upper boundary conditions on the ionosphere with a physical model. Model results have been provided to collaborators in the community. A documented version of the TIE-GCM, version 1.92, has been made public at http://www.hao.ucar.edu/modeling/tgcm/ . This work has been sponsored by NSF base support to NCAR, NSF Space Weather special funds, and NSF CEDAR special funds. It has also been supported by NASA and DOD programs.

For FY10, we plan to continue model upgrades, testing, and scientific analysis in collaboration with the community. Model developments will continue to be documented, and upgraded versions of the TIE-GCM source code will be made available at the http://www.hao.ucar.edu/modeling/tgcm web site. Results of scientific studies will be published. Particular foci will be testing and implementing the full electrodynamic coupling of the GIP plasmasphere model with the TIE-GCM, continuing to transfer and document process modules from the TIME-GCM to WACCM, and continuing to test and implement modules coupling the magnetosphere with the ionosphere and thermosphere.

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Space weather: Model development and data analysis

Space weather research seeks to understand and work towards predictions of the physical conditions in the geospace environment, particularly when

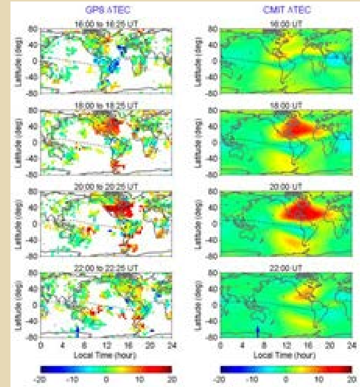

Figure 1. Global maps of GPS TEC measurements (left panel) and CMIT simulated TEC (right panels) during the progression of a geomagnetic storm on December 15, 2004.

High resolution figure

disturbed by energetic events occurring on the Sun. This is a multidisciplinary field of research which requires understanding of solar, solar wind, magnetospheric, and ionospheric physics. It covers a broad range of time scales, including solar cycle variations (years), recurrent solar wind streams (months), coronal mass ejection (CME) propagation and geomagnetic storms (days), flares and energetic particles (minutes). Understanding these phenomena is important for human spaceflight, satellite design, communication and navigation systems used by our increasingly technologically dependent society.

One highlight of this effort over the past year has been utilizing the Coupled Magnetosphere Ionosphere Thermosphere (CMIT) to study the evolution of ionosphere during magnetic storms driven by CMEs. A key aspect of any magnetic storm is how it effects the ionization level of the ionosphere and is commonly analyzed by examining GPS signals to calculate the total electron content (TEC). CMIT results for several of these storms show that the model is capable of producing the key features: 1) Enhanced TEC (positive response) at low and middle latitudes in the daytime; 2) Depleted TEC (negative response) around the geomagnetic equator in the daytime; 3) A north-south asymmetry in the positive response as the northern hemispheric response appeared to be more pronounced; and 4) Negative response at high latitudes as the storms progressed. Analysis of model results showed that storm-time enhancements in the daytime eastward electric field were the primary cause of the observed positive storm effects at low and middle latitudes as well as the negative response around the geomagnetic equator in the daytime. In addition, the CMIT model showed that high-latitude negative storm responses were related to the enhancements in molecular nitrogen seen in TIMED/GUVI observations, whereas the negative storm effects around the geomagnetic equator were not associated with thermospheric composition changes, but were rather the result of plasma transport processes.

Over the course of the next year efforts in this area will focus on conducting Sun to Earth simulation studies as well as continue our efforts to expand community utilization of the models. A particular focus of the Sun to Earth studies will be a detailed model data comparison of the Whole Heliosphere Interval (WHI) which covers an entire solar rotation during the recent solar minimum. This work will concentrate on understanding the role of recurrent high speed solar wind streams as well as the effect of low solar irradiance. Efforts for expanding community access and utilization will include deployment of CMIT and its component models at NASA's Community Coordinated Model Center. We will also continue our efforts to support the open source release of the Theremosphere-Ionosphere-Electrodynamic General Circulation Model.

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ESSL LAR 2009: IMPERATIVE III

Work with collaborators to advance world?leading numerical models of the atmosphere and Earth system, make them widely available, and support their use by the scientific community

A. Improve the Community Climate System Model (CCSM) and the Weather Research and Forecasting (WRF) model

1. Coupled carbon-nitrogen cycle modeling - CGD
2. CCSM: Development of scientific capabilities - CGD
3. CLIVAR climate process teams - CGD

- A1. Improve the Community Climate System Model (CCSM) and the Weather Research and Forecasting (WRF) model
  a. Community Atmosphere Model combined with the MOZART chemical Mechanism (CAM CHEM) - ACD
- A2. Develop and release Advanced Research WRF version 4, with improved data assimilation and microphysical and boundary-layer processes and exchanges
  a. Weather research and forecasting/Advanced research - WRF/ARW - MMM
  b. Model Physics - MMM
- A3. Continue development of WRF and CCSM variations, such as WRF-Chem, WRF-Fire, and the Whole Atmosphere Community Climate Model (WACCM)
  a. WACCM - ACD
  b. WACCM development and extension - HAO
  c. WRF-Chem - ACD/MMM

B. Develop and release new community modeling systems that incorporate new atmospheric components, offer state-of-the-art representation of a greater number of Earth system processes, and select and involve full testing of appropriate discretizations, grid refinement, and data assimilation approaches

1. MOZART - ACD

C. Continue research on data assimilation methods and parameterization, evaluate the impact of these new techniques on model performance, and continue enhancing the data assimilation capabilities of the NCAR community models

1. Parameterization - MMM
2. Data assimilation - MMM

D. Build innovative, extensible, and maintainable software design into the initial definition of Earth System Models. Determine a set of best practices for developing and modifying scientific model software, including requirement specifications, design reviews, and procedures for software testing and validation. Establish organizational incentives to follow these best practices

1. MPAS - MMM

Carbon / Nitrogen cycle modeling

Overview

ESSL scientists continued the development of and experimentation with a model of the terrestrial carbon and nitrogen cycles for use with the Community Land Model (CLM) and the Community Climate System Model

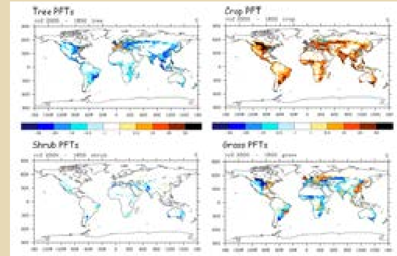

Figure caption: Historical changes in the percent coverage of tree, crop, shrub, and grass plant functional types as represented in the Community Land Model.

High resolution figure

(CCSM). A critical application of the model has been to study the influence of carbon-nitrogen cycle coupling on historical, present-day, and future climate-carbon cycle feedbacks and the role of human land uses on the climate-carbon cycle coupling. Development and evaluation of the simulated terrestrial carbon cycle and climate-carbon cycle feedbacks continues.

Recent Accomplishments

ESSL scientists implemented the carbon-nitrogen cycle model in a prototype version of CLM4 coupled to a prototype CCSM4 and evaluated the simulated carbon cycle. The simulated carbon cycle for the pre-industrial control (1850) replicates many of the features of the pre-industrial era. Preliminary transient climate simulations for the period 1850-2005 have been performed and capture key aspects of the carbon cycle during this period. These analyses reveal deficiencies in the model, and model development continues.

A key new feature in the model is the inclusion of transient land cover change and wood harvesting. The datasets to drive these changes were derived from historical analyses for the period 1850-2005 as well as datasets of future land cover change and harvesting for the period 2005-2100. Analyses of the CLM driven with these transient datasets revealed key features of the historical and future climate-carbon cycle coupling and indicate that human uses of land are an important driver of climate change.

Development of a fire module, coupling to the dynamic global vegetation model, implementation of land cover change, and a model of soil NO, N2O and N2 emissions adds to the functionality of the CLM.

2010 and Beyond

The work in FY 2010 continues to focus on the development and evaluation of the terrestrial carbon-nitrogen cycles as part of the release of CLM4 and CCSM4. The primary scientific focus beyond the CLM4/CCSM 4 release is to examine human and natural feedbacks and forcings in the earth system operating through the biogeochemical cycles.

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Community Climate System Model: Development of Scientific Capabilities

Overview

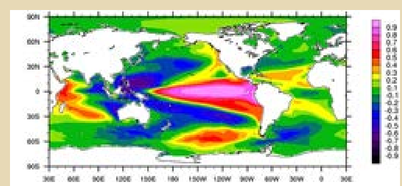

Figure Caption. The correlation of the Ni�o 3 and global sea surface temperature anomaly time series from 200 years of data from the latest version of the CCSM.

High resolution figure

The development and continuous improvement of a comprehensive climate modeling system that is at the forefront of international efforts to understand and predict the behavior of the Earth's climate is a high priority of NCAR research. This includes the Community Climate System Model (CCSM) as well as its component models. The CCSM, run on some of the world's most powerful supercomputers, simulates the many interconnected events that drive Earth's climate. These include changes in the atmosphere and oceans, the ebb and flow of sea ice, and the subtle impacts of forests and rivers.

CCSM is unique among the most comprehensive of global climate models. Primarily supported by the National Science Foundation (NSF) and the Department of Energy (DOE), with additional support from the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), it belongs to the entire community of climate scientists, rather than to a single institution. Hundreds of specialists from across the United States and overseas collaborate on improvements to CCSM. The model's underlying computer code is freely available on the Web. As a result, scientists throughout the world can use CCSM for their climate experiments.

The CCSM project was started in 1994, although climate modeling at NCAR has a much longer history, stretching back to about 1980. The first version of CCSM was unveiled in 1998, and CCSM-3 was released in 2004. In FY-10, the next version of the model will be released.

In addition to remaining at the forefront of international modeling efforts, the scientific goals of the CCSM project are as follows:

- to use the modeling system to investigate and understand the mechanisms that lead to seasonal, interannual and interdecadal variability in Earth's climate;
- to explore the history of Earth's climate through the application of versions of the CCSM suitable for paleoclimate simulations; and

- to apply this modeling system to estimate the likely future of Earth's environment in order to provide information required by governments in support of local, state, national, and international policy determination.

NCAR, in collaboration with scientific and software engineering partners from Universities and other government laboratories, has been busy developing new and improved versions of the component models, integrating those components into the next generation of the CCSM, and exploring these in a variety of ways for understanding the Earth System and climate change.

Recent Accomplishments

The core of the Community Atmosphere Model (CAM) has changed from the spectral core used in CAM-3 to a finite volume core. Major changes were also made to the deep convection scheme, and these resulted in a significant improvement in the simulation of ENSO in the CCSM. In addition, mean precipitation and double Inter-tropical Convergence Zone biases in the western tropical Pacific Ocean have been considerably reduced, but not eliminated. This version of the CAM will be used in many of the simulations in support of the Fifth Assessment Report (AR5) of IPCC. Further modifications to CAM, however, are continuing. These include changes to the radiative transfer calculation, a new cloud microphysics scheme, a modal aerosol scheme (required in order to include the indirect effects of aerosols), a new boundary layer parameterization and a new shallow convection scheme. Standalone simulations with this latest version of CAM indicate reduced biases relative to all earlier versions, but testing of the model in the fully coupled configuration has just begun.

There have also been a number of changes to the ocean component of CCSM. The near-surface eddy flux parameterization has been modified to be more in line with observations, and the isopycnal diffusivity is a function of space and time. The anisotropic horizontal viscosity scheme has been changed, and viscosity is now substantially smaller near the equator. The vertical mixing terms now have a term that is proportional to the tidal energy, and the advection scheme has been changed. A new scheme has been implemented to determine the effects of overflows over deep sills in the ocean, and a new parameterization of the effects of submesoscale eddies on the ocean mixed layer has been included. There are now 60 levels in the vertical, as opposed to 40 in CCSM 3.

The latest version of the Community Land Model (CLM) features changes to many parts of the model hydrology, such as the surface runoff, the groundwater scheme, and the frozen soil scheme. Other new features include a revised canopy integration, canopy interception scaling, and a plant functional type dependency on the soil moisture stress function. The CLM has a much improved representation of evapotransportation and the annual cycle of water storage.

The sea ice component in CCSM moved to the Community Ice Code, version 4.0 as its base code, which is maintained at the Los Alamos National Laboratory. This brought in improved treatments of ice ridging and snow on top of the ice. In addition, a much improved radiative transfer scheme and a new melt pond parameterization have been included.

In addition to these improvements to the physical components of the CCSM, a major development direction has been the addition of an interactive carbon cycle, an updated atmospheric chemistry component, a version in which the atmosphere component incorporates the whole atmosphere up to the lower mesosphere, rather than just the troposphere, and an early version of a new land ice component. The most widely used description of a model with these capabilities within the climate community is an Earth System Model, and for this reason the CCSM will be transitioning to the Community Earth System Model (CESM).

The interactive carbon cycle includes the effects of nitrogen limitation on the land carbon, land use changes due to human activity in the past, a dynamic vegetation component, and an ecosystem-biological module in the ocean component. All previous future projection runs using the CCSM have been based on future estimates of the atmospheric concentrations of carbon dioxide. However, the interactive carbon cycle in the CESM will change to using future estimates of carbon dioxide emissions, rather than concentrations. It will then determine internally how much carbon dioxide is taken up by the land and ocean, and consequently how much stays in the atmosphere. Thus, the interactive carbon cycle model will incorporate the positive feedback due to the carbon cycle, if the land and ocean take up less carbon dioxide in the future than they have in the past.

FY 2010

A major objective of the upcoming year is the release, for public web download, of standard resolution versions of the next generation CCSM and the first generation version of CESM. In addition, NCAR will make a major contribution to the Fifth Assessment Report (AR5) of IPCC through simulations performed with the latest versions of the CCSM, CESM and WACCM. Like other major international modeling centers, NCAR will follow the protocol of the CMIP5 Experimental Design. CMIP5 describes a set of coordinated climate model experiments designed to address outstanding scientific questions that arose from the last assessment report of IPCC, 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 a significant fraction of the experiments will be done in time to be included in AR5.

Under the CMIP5 strategy there are two distinct foci of the model experiments: (1) near-term, initialized decadal prediction simulations (10-30 years) with relatively high resolution climate models; and (2) long-term simulations from about 1850 through the end of the current century and beyond, using both physical climate system models such as CCSM and Earth System Models such as CESM. Experiments for both time scales are grouped into a "core" set, and then one or two "tiers" that reflect priority order.

Model development will continue as well, including the development of new components in order to address outstanding scientific challenges. For instance, one of the biggest unknowns about the future climate over the 21st century is how

much of the Greenland and Antarctic ice sheets will melt as the climate warms. This has large implications for the future sea level rise, with large consequences for the human population in low lying areas. The newly formed CCSM Land Ice Working Group will continue to develop a land ice component. The first version will be applied to the Greenland ice sheet, and will address how much ice will melt into the ocean for a given temperature rise. Subsequent versions will be more comprehensive, and include the interaction between ice shelves and the ocean. Such a model is needed to address the future behavior of the Antarctic ice sheet.

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Climate Process Teams (CPTs)

Overview

ESSL scientists remain actively involved in leadership of the Climate Variability and Predictability (CLIVAR) initiative of the World Climate Research Programme (WCRP) through membership on various national and international CLIVAR panels, as well as through research contributions to CLIVAR goals and objectives. The purpose of CLIVAR is to investigate climate variability and predictability on time-scales from months to decades, as well as the response of the climate system to anthropogenic forcing. CLIVAR, as one of the major components of the WCRP, started in 1998 with a 15-year charter, which focuses on the role of the coupled ocean and atmosphere within the overall climate system, with emphasis on variability, especially within the oceans, on seasonal to centennial time scales. CLIVAR aims to explore predictability and improve projections of climate variability and climate change using existing, reanalyzed, as well as new global observations, enhanced coupled ocean-atmosphere-land-ice models, and paleoclimate records.

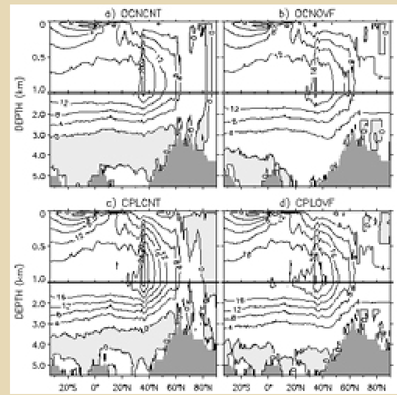

Figure Caption: Time-mean Atlantic meridional overturning circulation. The transports include the Eulerian-mean and parameterized meso-and submeso-scale contributions. OCNOVF and CPLOVF are the uncoupled and fully coupled simulations with the OVFP, respectively. OCNCNT and CPLCNT are the respective control integrations without the parameterized overflows. The positive and negative (shaded regions) contours denote clockwise and counter-clockwise circulations, respectively. The contour interval is 4 Sv. The figure clearly shows the deeper penetration of the NADW cell in OCNOVF and CPLOVF compared to those of the control cases.

High resolution figure

A major effort of the U.S. CLIVAR program has been the introduction and fostering of Climate Process Teams (CPTs). A CPT is a team of theoreticians, observationalists, process modelers, and coupled climate modelers formed around specific issues or uncertainties. CPTs aim to link process-oriented research to modeling for the purpose of addressing key uncertainties in coupled climate models. Expediting the incorporation of new parameterizations into ocean models and assessing their climate impacts are among their primary goals. Within ESSL, major ocean model developments have been proceeding under the auspices of the CPTs on both gravity current entrainment and eddy mixed layer interaction in collaboration with the external university and laboratory community. FY2009 was the final year of these projects and we focused our efforts on completing a general implementation of a new overflow parameterization (OVFP) as part of our activities on the gravity current entrainment CPT.

This new OVFP is for deep channel and continental shelf overflows and it has been successfully implemented in the NCAR CCSM4 ocean component. The parameterization represents exchanges through narrow straits and channels, associated entrainment, and subsequent injection of overflow product waters into the abyssal basins. These overflow physics have been largely absent in today's ocean general circulation models used in climate studies, because their explicit representation is prohibitively expensive, requiring fine resolutions both in the horizontal and vertical. Furthermore, the flows over stair-step topography in a level coordinate model tend to have excessive convective entrainment, resulting in deep waters that are too light and that remain too shallow. The present OVFP is based on the Marginal Sea Boundary Condition scheme of Price and Yang (1998, in Ocean Modeling and Parameterization, Kluwer Academic, 155-170). However, there are significant differences between the two. These include calculations of the overflow properties that are based on the evolving ocean model state and a new treatment of the baroclinic and barotropic momentum and continuity equations to conserve volume in the OVFP.

We have investigated the impacts of the parameterized Denmark Strait (DS) and Faroe Bank Channel (FBC) overflows on the ocean circulation and climate, considering two uncoupled and two fully coupled simulations. Each set consists of one case with the OVFP and a control integration without it. The uncoupled and coupled simulations produce stable overflow properties. In both, the DS and FBC source volume transports are within the range of observed estimates. The entrainment volume transports remain lower than observed, leading to similarly lower product volume transports in comparison with observations. Due to low entrainment, the product water properties largely reflect those of the source waters. The overflow temperature and salinity properties are in better agreement with observations in the uncoupled case than in the coupled simulation, reflecting surface flux deficiencies of the latter. The product water injection depths are in good agreement with observed.

Arguably the most significant impact of the OVFP is seen in the Atlantic Meridional Overturning Circulation (AMOC). Specifically, the North Atlantic Deep Water (NADW) penetrates much deeper to below 4000 m depth with the OVFP, eliminating a persistent shallow bias that exists in level coordinate models (see Figure). Associated with this deeper

penetration, the abyssal ventilation rates and the northward heat transport increase in the North Atlantic. The latter improves comparisons with observations. In the uncoupled simulation with the OVFP, the warm bias of the control simulation in the deep North Atlantic has been substantially reduced. There are similar, but more modest bias reductions in the deep temperature and salinity distributions especially in the northern North Atlantic in the coupled OVFP case.

The coupled simulations show the climate impacts of the OVFP through changes in the sea surface temperatures (SSTs). In particular, the SSTs are warmer by >5 degreeC off the North American coast and by >1 degreeC in the Nordic Sea with the OVFP. The surface heat flux changes mostly act to reduce these SST changes and exceed 140 W/m^2 off the North American coast. There are related changes in the sea level pressure, leading to about 15% weaker westerly wind stress in the northern North Atlantic. In response to the warmer Nordic Sea SSTs, there are reductions in the sea ice extent, improving comparisons with observations.

Along with the Labrador Sea deep convection, the DS and FBC overflow waters supply the NADW, directly affecting the AMOC. At present, there is intense interest in the AMOC and its variability, largely due to potential predictability of its variations on decadal time scales. This is based on coupled modeling studies, showing prominent decadal variability in their AMOCs. However, a proper representation of the Nordic Sea overflows is either completely absent or rather ad hoc in these models. Therefore, how these overflows impact the AMOC variability is an open question. Indeed, our preliminary simulations with CCSM4 indicate muted AMOC variability with the OVFP due to its stabilizing effects.

The OVFP is being used in all the CCSM4 simulations for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) as a standard option. In addition to the DS and FBC overflows, the Weddell and Ross Sea overflows are parameterized.

In response to a call from the NSF and NOAA, a fresh set of CPT proposals has been submitted. Many ESSL scientists are participating in all these projects as co-principal investigators. Our work on funded proposals will start in May 2010.

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Community Atmosphere Model combined with interactive chemistry (CAM-chem)

CAM is the latest in a series of global atmosphere models developed at NCAR for the weather and climate research communities. CAM also serves as the atmospheric component of the Community Climate System Model (CCSM). The continued incorporation of interactive chemistry capability in the Community Atmosphere Model (CAM) has reached a fairly stable state and now encompasses a variety of options to accommodate the needs of the coupled climate model, including a full interaction with the cloud microphysics (to represent the indirect effect, through collaboration with CGD and MMM scientist); in particular, using the implemented MOZART framework, CAM-chem can now be configured to combine prognostic and diagnostic variables. As a result, aerosols can either be prescribed, simulated using simple input oxidant fields, or simulated using the full MOZART-4 aerosol parameterization, or a combination of both; this flexibility is important to understand the specific role (radiatively and through cloud-aerosol interaction). In addition, the flexibility enabled the quick implementation of the modal (3 and 7 modes) aerosol scheme developed by S. Ghan (PNNL). This is the basis for one of the two CCSM versions which will be used in IPCC AR5.

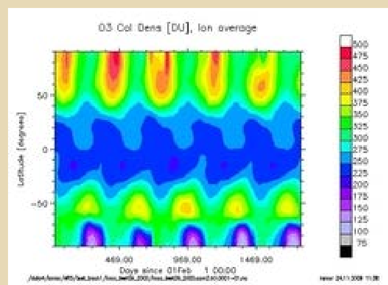

Figure 1. Time evolution of total ozone column for year 2000.

High resolution figure

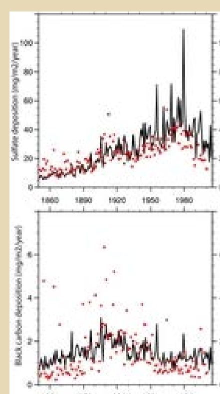

Figure 2. Sulfate (top) and black carbon(bottom) deposition from model (black line) and observations (red dots) at the D4 site in Greenland.

High resolution figure

A version of CAM-chem with a representation of stratospheric chemistry was developed as a tool to represent ozone changes in the lower stratosphere; transient simulations were performed for 1850-2005; preliminary analysis indicates a reasonable comparison of ozone trends with respect to observations and a very good representation of aerosol deposition in ice-cores (Figure 2). This version will be used in 2009 for chemistry simulations in support of IPCC AR5. It has been used for CCMVal-2 simulations and is currently being analyzed. A variety of publications will be using the results.

For extended chemistry-climate studies, a number of different options exist for simulating aerosols and chemistry to facilitate using the model in the optimal configuration. In collaboration with scientists from Lawrence Livermore National Laboratory and University of California, Irvine, we have developed a very reduced tropospheric chemistry mechanism coupled with a linearized representation of stratospheric ozone to capture ozone holes (Figure 1) in the later part of the 20th-century. This version is being tested and will be used for 20th-century simulations in CCSM in support of IPCC AR5.

FY2009 plans include continued evaluation of the model performance under the different options described above. This work is funded by NSF/NCAR, NSF Biocomplexity, and DOE.

The computation of the radiative effects of the atmospheric composition is central to efforts to understand climate. A new radiative transfer model (RRTMG), developed by AER, Inc., has been incorporated into CAM/CCSM. The interface between the atmospheric specifications in CAM and the radiative solver has significantly improved user flexibility in testing new optics and testing radiative forcing due to changes in atmospheric composition as well the extensibility for new species. Microphysical specifications in CAM have been made consistent with optical parameterizations. Collaborators from LBL, UC Berkeley, PNNL, DRI, and AER have contributed optics, solvers, and validated the new package. This work is funded by DOE/SCIDAC.

FY2010 plans include efforts to study the new radiation budget of the climate system.

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Weather Research and Forecasting / Advanced Research – WRF / ARW

The overall goal of the WRF model project has been to develop a next-generation mesoscale forecast model and data assimilation system to advance both the understanding and prediction of mesoscale weather and accelerate the transfer of research advances into operations. The WRF effort provides the primary facility for supporting the NCAR strategic priority of the investigation of the dynamics and predictability of weather systems on time scales of 0–48 h. In addition, it furthers NCAR's mission to provide and support state-of-the-art modeling systems for the research community.

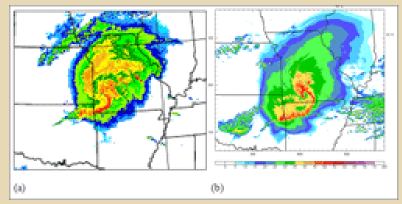

Figure: Observed and forecast radar reflectivity of a severe wind-producing derecho over southern Missouri at 1300 UTC 8 May 2009. (a) Observed composite radar reflectivity. (b) ARW reflectivity for hr 25 of forecast initialized at 1200 UTC 7 May 2009, valid 1300 8 May.

High resolution image

Within MMM, project activities cover three areas: 1) development and enhancement of WRF capabilities to meet the needs of MMM and atmospheric community research objectives; 2) research to advance the understanding and prediction of high-impact weather systems; and 3) model support to the research community. During the past year NCAR continued to develop new WRF capabilities and to support the system to the community. Over 3500 new individuals registered to download the code, bringing the total number of registered users to over 11,200. Over 60% of the total is non-US users, and 124 countries are represented. The *wrfhelp* service in MMM currently fields about 425 e-mail inquiries a month, and the number of subscribers to the *wrfnews* mailing list is over 4400.

In June 2009 MMM organized the 10th Annual WRF Users' Workshop, with over 250 participants attending. Over the past year MMM personnel also conducted four tutorials on the ARW and WRF-VAR. Two tutorials, with approximately 60 persons each, were in Boulder, while the two others were in Seoul, Korea and Cambridge, UK.

MMM manages the WRF code repository, coordinates code additions, oversees the testing and preparation for new releases, and assists community researchers in development. This past year MMM issued major release Version 3.1 (April 2009). Key features of V3.1 included: new microphysics and PBL schemes; a monotonic transport scheme; polar modifications; a multi-layer urban canopy model; and a gravity wave drag parameterization.
WRFDA is the data assimilation system contained with the WRF software that provides state-of-art 3D/4D variational (3DVAR/4DVAR) and hybrid variational/ensemble techniques. WRFDA can assimilate standard surface and upper-air observations, a wide variety of satellite observations (e.g., atmospheric motion vectors, SATEM, SATOB, SSM/I winds), COSMIC and ground-based GPS measurements, radar data, wind profiler data, and satellite radiances. In 2009 WRFDA 3.1 was released in April and WRFDA 3.1.1 in July.

MMM continued to apply the ARW in the Antarctic Mesoscale Prediction System (AMPS) for real-time NWP guidance for the United States Antarctic Program (USAP). The AMPS effort has supported the development of WF polar modifications, which better represent conditions over high latitudes and extensive ice sheets, over the years. This year saw the incorporation of these modifications into the official WRF repository and their release in V3.1.

MMM has continued to assess and enhance the accuracy of convection-permitting forecasts with the ARW. In support of the National Severe Storms Lab (NSSL) 2009 Spring Experiment and the VORTEX2 field campaign, and to test the latest improvements in the ARW, MMM ran twice-daily, convection-permitting (3-km grid) forecasts over the central US for the period 1 May–30 June 2009. This year, for the first time, the runs were initialized using first-guess fields from the 13-km Rapid Refresh (RR) system in a collaboration with NOAA ESRL. The RR forecasts used a Diabatic Digital Filter Initialization (DDFI) procedure along with 3DVAR techniques to represent convection into the initial state. Analyses suggest that this initialization procedure has produced a significant improvement in convective forecast accuracy over past exercises, especially during the first 6 h. Figure 1 shows an example, with the model realistically simulating a derecho-producing system.

Last year's goals for the ARW effort included assisting domestic and international users of the ARW, conducting the 10th WRF Users' Workshop in June 2009 and tutorials in January and July 2008, and issuing a major new release, V3.1. All of these were accomplished. In addition, the goal of making Polar WRF available to the community was achieved through the release of WRF V3.1. Plans for next year include a major release in spring 2010 (V3.2), the 11th WRF Users' Workshop, tutorials in winter and summer, and continued community support.

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Model physics

The Weather Research and Forecasting (WRF) Model is being used in an increasingly wider set of applications as computing power improves. WRF was developed as a community mesoscale model for numerical weather prediction, case study, and idealized simulations, and as a tool for related applications such as air quality research and forecasting. Some examples of newer applications that have resulted from improved computing resources are real-time cloud-resolving forecasting, including moving-nest hurricane forecasting, and nested regional climate modeling. With these applications come new priorities in physics development to enable better hurricane and regional climate modeling. These priorities fit with several of ESSL's priorities, including those of weather prediction and simulation across scales. Furthermore the aim of providing the university research community with a relevant up-to-date modeling system is met by continually updating the model to make use of the new capabilities in the current computing era, and improvements in model physics form one critical aspect of this development.

WRF already has a large set of physics options designed for its range of uses, from fast physics packages for operational uses, to more complex packages for scientific studies. The table shown summarizes the current WRF physics options available to the ARW dynamical core as of its last release (Version 3.1) in April 2009. Version 3.1 also included additional nudging capabilities for surface analysis nudging and spectral analysis nudging. Physics for polar regions was improved with a sea-ice fraction capability. Several regional climate enhancements were aimed at improving long-term simulations. For high-resolution hurricane simulations, surface fluxes were updated to newer versions.

Ongoing physics collaborations exist with NCEP, NASA Goddard, the EPA, NRL, NOAA/ESRL, RPN of Environment Canada, the Pacific Northwest National Laboratory, Lawrence Livermore National Laboratory, the University of South Florida, University of Miami, Penn State University, and YonSei University (Seoul, Korea), University of Santiago de Compostela (Spain), CIEMAT (Spain), Arizona State University, Ohio State University, AER Inc., as well as across the NCAR Divisions and Laboratories. Many of these reached fruition with more options for the WRF user community in the Version 3.1 release. Support for this work included NSF, KMA, AFWA, ARO, and the FAA.

Plans for FY10 include further collaboration with the CCSM modeling group to include some CCSM physics options and capabilities for regional climate simulations. For large-eddy simulations, a new turbulent stress scheme with backscatter is being added. There is also a triple-moment microphysics option being incorporated in preparation for Version 3.2 to be released in April 2010. Continued interaction exists with the earlier listed collaborating groups on physics improvements for WRF. New work on hurricane physics includes a MMM/DTC/NCEP collaboration on HWRF physics that is being incorporated for a release of an ocean-coupled HWRF model in 2010.

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WACCM (Whole-Atmosphere Community Climate Model) - ACD

ACD scientists used WACCM to perform a transient climate simulation to quantify the impact of geo-engineered aerosols on atmospheric processes. The impact of enhanced sulfate aerosols in the stratosphere on temperature, chemistry and dynamics was quantified. In the geo-engineering simulation, a constant stratospheric distribution of volcanic-sized, liquid sulfate aerosols was imposed in the period 2020-2050, corresponding to an injection of 2 TgS/year. The simulation shows that the aerosol cools the troposphere compared to a baseline simulation. Assuming an IPCC A1B emission scenario, global warming is delayed by about 40 years in the troposphere with respect to the baseline scenario. Large local changes of precipitation and temperatures may occur as a result of geo-engineering. Comparison with simulations carried out with the Community Atmosphere Model (CAM) indicates the importance of stratospheric processes for estimating the impact of stratospheric aerosols on the Earth's climate. Changes in stratospheric dynamics and chemistry, especially faster heterogeneous reactions, reduce the recovery of the ozone layer in mid and high latitudes for the southern hemisphere. In the geo-engineering case, the recovery of the Antarctic ozone hole is delayed by about 30 years based on this model simulation. For the Northern Hemisphere, a one- to two-fold increase of the chemical ozone depletion occurs due to a simulated stronger polar vortex and colder temperatures compared to the baseline simulation, in agreement to observational estimates.

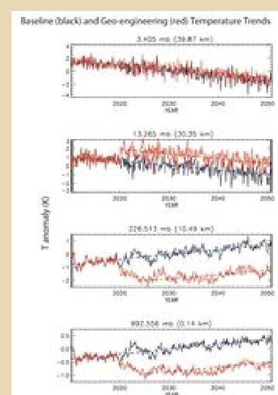

Figure 1: Temperature anomalies (between 2010 and 2050) for the geo-engineering run (red) starting in 2020, and the baseline run (black) in the Tropics (between 22°N and 22°S) for different altitudes. The reference state is the mean temperature of the baseline model simulation between 2010 and 2050.

High resolution figure

Another set of simulations used WACCM to model the transport from the Asian monsoon to the stratosphere, which was confirmed by satellite observations and model calculations. Transport of air from the troposphere to the stratosphere occurs primarily in the tropics, associated with the ascending branch of the Brewer-Dobson circulation. There are also suggestions, based on model or trajectory calculations, that during boreal

summer such transport occurs preferentially over the region of the Asian monsoon, although this has not been isolated observationally from broader-scale tropical upwelling. ACD scientist have identified for the first time that air masses are transported from the surface, through the Asian monsoon, and deep into the stratosphere, using observations derived from the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) satellite instrument and WACCM simulations. This version of WACCM is relaxed to observed meteorological fields from the Goddard Modeling and Assimilation Office (GMAO) GEOS5.1 data assimilation system. This allows model results to be compared to event driven observations. In this study, HCN has been added to the standard WACCM chemical mechanism with a chemical loss by reactions with OH (with a corresponding lifetime of 4.3 years) and with $O(^1D)$. The model also includes wet deposition through washout (which is weak as HCN is insoluble), and parameterized dry deposition over open-ocean (with a corresponding lifetime of 3 months). HCN emissions were determined by scaling CO emissions (using 0.012 HCN/CO molar ratio) for biomass burning and anthropogenic biofuel combustion.

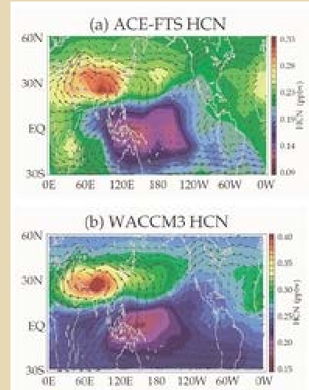

Figure 2. Time average mixing ratio (ppb) of hydrogen cyanide (HCN) near 13.5 km during boreal summer (June-August) derived from (a) ACE-FTS observations during 2004-2008, and (b) SD-WACCM chemical transport model calculations. Arrows in both panels denote winds at this level derived from meteorological analysis, showing that the HCN maximum is linked with the upper tropospheric Asian monsoon Anticyclone.

High resolution figure

Figure 2 shows latitude / longitude slice of HCN near 13.5 km during boreal summer. A key factor in this identification is that HCN has a strong sink from contact with the oceans; much of the air in the tropical upper troposphere is relatively depleted in HCN, hence broad tropical upwelling cannot be the main source in the stratosphere. This is clearly seen in Figure 2 with low HCN values shown in both model and observations over the ocean. The satellite measurements and model calculations also indicate (not shown) that the interannual variations in stratospheric HCN are linked to input from the Asian monsoon region. The monsoon circulation provides a pathway for pollution from Asia, India and Indonesia to enter the global stratosphere, with resulting impact on stratospheric ozone chemistry, aerosol and radiative balances. Ongoing changes in surface pollution and evolution of the monsoon circulation in a changing climate will likely influence chemical composition of the stratosphere (Randel et al., 2009).

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WACCM development and extension

The goal of the Whole Atmosphere Community Climate Model (WACCM) is to develop a model that extends from the Earth's surface to the upper thermosphere, and self-consistently resolve the dynamical, chemical, radiative, and electrodynamical processes and the coupling between atmospheric regions. The current standard WACCM version (WACCM3) goes to the lower thermosphere (~140 km).

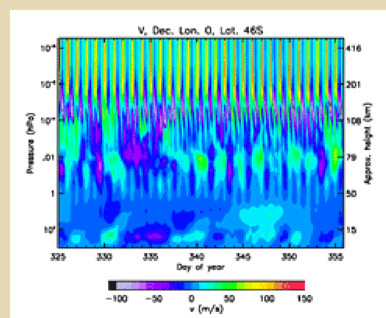

Figure: Meridional wind from the ground to the upper thermosphere from WACCM-X. At this southern mid-latitude (46S), variability associated with quasi-two-day waves, semi-diurnal tides, and diurnal tides are clearly seen in the mesosphere, lower thermosphere, and upper thermosphere, respectively. The model also produces short-term variability in tidal amplitude in the upper thermosphere.

High resolution figure

We have developed a WACCM extended (WACCM-X) to the upper thermosphere at 3.4×10^{-7} Pa (~500 km), and implemented thermospheric physics modules, including major species diffusion, the constituent-dependent specific heats, gas constant, and mean molecular weight in physics modules, and revised the treatment of the vertical diffusion equations for minor species and heat conduction equation. We have built on the WACCM-X and further tested and validated the model. The model has now been merged with WACCM 3.5 and a part of the CCSM framework. Major achievments include:

1. Full model-year runs of WACCM-X under solar maximum, medium, and minimum conditions. Monthly mean climatology of winds and temperature structures in the upper atmosphere show general agreement with empirical model (MSIS-00 and HWM) and TIME-GCM.
2. The semi-annual variation of the O/N2 ratio in the upper thermosphere is reproduced by the model, including the magnitude of the variation and its dependence on the solar flux.
3. Tides from the model are compared with TIMED/SABER and TIDI observations. The seasonal variability of the migrating diurnal tide, with maximum at March equinox and secondary maximum at September equinox, are in good agreement with observations, though the tidal amplitude from the model is weaker. We also

demonstrated that the model amplitude is in much better agreement with observations when the vertical resolution of the model is doubled.

4. The nonmigrating eastward wavenumber 3 component from the model, which is the second strongest diurnal tide in the lower thermosphere, shows excellent agreement with that derived from SABER and TIDI in both its amplitude and seasonal variability.
5. The thermospheric tides show strong short-term variability, which is likely due to penetration of the lower atmospheric perturbations and their interaction with tides.
6. Identified thermospheric temperature anomalies in the WACCM-X simulation that are similar to the midnight temperature maximum, which is probably related to high wavenumber components of tides and the terminator wave.

We are currently working on several fronts in further developing the model. These include:

1. Development of ion and electron energy modules;
2. Development of ambipolar diffusion modules;
3. Development of wind dynamo modules;
4. Development of a gravity wave parameterization scheme that addresses the interaction of inertia-gravity waves that are important for stratospheric dynamics.

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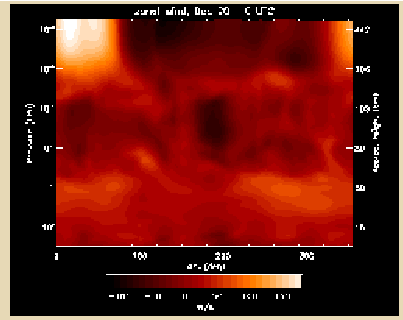

Movie: This animation shows the zonal wind from 20 to 29 December at 52N from a WACCM-X simulation. The output interval is 3 hours. From the simulation it is evident that planetary waves and migrating tides dominate below the mesosphere and in the upper thermosphere, respectively. In the mesosphere and lower thermopshere, the temporal and spatial scales are very complex with the presence of tides, planetary waves, resolved gravity waves, and probably the interaction of these waves.

High resolution figure

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/ESSL scientists. The model is used for investigation of regional-scale air quality, field program analysis, and cloud-scale interactions between clouds and chemistry. ESSL scientists and staff provide support by integrating and maintaining the chemistry components in the evolving WRF modeling system, as well as contributing new code in the development of WRF-Chem. Models such as WRF-Chem are used to further the understanding of precipitation and chemical processes, including multiscale atmospheric chemical constituent transport, dispersion and transformations. Because WRF-Chem is able to simulate the coupling between dynamics, radiation, chemistry and aerosols, science issues that depend on these interactions are one of our major objectives.

Version 3.1 of WRF-chem, released in April 2009, contains some minor updates from the NCAR/ESSL scientists. This version includes an improved photolysis rate calculation that speeds up its computation, and fixes the reading of biomass burning emissions and biogenic emissions for the MEGAN routine.

Development of new modules has been ongoing. These new modules will be included in the next version of WRF-Chem. A tracer code to track air from the stratosphere, the boundary layer, and the horizontal boundaries and can be run along with any chemistry mechanism will become part of the next released version. The chemistry mechanism from the NCAR/ACD global model MOZART will also be part of the next WRF-Chem version. Having the MOZART chemistry mechanism will allow us to contrast regional-scale and global-scale analyses of field campaigns and chemical weather using the same chemistry at both scales. A module depicting the production of nitrogen oxides from lightning at cloud resolving scales has been implemented. Aircraft emissions and diagnostic features in the model, e.g. collecting output along specified latitude-longitude tracks, are also being implemented in the next version of WRF-Chem.

In addition, we have developed tools to improve initialization of the WRF-Chem model. A utility to download the MOZART model results and use them as initial and boundary conditions for the chemical species in WRF-Chem has

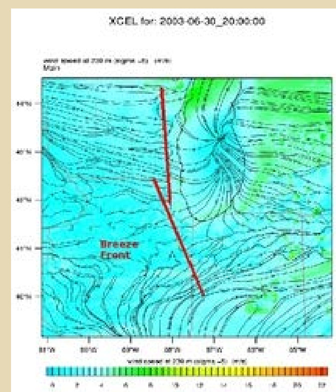

Figure 1.

High resolution figure

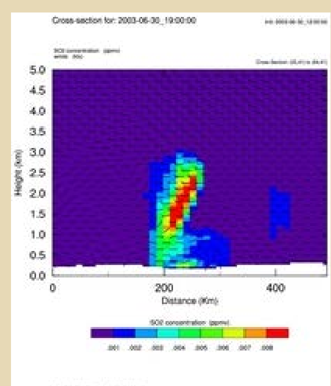

Figure 2.

High resolution figure

Figures 1 and 2: WRF-Chem model simulation for July 1, 2003. Figure 1 shows the wind vectors and possible lake breeze

been developed, and is being released to the community. Additionally, a preprocessor for the MEGAN biogenic emissions module has been developed to enable users to create input files for the module. Fire emissions, calculated with a framework described by Wiedinmyer et al. (2006) have been used in many of the WRF-Chem simulations.

The MIRAGE-Mexico City WRF-Chem simulations are undergoing extensive evaluation of the ozone and aerosol chemistry with the field campaign observations and routine air quality network data. Although the main gaseous pollutants are reasonable predicted, aerosol composition and concentrations are not well predicted with WRF-Chem. Several existing secondary organic aerosol modules are currently being tested and improved and will eventually be implemented in the WRF-Chem model. Simulations of the Shanghai region have been conducted to understand sources of ozone and to guide the September 1-21, 2009 field campaign in predicting daily ozone and ozone precursors. The Shanghai WRF-Chem simulations are being used as a pilot case for development of WRF-Chem as a chemical weather forecast tool in megacities.

A high resolution (Δx=4 km), large domain (4800x3600 km^2) WRF-Chem simulation of the 2006 North American Monsoon is being conducted to understand the role of the monsoon (thunderstorms) in affecting the composition and chemistry of the upper troposphere (UT) and to examine air quality during the summer 2006 heat wave. Preliminary evaluation of the model results shows good agreement between observed and predicted meteorological variables and major gaseous species. Convective transport of ozone precursors and lightning-generated nitrogen oxides are seen to contribute to ozone in the UT. Additional simulations of thunderstorms and chemistry are being done in preparation for the Deep Convective Clouds and Chemistry field experiment.

As part of the ARCTAS-Carb field campaign analysis, WRF-Chem simulations together with the global chemistry transport model, MOZART, are being conducted to understand the contributions to ozone from long-range transport, wildfires, and emissions from vegetation. WRF-Chem simulations are also being conducted as part of the BEACHON project to investigate connections between emissions from vegetation, aerosol and cloud condensation nuclei formation, and clouds and precipitation.

This work is supported by the NSF, the NCAR-MIRAGE strategic initiative funds, and NASA.

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front at 3 p.m. local time, whereas Figure 2 shows the vertical distribution of SO2 across the lake at 2 p.m. local time (cross section along 42N).

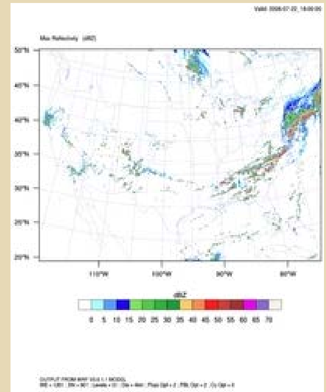

Figure 3a.

High resolution figure

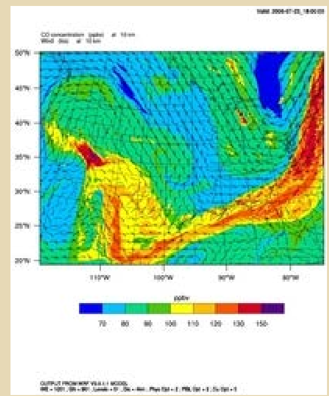

Figure 3b.

High resolution figure

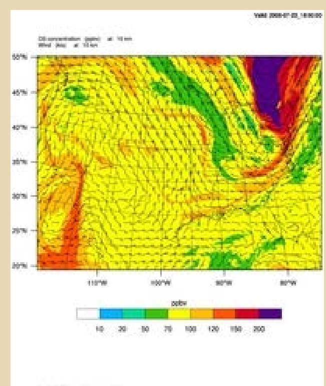

Figure 3c.

High resolution figure

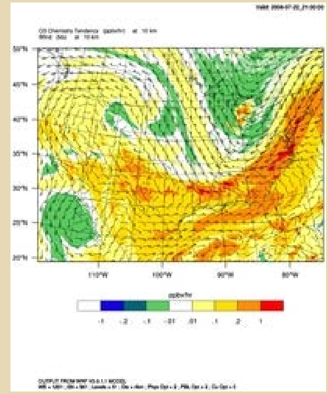

Figure 3d.

High resolution figure

Figure 3: WRF-Chem model simulation for 2100 UTC on 22 July 2006. a) The simulated radar reflectivity indicating thunderstorms along an east-west front from New Mexico to Virginia. At 10 km altitude, b) CO mixing ratios showing the effect of convective transport coincident with the storms, c) O3 mixing ratios showing somewhat higher values near the storms, and d) the change of O3 due to chemistry during the past hour indicating production rates over 1 ppbv/hour near the storms.

The Model for Ozone and Related chemical Tracers - MOZART

The Model for Ozone and Related chemical Tracers (MOZART) is a family of global offline chemical transport models. Version 2 (MOZART-2) has been available for several years to the public through the NCAR Community Data Portal and has been downloaded by 135 users.

Two new versions, MOZART-3 and MOZART-4 have been recently completed and are actively used by ACD scientists. MOZART-3 is an extension of MOZART-2 into the stratosphere, with the addition of halogen chemistry and heterogeneous processes on polar stratospheric clouds (Kinnison et al., JGR, 2007). The chemical scheme of MOZART-3 has been incorporated in the coupled chemistry-climate model WACCM. MOZART-3 chemistry is also being used in the ECMWF chemical forecasting GEMS project.

MOZART-4 has been updated over MOZART-2 to improve tropospheric chemistry simulations, with more detailed representation of hydrocarbons and tropospheric aerosols (Emmons et al., Geosci. Model Development Disc., 2009). MOZART-4 was released to the community in October 2009 and is available from the NCAR Community Data Portal. The MOZART-4 chemical scheme has been incorporated in the coupled chemistry-climate model CAM-Chem.

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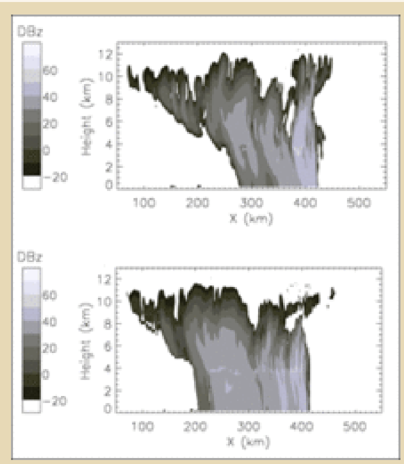
Parameterization

Representation of cloud microphysical processes in models of various complexity (from small-scale to global) remains one of the most challenging aspects of numerical weather prediction and climate modeling. This is mostly because of the disparity between scales at which cloud microphysical processes operate (millimeters and centimeters) and scales resolved by models and observations. With the advent of convection-permitting numerical weather prediction using the Weather Research and Forecasting (WRF) model and application of the superparameterization approach to climate modeling (Grabowski and Smolarkiewicz 1999; Randall et al. 2003) representation of cloud microphysics emerges as the next "key problem", similarly to the "convection parameterization problem" in the past. The superparameterization approach to climate modeling is the focus of the NSF's Science and Technology Center for Multiscale Modeling of Atmospheric Processes (CMMAP) at Colorado State University. Several NCAR scientists are part of the CMMAP team and actively involved in the CMMAP research.



MMM continued development, improvement, and application of various cloud

microphysics schemes, both bulk and bin. Further enhancements were included into the novel comprehensive two-moment bulk microphysics scheme to represent warm-rain and ice processes (Morrison and Grabowski 2007, 2008a, 2008b). A new multicomponent bin microphysics scheme was also developed to serve as a benchmark for bulk scheme (Morrison and Grabowski 2009). The bulk and bin schemes were compared in a kinematic flow model mimicking precipitating shallow cumulus. The bulk scheme has been implemented in both WRF and the Eulerian-Lagrangian cloud model (EULAG). Work is in progress to test the scheme against observations using these models for a range of case studies, including the Tropical Warm Pool - International Cloud Experiment (TWP-ICE); the latter effort is part of Grabowski and Morrison's contribution to the DOE ARM (Atmospheric Radiation Measurement) Program. A key aspect of these studies is to document sensitivity to various microphysics parameters and settings, and compare this with other model sensitivities (e.g., model dimensionality, resolution, etc.). Preliminary work suggests the importance of interactions between the ice phase and the supercooled liquid water (i.e., the growth by riming) on simulated deep convection and associated anvil clouds. Together with French colleagues a novel approach was developed to model warm-rain processes that merges techniques used in bin (spectral representation) and bulk (saturation adjustment) schemes. The new hybrid bulk-bin scheme was included into EULAG (Grabowski et al. 2009).

Figure: X-height plot of simulated radar reflectivity at t = 6 hr for an idealized 2D squall line using the one-moment microphysics scheme (top) or two-moment scheme (bottom) (Morrison et al. 2009). Note the significantly larger extension of the trailing stratiform precipitation in the two-moment scheme.

High resolution figure

Work has also continued on testing and further development of the two-moment Morrison microphysics scheme currently available in WRF (Morrison et al. 2009). The two-moment scheme was compared against a one-moment version of the same scheme to assess the impact of predicting particle number concentration. It was found that prediction of rain number concentration was important in simulating the trailing stratiform region of an idealized mid-latitude squall line (see Figure). This effort is being extended to examine the role of various rain microphysics parameters and processes (breakup, evaporation, size distribution shape) on the characteristics of organized deep convection. This effort will also compare the Morrison scheme against other bulk microphysics schemes (e.g., Thompson, Milbrandt-Yau) for dealized and detailed observationally-based case studies.

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Data assimilation / ensembles

Data assimilation is the process of combining observations and a previous forecast to provide a gridded estimate of the atmospheric state at a certain time. These estimates can then be used as initial conditions for subsequent forecasts or as tools to analyze and understand the atmosphere. While much progress has been made at global scales, data assimilation for scales of less than a few hundred kilometers (the "mesoscale," where most severe and damaging weather occurs) remains a significant open problem in atmospheric science. Mesoscale data assimilation is especially challenging for two reasons. First, mesoscale motions are intimately coupled to complex physical processes such as those involving moisture, cloud and rain or interaction with the land or ocean surface. These processes are difficult to represent accurately in numerical models. They also lead to distinct and strongly nonlinear dynamics at the mesoscale, so that balances between mass and wind, which pertain at large scales in the atmosphere and underlie global data assimilation schemes, are questionable at the mesoscale. Second, observations that are plentiful (e.g., Doppler radar measurements of wind and reflectivity) involve only a subset of atmospheric variables, while observing platforms that measure all relevant variables (i.e., radiosondes) are sparse and resolve mesoscale motions poorly. To overcome these difficulties, there has been substantial effort within ESSL/MMM to advance mesoscale data assimilation.

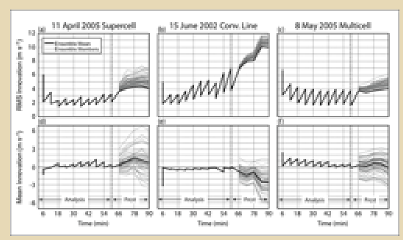

Figure: RMS (top) and spatial mean (bottom) innovations, or observation-minus-forecast differences, for radial velocity from three cases of Doppler-radar assimilation using WRF/DART. Observations are assimilated for the first 60 min, while the last 30 min are free forecasts. (Times are relative to the beginning of the assimilation experiment.) During the assimilation window, observation-minus-analysis differences are also shown. Thick black lines represent statistics computed from the ensemble mean, while individual member statistics for rms and mean innovations are also computed for the 60-90-minute forecast periods and plotted using thin gray lines.

High resolution figure

ESSL/MMM has a strong research program in the area of ensemble-based data assimilation. In collaboration with the Data Assimilation Research Section within CISL/IMAGe, an ensemble Kalman filter for WRF has been developed within the Data Assimilation Research Testbed; this assimilation system is known as WRF/DART. Figure 1 shows results from the assimilation of Doppler-radar observations with WRF/DART at 2-km resolution in three cases having distinct modes of convective organization. Ensembles of WRF forecasts (also at 2-km resolution, sufficient to capture moist convection explicitly) were preformed during the past year and results are also shown in Fig. 1. The forecasts maintain the convection and capture its evolution, though forecast errors grow on a time scale of 10's of minutes, as expected for convective-scale motions. In the coming year, the results will be extended to larger domains, in which the 2-km convection-resolving domains are nested within mesoscale domains that allow for the effects of terrain and realistic variations in the convective environment. Assimilation of surface observations is also an active area of research and will be crucial to produce accurate mesoscale initial conditions.

MMM scientists lead the development of and community support to WRFDA -- the Weather Research and Forecasting Data Assimilation system. WRFDA is an advanced data assimilation system, contained with the WRF software that provides state-of-art 3D/4D variational (3D/4D-Var) and hybrid variational/ensemble techniques. In 2009, NCAR developed the WRFDA website, http://www.mmm.ucar.edu/wrf/users/wrfda, where one can browse or download WRFDA documentation, tutorials, test data, participate in user forums, and obtain the latest code. Many new features and options have been released to the community in 2009, including 4D-Var and radiance capabilities. Also starting from 2009, WRFDA is being used to conduct research for the development of a three-dimensional cloud analysis and prediction algorithm as part of the Air Force Weather Agency Coupled Assimilation and Prediction System (ACAPS).

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Model for Prediction Across Scales (MPAS)

The Model for Prediction Across Scales (MPAS) project seeks to develop a new atmospheric forecast system that is appropriate for use in weather, climate and regional climate applications, and that has the ability to simulate a broad range of spatial and temporal scales – from clouds to global circulations. Existing NCAR-supported community atmospheric models do not run efficiently on the emerging supercomputing architectures and are in other ways unsuitable for multiscale simulation. To address these pressing needs, a nonhydrostatic variable-resolution global/regional atmospheric solver is being developed that is based an icosahedral grid in NCAR's MMM division in the MPAS effort. This is a collaborative effort with DOE sponsored Los Alamos, Sandia, and Lawrence Livermore National Labs, US universities (Univ. South Carolina and Florida State University) and Exeter University in the UK.

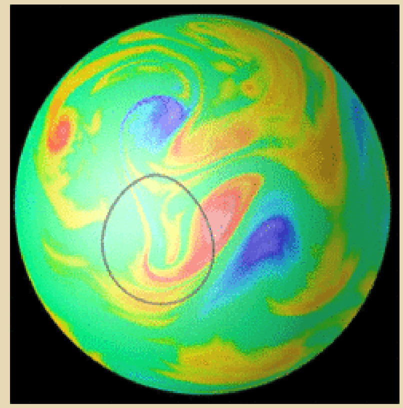

Figure: Relative vorticity at 50 days in a shallow-water model simulation of flow over a isolated hill (indicated by the black contour). Energy is conserved and enstrophy is dissipated in this turbulent-flow simulation. The refined grid region is centered on the hill and uses refinement similar to that depicted in figure 1. Image is provided courtesy of Todd Ringler, LANL.

High resolution figure

Over the past year we have developed an unstructured-grid shallow water equations model in order to test critical developments in the numerical methods used to solve fluid flow equations using these irregular icosahedral grids and also to test software engineering approaches for handling the unstructured grid and for parallelizing the solver. This new icosahedral-mesh discretization uses a C-grid approach and it solves a longstanding problem with erroneous behavior of the rotational modes for this discretization. The new scheme also has the desirable properties of exact conservation of potential vorticity and conservation of total energy to time truncation error. Figure 1 shows a solution at day 50 from the shallow-water model for flow over a large hill in the sphere. This popular test case is typically simulated for 15 days because the flow becomes turbulent shortly thereafter. The solution is from the shallow water solver that has been configured to directly dissipate enstrophy while conserving energy, as is appropriate for two dimensional turbulence and large scales in the atmosphere. This solution was also computed using a grid that is locally refined around the hill.

In this past year, a 3D icosahedral grid cloud model was constructed to test the performance of the numerical methods for cloud-scale simulation. The icosahedral-grid cloud model produced results as accurate as existing state-of-the-art rectangular-grid cloud models and proved slightly more efficient. Based on the success of these early tests, a 3-dimensional global/regional hydrostatic atmospheric solver is being developed to be followed by a 3-dimensional global/regional nonhydrostatic solver that will become the atmospheric component of the MPAS system.

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ESSL LAR 2009: IMPERATIVE IV

Develop and provide state-of-the-art supercomputing and data services that will drive the advancement of the atmospheric and related sciences

A. Curate and develop research data sets, enable information extraction, and make the data and information openly and easily available to users

1. Community Spectro-polarimetric Analysis Center (CSAC) - HAO

Development of a Coronal Solar Magnetism Observatory

The Community Spectro-Polarimetric Analysis Center (CSAC) Strategic Initiative was conceived to strengthen HAO's position in the rapidly growing spectro-polarimetry community and also to transfer its 30+ years of heritage and leadership in the field to the broader community. CSAC is providing support for a host of new instruments for measuring vector magnetic fields in a range of solar atmospheric layers.

During FY2009, the CSAC program continued intensive support of the Hinode space mission (link to Hinode section of the LAR) by providing processed data and vector magnetic field inferences to the community. Significant effort was devoted to maintenance of the Hinode data reduction procedures in order to accommodate changes in the quality of the data experienced as a result of failure of the X-band telemetry unit onboard the spacecraft. Also, the processing pipeline for Hinode data succeeded in eliminating the backlog of unprocessed data.

The VFISV inversion code that will be used to analyze data on the upcoming Solar Dynamics Observatory/Helioseismic and Magnetic imager (SDO/HMI), and the LILIA general purpose detailed inversion code have both been added to the CSAC website for download and use by the community.

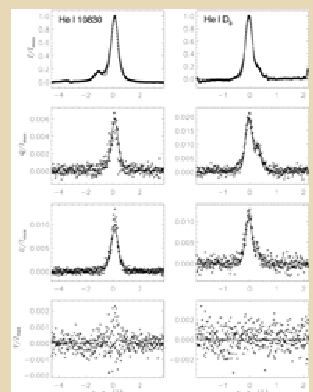

Figure 1. An example is shown of multi-line inversion of simultaneous and co-spatial spectro-polarimetric observations of He I 10830 (left) and D3 (right) using the multi-line PCA inversion code described in the text. The data used for this example was taken on June 29, 2007, in a quiescent prominence, at the French-Italian solar telescope THEMIS (Tenerife, Spain). The inverted vector magnetic field for this example is B=3.0 G, theta_B=57.8 deg, phi_B=42.7 deg, in a reference frame with the z-axis along the local solar vertical, and the x-axis pointing towards the observer. Clearly for these weak prominence fields the scattering polarization (Stokes Q, U) dominates over the mainly Zeeman effect polarization (Stokes V), underscoring the necessity of development of diagnostics including the Hanle effect on scattering polarization.

High resolution figure

The CSAC program is moving toward implementation of new techniques for analysis of polarization data to extract measures of the magnetic field vector higher in the solar atmosphere. Measurement of magnetic fields above the solar photosphere represents a major challenge to modern solar physics. To this end, a new analysis code for the simultaneous inversion of the Hanle-Zeeman polarization of multiple lines, formed under the conditions of anisotropic illumination and no polarizing collisions, has been implemented using pattern recognition techniques (Principal Components Analysis). The purpose of the code is to determine a unique set of plasma conditions that may be compatible with the observed polarization signals of multiple lines from the same atomic species. Such an approach is justified for the spectro-polarimetric study of several spectral lines that are relevant for the magnetic diagnostics of the solar chromosphere, such as the Ca II H and K lines, the Mg I b1 and b2 lines, the Na I D1 and D2 lines, and the He I D3 and 10830 multiplets. This code was used to perform a statistical analysis of the errors on the inferred magnetic field vector from the simultaneous inversion of the He I D3 and 10830 multiplets (see Figure 1), which are commonly observed in solar prominences and at the base of the corona. These are also the two multiplets that will be observed with HAO's Prominence Magnetometer (ProMag), which was deployed during FY2009 at the Evans Solar Facility of the National Solar Observatory on Sacramento Peak (Sunspot, NM). The simultaneous inversion of the two He I chromospheric lines significantly improves the inference of the magnetic field vector, thanks to the different magnetic sensitivities of the two multiplets to the Hanle effect (Casini et al. 2009, ApJ 703, 114).

In the coming year, the CSAC program will concentrate on further development of analysis techniques for inference of chromospheric vector magnetic fields, as this is widely viewed in the community as the new frontier for advancement of our understanding of magnetic phenomena in the solar atmosphere. Many new instruments are geared to simultaneous observation of multiple lines, including the ProMag and SPINOR instruments developed at HAO/NCAR, and the French-Italian telescope THEMIS. Furthermore, major new instrumentation with multi-line polarimetry is planned, including the Advanced Technology Solar Telescope (a major instrumentation development by NSF) and the possibility of a new international space mission, Solar-C, following from Hinode. During FY2009 HAO/NCAR scientists participated in a study group considering the possibility of vector magnetic field measurement in the chromosphere/corona from Solar-C.

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ESSL LAR 2009: IMPERATIVE V

Develop and provide state-of-the-art observational facilities that meet the needs of NSF, NCAR, and the atmospheric and related sciences community

A. A. Ensure that the atmospheric observing facilities required for anticipated community research remain in ready-to-deploy status and operate these systems in support of those research programs

1. Community "chemistry" instruments - ACD
2. HIRDLS - ACD
3. Measurements of Pollution in the Troposphere (MOPITT) - ACD
4. Atmospheric chemistry instrumentation - ACD

B. Complete development and begin operation of all initial instruments on the NSF/NCAR G-V high-altitude research aircraft

1. High-performance Instrumented Airborne Platform for Environmental Research (HIAPER) instrumentation - MMM

C. Enhance the Mauna Loa Solar Observatory through upgrade of existing instruments and addition of new instruments

1. Mauna Loa Solar Observatory facility - HAO
2. Development of a Coronal solar Magnetism Observatory - HAO

D. Advance observational capabilities for atmospheric chemistry research, including developing and deploying time-of-flight mass spectrometry systems for analyzing organic trace gases and aerosols

1. Time-of-flight mass spectrometers - ACD

Community "chemistry" instruments

ACD's CARI group, in collaboration with EOL staff, developed, maintains, and operates several instruments that are available to the community for use on NSF aircraft operated by NCAR. These instruments measure CO, CO_2, water vapor, Fast time resolution (5Hz) ozone (Fast-O3), and oxides of nitrogen in a 2-channel NO-NOy instrument. These instruments can be requested for any particular campaign as a part of the procedure for requesting the aircraft facility (NSF-LAOF). Both the Fast-O3 and the NO/NOy instruments are certified for flight on the NCAR/NSF GV aircraft. They can also be configured for the NCAR/NSF C-130 and other aircraft in the U.S. and European research fleet.

Figure 1. The CARI Fast-O3 and CO instrument combined in one aircraft rack, ready to be installed on the NCAR/NSF GV aircraft in support of the START-08 mission.

CARI supported five field campaigns in FY2009. Water vapor, CO, CO_2 and Fast-Ozone measurements were provided for the VOCALS campaign flown on the C-130 in late fall of 2008; CO and water vapor measurements were made during HIPPO on board the GV. Ozone, CO, CO_2, and water vapor are also provided for the PLOWS campaign (C-130). Upload for HIPPO-2 (CO measurements) is ongoing. In addition, CARI supported two ground-based measurement campaigns, OASIS, conducted in Barrow, AK between February and April, with measurements of NOx, NOy, ozone, VOCs (TOGA) and PANs, and MIRAGE-Shanghai, conducted in September, with measurements of NOx, NOy, ozone and VOCs (TOGA). All instruments worked very well and data from the campaigns is currently being processed.

FY2010 work will include data workup and submission for the missions listed above, data analysis for these projects, continued data analysis from ARCTAS and START-08 as well as post-mission calibration efforts for each instrument.

Results from START-08, ARCTAS and OASIS will be presented at the 2009 AGU Fall meeting. Instruments will be reconfigured, calibrated, and prepared for field deployments during FY2010.

This work is funded by NSF/NCAR with supplemental funding from NASA for ARCTAS and INTEX-B.

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HIRDLS Recovery and Application

The High Resolution Dynamics Limb Sounder (HIRDLS) is a 21 channel infrared limb scanning radiometer, jointly developed by ACD, the University of Colorado, and the Physics Department of Oxford University. It is designed to make observations of temperature, ozone, water vapor, and 8 other trace species, as well as PSC's, aerosols and cirrus clouds, from the upper troposphere to the mesosphere, with higher vertical resolution than has previously been available from space observations. HIRDLS was launched on the Aura spacecraft in July 2004. HIRDLS scientists have worked intensively to develop algorithms to correct for the effects of a launch-induced obstruction that limited the view to the atmosphere to a small fraction of the width of the optical beam, as discussed under Goal 5, sec. 4. Initial algorithms have produced Version 4 of the data, which provides retrievals of temperature, ozone, nitric acid, CFC 11, CFC 12, aerosol extinction plus cloud top location and types with the planned 1 km vertical resolution. These data are an improvement over the V3 data described in five published validation papers. V4 data have improved cloud detection, leading to more reliable ozone data in the upper troposphere lower stratosphere (UTLS) region of the atmosphere. In addition, the mean accuracy of the temperature and ozone data has improved. Both versions were made available to the community.

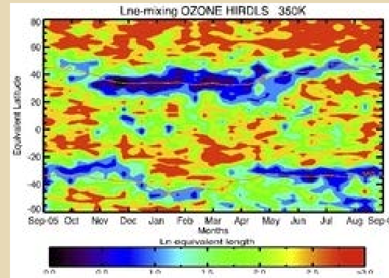

Figure 1. Logarithm of Equivalent Length (in relation to undistorted contour) as a function of equivalent latitude and time of year. Blue colors indicate low mixing, or barrier regions, while reds indicate regions of high mixing. Yellow lines are the thermal tropopause locations in both hemispheres from GMAO data. High values indicate contorted boundaries and correspondingly greater lengths over which mixing can occur.

High resolution figure

An example of an application of these data is shown in Figure 1. This illustrates that in the UTLS, in the equivalent latitude regions with a steep gradients in potential vorticity in both hemispheres, which are around the thermal tropopause, there is a strong barrier to latitudinal mixing from November until May in the northern hemisphere, i.e. during northern winter and transition seasons. A similar indication of winter barriers can be seen in the southern hemisphere. This is borne out by plots of ozone mixing ratios on equivalent latitudes as a function of time. There is very little change during the winter periods in the vicinity of the barrier. These results are in good agreement with results of Haynes and Shuckburgh (J. Geophys. Res., 2000).

The results in Figure 1 were obtained using HIRDLS ozone data and GMAO winds to calculate the Equivalent Length Le, as defined by Nakamura (J. Geophys. Res., 1996), on the 350K isentropic surface. Here the log of Le, normalized by the length of an undistorted contour, is plotted as a function of equivalent latitude and date during the year. The year is displayed from September 2005 to September 2006, so that northern winter is in the center of the plot. Blue indicates regions of low equivalent length, therefore barriers to mixing, while yellows and reds show regions of rapid mixing. The yellow line passing through the blue region shows the region of the thermal tropopause.

The plot was obtained by using HIRDLS data with a Reverse Domain Filling (RDF) code to calculate a high-resolution ozone map on potential temperature surfaces in the UTLS region for each day for 2 years. (The trajectory code was provided by Prof. Ken Bowman of Texas A&M University. It is described in Bowman (J. Geophys. Res, 1993) and Bowman and Carrie (J. Atmos. Sci., 2002). These high-resolution maps permitted the calculation of the equivalent length, as defined by Nakamura (J. Geophys. Res., 1996).

This work was supported by NASA and the NSF.

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Measurement Of Pollution In The Troposphere (MOPITT)

MOPITT Operational Production of Carbon Monoxide Data

The daily operational processing of Measurement Of Pollution In The Troposphere (MOPITT) instrument raw counts into the final retrieved geophysical products, delivery of products to NASA for free public access, and user education and support, constitutes a major service to the scientific community. MOPITT is also unique in providing the community with the longest continuous validated global CO data product, now approaching a full decade. Scientific results have been presented worldwide at numerous scientific meetings and show a documented strong presence on the Internet. MOPITT data distribution, publications, literature citations, and conference presentations all demonstrate sustained demand and wide scientific interest.

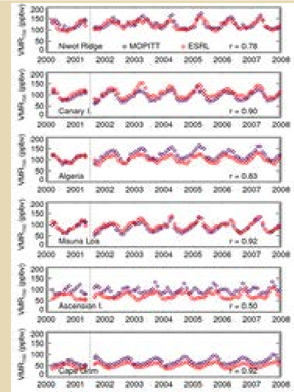

Figure 1. Timeseries comparisons of MOPITT retrieved CO VMR (700 hPa) with NOAA/ESRL surface station measurements.

High resolution figure

Activities during FY09

Algorithm Development and Product Evaluation

Products based on the new 'Version 4' retrieval algorithm were released to the public in April, 2009. Major features of the new retrieval algorithm include: (1) a new forward model with improved description of the MOPITT gas correlation cells and applicability to a wider range of CO mixing ratios; (2) a new description of the retrieval a priori surface emissivity; (3) a new seasonally and geographically variable CO retrieval a priori; and (4) the use of an assumed log-normal variability for CO volume mixing ratio. The new product also includes more extensive diagnostics, including the retrieval averaging kernels. Overall, V4 validation results indicate negligibly small retrieval biases at all levels and demonstrate significantly weaker long-term drift than was observed in the previous MOPITT V3 Product. The figure below compares V4 monthly-mean MOPITT retrieved CO volume mixing ratio at 700 hPa with in-situ measurements at six NOAA/ESRL surface-station sites: Niwot Ridge, Colorado; Tenerife, Canary Islands; Assekrem, Algeria; Mauna Loa, Hawaii; Ascension Island; and Cape Grim, Australia. Excellent correlation is indicated at all sites except Ascension Island. Low thermal contrast conditions typically result in low sensitivity to CO in the lower troposphere over oceans.

A manuscript describing the V4 retrieval algorithm and retrieval products in detail is currently under review by the Journal of Geophysical Research – Atmospheres. In support of the new V4 product, a new User's Guide was also written and posted on the MOPITT website. The MOPITT website itself was completely redesigned in FY09 for consistency with other NCAR websites and includes updated content and new tools to aid visualization (e.g., Google-Earth).

Long-term goals for the MOPITT Team include the incorporation of MOPITT's near-infrared measurements (i.e., 'solar channels') to provide additional information with respect to the CO total column measurement. The current V4 product does not exploit these measurements because of challenges in understanding and representing apparent 'geophysical noise' specific to these channels. Building on earlier efforts to use the MOPITT measurements in the near-IR (2.3 microns), the MOPITT team is now able to demonstrate the first satellite multispectral retrievals of CO which use both thermal-IR (4.6 microns) and near-IR measurements. These new MOPITT retrievals show a significant increase in the number of daytime land scenes with sensitivity to CO in the planetary boundary layer (PBL), especially near regions with large sources of CO such as urban pollution and biomass burning. When used in an inverse modeling analysis, these measurements should improve both the accuracy and horizontal scale for CO emissions estimates. A publication showing the multispectral MOPITT retrievals with initial validation is in preparation.

Data Processing

In FY09, the MOPITT Science Investigator-Led Processing System (SIPS) at NCAR transitioned to a new cluster architecture to decrease processing times and move MOPITT toward near real-time data processing and dissemination. With the new system, the time required to reprocess retrieval products for the entire mission has decreased from many months to a few weeks. These efforts also support rapid assimilation of MOPITT CO into ESSL daily MOZART forecasts and chemical weather forecasting models at other international institutions. In addition, new retrieval processing diagnostics have been developed to quickly identify potential problems in the radiance calibration, cloud detection, and retrieval algorithm modules.

Plans for FY10

Continued Operational Processing of V4

Operational processing of the MOPITT Version 4 product will continue in FY10. When and if instrument anomalies develop (such as a recent problem with a molecular sieve heater), instrument models underlying the retrieval algorithm will be revised, tested, and incorporated into the operational processing software. Quality assurance activities will continue to maintain product integrity and continuity.

Continued Analysis of Operational MOPITT Products

The MOPITT Science Team will continue to evaluate operational V4 products both in the context of traditional validation (e.g., using available in-situ data from aircraft and ground-based spectroscopic measurements) and in comparison to

models. The MOPITT Science Team will also continue to comply with requests for technical support from MOPITT users.

Version 5 Development

Development of the Version 5 product will also continue in FY10. Primary objectives for V5 development include the incorporation of MOPITT's solar channels (yielding the first multispectral satellite product for CO) and inclusion of a time-dependent forward radiative transfer model to explicitly account for observed gradual instrument changes over the full ten years (so far) of MOPITT operations. This objective is critical to the use of MOPITT products in climate analysis.

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Atmospheric chemistry instrumentation

ACD scientists are involved in ongoing efforts to develop, improve, operate, and maintain a number of instruments designed to measure trace gases, radicals, optical properties, and aerosols in the atmosphere.

Figure 1. The compact PAN-CIGARette instrument was used for fast (1-2 sec), continuous measurements of PAN and related species on the C-130 for the MIRAGE and INTEX-B programs. We are planning to deploy it during BEACHON in the summer of 2010 to measure PAN fluxes in a forested environment.

High resolution figure

CARI Instrumentation

The CARI Group maintains a number of community chemistry instruments and HIAPER Instruments and continued to improve a four channel chemiluminescence (CL) instrument for the simultaneous measurement of NO, NO_2, NOy, and Ozone with a time resolution of 1 second or better. This instrument can be configured to fly on a variety of aircraft such as the NCAR C-130, the NASA WB-57, the NASA DC-8, and others. It can be flown unattended or with an operator and was deployed successfully during the NASA led ARCTAS experiment in 2008, and in 2009 on the ground during OASIS and the MIRAGE-Shanghai experiments. CARI also maintains a compact chemical ionization mass spectrometer (PAN-CIGARette, Figure 1) which measures PAN at up to 4 Hz frequency or a number of different PAN species at 0.5-1Hz, depending on the number of ions monitored. For the long-term, CARI plans to discuss with NSF the possibility of adding this to the deployment pool instruments which are requestable for use on the NCAR/NSF aircraft. Both the four-channel CL instrument and the PAN CIGARette were successfully deployed during the OASIS field mission in the spring of 2009 in Barrow, AK. The 4-channel CL instrument was also deployed during MIRAGE-Shanghai in September of 2009. For 2010, we plan to deploy the PAN CIGARette during the BEACHON intensive at Manitou Experimental Forest to measure PAN fluxes.

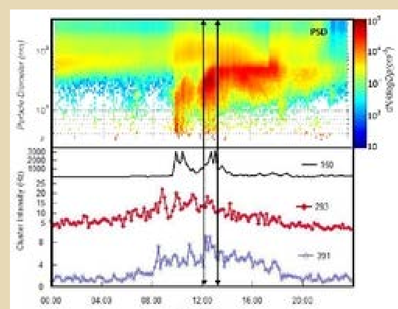

Figure 2. Particle size distribution (top) and ion concentrations from the cluster-CIMS (bottom) measured at the Manitou Experimental Forest site. Legends for lower plots refer to the sulfuric acid cluster: 160 = monomer; 293=trimer; 391=tetramer.

High resolution figure

Ultrafine Aerosols

1. During the winter 2009, ACD scientists worked with scientists from Tofwerk AG (Thun, Switzerland), Aerodyne, Inc. (Boston, MA), and J. Jimenez's research group at the University of Colorado to develop an interface between the Thermal Desorption Chemical Ionization Mass Spectrometer inlet and Tofwerk ToF mass spectrometers. This s effort culminated in a successful demonstration of a new instrument: the Time-of-Flight TDCIMS (ToF-TDCIMS). The demonstration system featured rapid spectra acquisition (up to 100 kHz), moderately high –resolution mass spectra (800 Th/Th), and high mass range (for our studies, scanning up to 800 Th). Sensitivity was ~5 times better than the quadrupole-based system. Since that time, ACD has received funds from NSF for the purchase of a high-resolution time-of-flight mass spectrometer (HToF) with a resolution even higher than the demonstration instrument. Delivery is expected in Fall 2009. The HToF-TDCIMS will usher a new era in nanoparticle composition measurements.
2. During 2009, ACD scientists completed development on the cluster chemical ionization mass spectrometer (cluster-CIMS) for measurements of atmospheric neutral clusters. The cluster-CIMS employs a highly sensitive atmospheric chemical ionization technique, combined with two neutral cluster separation methods to measure very low concentrations of clusters formed during nucleation events. Calibration of the cluster-CIMS using an electrospray coupled to a high resolution differential mobility analyzer (ES-HDMA) show that the instrument has a relative flat response for the sensitivity in a mass range of 190-400 amu, corresponding to the masses of sulfuric acid clusters containing 2-4 H_2SO_4. Recent measurements at a forested site (Figure 2) and two urban sites show that the concentrations of neutral clusters containing 3 and 4 H_2SO_4 are on the order of 104 - 105 cm-3 during relatively strong nucleation events. The concentrations of the nucleating clusters are shown to be highly correlated with SO_2 in local

Figure 3. Zenith and nadir optics and instrument rack as deployed on the NASA DC-

plumes and also the concentrations of 1-3 nm nanoparticles measured simultaneously with gas and particle instruments respectively during these events.

8 aircraft.

High resolution figure

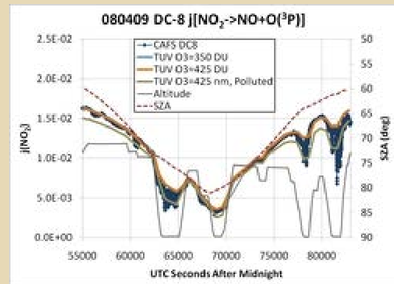

Figure 4. CAFS measured and TUV (clear sky) modeled j(NO2) during the ARCTAS deployment. The measurement/model differences are due to clouds and aerosol layers.

High resolution figure

Photochemical Oxidation and Products

In the Photochemical Oxidation and Products Group (POP), instrumentation for the measurement of HOx has been present in ACD since the late 1980s when an improved chemical amplifier was developed and deployed during MLOPEX II (1991-1992) (Cantrell et al., 1984; Cantrell et al., 1996). This instrument provided valuable information in this ground-based study. Follow-on studies saw further improvements. The presence of the NCAR chemical amplifier was instrumental in assessing the status of HOx measurements during the PRICE-I campaign in southern Germany. While useful, the chemical amplifier has a number of limitations. After MLOPEX II, Fred Eisele moved from the Georgia Institute of Technology bringing his mass spectrometric-based method for measurement of tropospheric OH and sulfuric acid (H2SO4) (Eisele et al., 1996). This enhancement to the measurement capability at NCAR also offered the opportunity to develop a new technique for quantification of peroxy radicals (HO2 and RO2). In addition, through internal and external support, the previous ground-based instrumentation was improved to allow deployment aboard aircraft platforms (Mauldin et al., 2001). Improvements continue with the development of smaller, lighter single channel OH and HO2 instruments, which were deployed during the recent NASA-sponsored ARCTAS campaign (spring & summer 2008). Currently, instrumentation for deployment on the NSF Gulfstream-V aircraft is under development, and University of Colorado graduate student, Josh McGrath, is developing a new tool to measure the reactivity of OH in the ambient troposphere. In the past, mass spectrometric-based instrumentation was used to measure DMSO and DMSO2 (DMS oxidation products, Nowak et al., 2002), HNO3 (Zondlo et al., 2003), and NH3. In FY2009 the group participated in ground-based study measuring a large suite of species, including OH, H2SO4 and peroxy radicals during the spring of 2009.

Atmospheric Radiation Investigations and Measurements

The Atmospheric Radiation Investigations and Measurements (ARIM) group maintains Charged-coupled device Actinic Flux Spectroradiometers (CAFS) and Scanning Actinic Flux Spectroradiometers (SAFS) to measure up and down-welling wavelength dependent actinic flux in the UV and visible wavelengths. The measurements are based on a 2π steradian hemispherical zenith and nadir optical collectors coupled with UV enhanced fiber optic bundles to small, lightweight, monolithic CCD monochromators and double monochromator with photomultiplier tube detection, respectively. The instruments have an excellent record of performance on the NCAR HIAPER GV and C-130, the NASA DC-8, WB-57 and P-3B, the NOAA WP-3D and at numerous ground stations. The CAFS and SAFS detectors were deployed in Barrow, AK for the OASIS field study. CAFS detectors were delivered to the EOL Gulfstream-V as a part of the HIAPER Airborne Radiation Package (HARP).

The ARIM optical calibration facility is equipped with precision radiometric power supplies and multiple NIST traceable 1000W quartz tungsten halogen lamps to determine the spectral and angular response of each instrument. Secondary lamp standards are applied in the field. Mercury line calibrations are also performed to track the wavelength accuracy. This year, the ARIM group hosted a NIST standard intercomparison for the actinic flux community and provided the angular response calibration system to university collaborators for the improvement of irradiance optical collectors.

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High-performance Instrumented Airborne Platform for Environmental Research (HIAPER) instrumentation

PI: Andrew Weinheimer (UCAR/NCAR) - completed FY2008

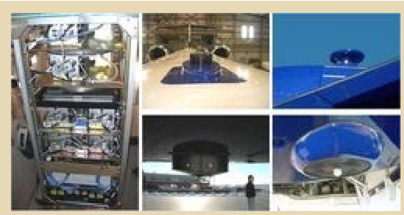

Figure 1. HARP rack installed on the NSF HIAPER GV aircraft, irradiance and actinic flux zenith and nadir optics.

NO-NOy Instrument - Two-channel instrument for the in situ measurement of NO (nitric oxide) and NOy (total reactive nitrogen).

The CARI two-channel chemiluminescence instrument is capable of 1-sec *in-situ* measurements of NO and NOy. The instrument was completed and certified for the GV early in FY2008, and was flown successfully on the NCAR/NSF GV aircraft during the START08 mission in April/May and June/July of 2008. The instrument worked very well and we collected a complete data set during the START08 mission, which will contribute to the characterization of stratosphere-troposphere exchange processes in mid-latitudes. Plans for FY2010 include a re-design of the inlet to optimize pressure control and minimize wall losses of nitric acid. This inlet design will also support the needs of the GA Tech CIMS HAIS instrument, which the CARI group expects to receive during FY2010. An option of measuring NO2 (using photolytic conversion to NO) instead of NOy is planned. A number of software changes and reprogramming are also planned to improve communication with the GV the aircraft data system.

PI: Teresa Campos (UCAR/NCAR) - completed in FY2008

***Fast Ozone Instrument* - Quantification of ozone mixing ratios at 5 Hz using the method of chemiluminescent reaction of ozone with nitric oxide.**

The Fast-Ozone instrument was completed and certified to fly on the GV in early FY2008. The instrument was then flown on the START08 mission, together with the NO/NOy instrument. Both systems used an integrated pumping system and shared the data system which was redeveloped to accommodate both instruments to save space and weight when deployed together on the GV. Laboratory tests confirmed that the time resolution of the fast-Ozone instrument is indeed 5 Hz or better. A complete data set was collected during the START08 mission and the ozone data compared extremely well with two additional ozone sensors flown during START08 and operated by NOAA. The instrument has already been requested for a number of future GV and C-130 missions.

PI: Eric Apel (UCAR/NCAR) - estimated completion: FY2010

***Trace Organic Gas Analyzer (TOGA)* - In situ measurements of oxygenated volatile organic compounds (OVOCs), non-methane hydrocarbons (NMHCs), and halocarbons.**

The Trace Organic Gas Analyzer (TOGA) will be completed in FY2010. It will have the unique capability of simultaneously measuring, with one instrument, a suite of organic compounds that play important functions in many areas of atmospheric chemistry. Several of the compounds are precursors or intermediates in atmospheric oxidation sequences. Others are indicators or tracers of different anthropogenic and biogenic processes. The compounds that TOGA will measure consist of a series of hydrocarbons, oxygenated compounds, halocarbons (including HCFCs and CFCs), and a few nitrogen and sulfur containing compounds. These species are identified in the HIAPER Advisory Committee Report as high priority. A prototype of this instrument was flown successfully on the NASA DC-8 aircraft during the ARCTAS mission in 2008. Excellent data was collected during ARCTAS including quite possibly the first accurate data of acetaldehyde in clean air masses.

PI: Rick Shetter (UCAR/NCAR) completed in FY2009

***HIAPER Atmospheric Radiation Package (HARP)* - Spectrally resolved actinic flux and stabilized platform irradiance measurements.**

Rick Shetter and the Atmospheric Radiation Investigations and Measurements (ARIM) team, in collaboration with Peter Pilewskie and Bruce Kindel of the University of Colorado, Manfred Wendisch of the Leibniz-Institute for Tropospheric Research, Rainer Schmitt of Metcon, Inc and Dieter Schell of Enviscope GmbH, Germany, developed the HIAPER Airborne Radiation Package (HARP), a comprehensive atmospheric radiation suite to measure in situ actinic flux and irradiance. The completed package was delivered to EOL in FY2009. The ARIM group will be essential to the continuing operations and science related to the HARP.

The ARIM group developed the actinic flux package by incorporating the CCD Actinic Flux Spectroradiometer (CAFS) detector. They also were responsible for designing and building the data acquisition and control hardware and software, coordinating the assembly of the aircraft racks, equipment, input optics and stabilized platforms, and leading the integration and flight management of the instrumentation. The irradiance measurements rely on horizontal stabilization to determine layer properties, such as reflectance, transmittance and absorbance. The HARP irradiance package is mounted on zenith and nadir stabilized platforms to account for aircraft attitude changes.

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Mauna Loa Solar Observatory Facility

The Mauna Loa Solar Observatory (MLSO) is a facility of the National Center for Atmospheric Research (NCAR) and operated by the High Altitude Observatory (HAO)(Figure 1). It provides observations of the Sun's atmosphere in support of the solar and space physics 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 was constructed in 1965 and is located at 11,200 feet on the northern flank of Mauna Loa on the island of Hawaii. The site was chosen for its ideal sky conditions (e.g. dark skies, low water vapor, few cloudy days) that allow observations of the corona and chromosphere, on average, about 345 days per year. The nominal observing schedule is 9 hours per day weather permitting between 1700 and 0230 UT.

Figure 1. The Mauna Loa Solar Observatory

Current Instrumentation

MLSO began operation in December 1965. HAO operates 4 instruments at MLSO:

1. MK4 K-Coronameter

2. Polarimeter for Inner Coronal Studies (PICS)
3. Chromospheric He-I Imaging Photometer (CHIP)
4. Precision Solar Photometric Telescope (PSPT)

New Instrumentation in Spring 2010

1. Coronal Multi-channel Polarimeter (CoMP)
2. New Hα telescope to replace PICS

MLSO Staff

Mauna Loa has been operating with only 2 FTEs since the retirement of Eric Yasukawa in January of 2009. HAO recently hired a third observer, Benjamin Berkey, to work with Head Observer, Darryl Koon and observer Allen Stueben. Benjamin interned at Keck Observatory and will join the MLSO team in January.

Scientific Usefulness

Ground-based observations, such as those from Mauna Loa, are cost-effective and can be maintained for decades at a very modest price. The unique observations provided by Mauna Loa significantly enhance the value of space-based missions such as Solar Dynamics Observatory (SDO), Hinode and STEREO.

CoMP: The Coronal Multi-Channel Polarimeter (CoMP) will be installed at Mauna Loa in the spring of 2010. CoMP will provide the community with exclusive, routine observations of the global coronal magnetic field (Figure 2).It records the full Stokes (I,Q,U,V) of the forbidden FeXIII lines at 1074.7 nm and 1079.8 nm and the He-I line at 1083.0 nm. CoMP can determine both the coronal magnetic field plane-of-sky (POS) direction and line-of-sight (LOS) strength. The LOS plasma motions are determined from the wings of the intensity line and the POS density is determined from the line ratios. CoMP data products have been deemed a top priority and will be served to the community as soon as possible following first light.

MK4: The MK4 furnishes unique observations of the density structure of the low corona used for studying features such as coronal mass ejections (CMEs), coronal cavities, helmet streamers, transient dimmings and polar plumes. These data are essential for determining the onset times and early dynamics of CMEs and their interaction with ambient coronal structures. The combined MK3/MK4 observations provide continual information on the density structure of the low corona over the last 3 solar cycles (Figure 3).

PSPT: The PSPT provides full Sun images of the solar photosphere and chromosphere with a relative pixel-to-pixel photometric precision of 0.1%. PSPT has contributed to significant enhancements in our understanding of the physical causes underlying solar irradiance variability (Figure 4).They have been used to identify spatial variations in the solar intensity at both global and local scales and have provided detailed quantification of the temporal variability in magnetic structure distributions over the declining phase of the solar cycle. PSPT observations support the Solar Radiation Physical Modeling at the University of Colorado LASP and provide pre-launch support for the ESA Picard mission. The PSPT has provided continuous photometric imaging observations over a whole solar cycle, which along with historical data from Mt. Wilson and Arcetri observatories yields a synoptic solar irradiance database spanning many decades, important for studying sun-climate interactions. PSPT data are provided through a joint agreement between HAO and the University of Colorado.

PICS (Hα): The wide field-of-view (FOV) of PICS, coupled with long-exposure occulted observations provide unique information on prominence dynamics in Ha from the pre-eruptive state to their eruption and propagation beyond 2 Rsun. PICS disk images are used to study filament evolution and eruption, optical flares and global (Moreton) waves (Figure 5). The PICS Halpha instrument dates back to the 1970s. It will be replaced with a new commercial Halpha telescope and detector in the spring of 2010. The new detector will provide higher spatial resolution and greater dynamic range.

HAO combines Mauna Loa observations with complimentary space-based data to provide the community with a more complete view of the solar atmosphere. Current products include combined MK4 observations with

Figure 2. CoMP image of the solar corona in the Fe XIII emissions line.

High resolution figure

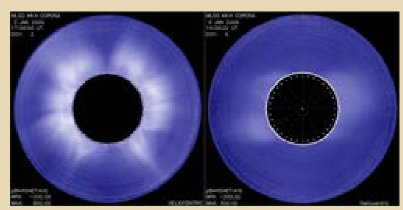

Figure 3. Mk4 images taken at solar maximum activity in year 2000 (at left) and at minimum activity in 2009 (at right).

High resolution figure

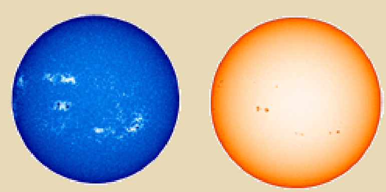

Figure 4. PSPT (Ca IIK, red,blue).

High resolution figure

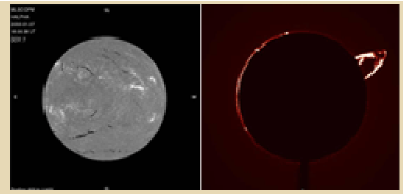

Figure 5. PICS (Hα).

High resolution figure

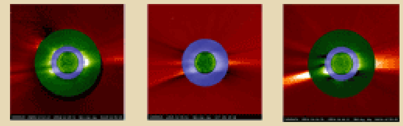

Figure 6. Combined MK4 observations with NASA STEREO and SOHO observations.

High resolution figure

NASA STEREO and SOHO observations (Figure 6). New products in 2010 will include CoMP, new Halpha and combined observations from Mauna Loa with the upcoming NASA Solar Dynamics Observatory (SDO) mission.

MLSO Data Usage

All data are provided on the MLSO web site: http://www.mlso.ucar.edu.

MLSO provides the public with the largest quantity of solar data from a single ground-based observatory and is the largest provider of observations of any HAO facility. The data are widely used, and usage has increased dramatically over the last 6 years. User statistics are provided:

- 392 registered users (106 new registered users over the past year)
- 36 U.S. and 37 intl. universities, 22 U.S. and 51 intl. labs and observatories
- 2.8 million web page hits/year
- Serves 300 GBytes / year
- 581 verified publications as of Feb 2009

Future Plans

COSMOS: The Coronal Solar Magnetism Observatory (COSMO) is the next generation NCAR facility dedicated to studying coronal and chromospheric magnetic fields and plasma conditions in order to understand the origin of solar eruptive events and to investigate long-term evolution of the Sun's magnetic field. These dynamic and evolutionary changes are ultimately driven by solar dynamo processes. COSMO consists of 3 instruments:

1. A 1.5-meter coronagraph with two detectors to routinely measure the coronal magentic field and doppler motions in coronal plasma. This instrument is the centerpiece of COSMO. CoMP is the prototype instrument for a 1.4 meter coronagraph (COSMO) to measure coronal magnetic fields at significantly better temporal and spatial scales. For more information on CoMP and COSMO see: http://cosmo.ucar.edu
2. A Chromospheric Magnetometer (ChroMag) to measure magnetic fields in the chromosphere and prominences.
3. A modern 20-cm coronagraph to study the density structure of the low corona, replacing the MK4 K-coronameter, which currently employs 1970s hardware. The new coronagraph has recently been funded through NCAR. The new instrument will have a 2D detector (replacing the 1D detector on Mk4) and will be capable of imaging the corona down to 1.05 solar radii at a temporal cadence of 15 seconds, compared with the current 3 minutes. The lower FOV is extremely important for observing the formation of CMEs and other dynamical events. The new coronagraph will be installed at the end of 2012. The coronagraph design is available at: http://www.cosmo.ucar.edu/publications/elmore_tech8r4_1-07.pdf.

Funding for the large coronagraph and ChroMag instruments is not yet available. CoMP was designed and fabricated with funds from HAO and NCAR, which is supported by the National Science Foundation (NSF).

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Development of a Coronal Solar Magnetism Observatory

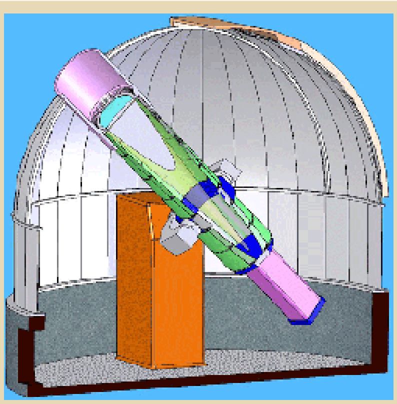

Figure 1. Concept drawing of the COSMO 1.5-meter coronagraph and dome. The telescope

Driven by society's need to understand the origins of space weather, NCAR scientists at the High Altitude Observatory, along with colleagues at the University of Hawaii and the University of Michigan, plan to build the Coronal Solar Magnetism Observatory (COSMO). 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 1.5-m coronagraph with two detector systems: a narrow-band filter polarimeter and a spectropolarimeter. Supporting instruments are a white-light coronagraph to record the evolution of the electron scattered corona (K-corona) and a chromosphere and prominence magnetometer. This new facility will replace the current NCAR Mauna Loa Solar Observatory which has been collecting synoptic coronal data for over 40 years in support of the solar and heliospheric community.

In order to demonstrate the feasibility of measuring coronal magnetic fields, prototype instruments have been developed over the past 5 years at

is a simple tube structure on an equatorial mount. The diameter of the dome is 12.2 meters.

High resolution figure

NCAR and the University of Hawaii. The Coronal Multi-channel Polarimeter (CoMP) instrument, built at NCAR/HAO, is a prototype of the COSMO coronal magnetometer. Recently, the CoMP enabled a scientific breakthrough by imaging, for the first time, Alfven waves in the solar corona. These waves were found in observations of the Doppler shift of coronal plasma in the FeXIII emission line at 1074.7 nm. These waves are important in that they may transport energy from the turbulent photosphere out into the solar corona and could explain why the solar corona is heated to a temperature of 1-2 million degrees. In 2008, we exploited the fact that the speed of propagation of these waves depends on the magnetic field of the corona. This allows us to use the wave speed measurements from CoMP to determine the strength of the magnetic field in the corona. This effort is part of an exciting new field called Coronal Seismology.

In 2010, we will move CoMP from the NSO Sacramento Peak Observatory in New Mexico to HAO's Mauna Loa Solar Observatory in Hawaii. This will allow us to obtain coronal observations under excellent sky conditions and fully exploit the scientific potential of the CoMP instrument.

Planning for COSMO has been assisted by a Scientific Advisory Panel of community members who have set the scientific requirements for the facility. Operation of the facility will continue to be guided by the Scientific Advisory Panel which will insure that the facility will continue to meet the needs of the solar and heliospheric community which it serves. The development of the CoMP instrument was supported by the NSF through the NCAR Strategic Initiative Fund and HAO base funds.

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ESSL LAR 2009: IMPERATIVE VI

Develop and transfer scientific applications, technology, and information products that address societal needs

A. Develop, test, and transfer to operational agencies state-of-the-art numerical techniques for atmospheric, climatic, and space weather modeling, and support the research community by providing repositories of tested code, tutorials, and help desks

1. WRF - MMM

Weather Research Forecasting (WRF) model

During the past year, NCAR continued to develop new capabilities for the Advanced Research WRF (ARW) and provide support for it to the community. Since last year, over 3,800 new users registered to download the code, bringing the total number of registered users to over 11,000. Over half of this total is non-U.S. users, and 131 countries are represented. There are 1,810 U.S. affiliations and over 4,350 university users.

Figure: Group photo taken outside The Centre for Mathematical Sciences (CMS) at Cambridge University.

High resolution figure

As in the past, MMM continues its support to the community by providing a number of workshops and tutorials. In June 2009 MMM organized and conducted the 10th Annual WRF Users' Workshop, with over 260 participants attending from many different countries. In addition, a WRF GRAPES Workshop, attended by 20 participants, was held in Boulder in late July 2009. The most current workshop, the Joint NCAR-NCAS WRF Workshop and Tutorial, began in FY09 and will end in FY10 (28 September 2009 thru 2 October 2009). This event was held at the Centre for Mathematical Sciences in Cambridge.

MMM personnel also conducted three other user tutorials on the ARW and WRF-VAR. Two WRF tutorials were held in Boulder with the first occurring January 26th through February 4th and the second during July from the 13th through the 24th. Both of these tutorials have been expanded to include specific tutorials to meet the needs of the community. The attendance varied for each tutorial component with the Jan/Feb session attracting 65 participants for the Basic, 33 for the WRF/VAR, and 34 for the WRF/MET. The July session had four components with 74 attending the Basic, 43 for the WRF/VAR, 40 for WRF/Chem, and 38 for WRF/MET. In addition, MMM divisional staff conducted the 3rd East Asia Weather Research and Forecasting (WRF) Model Workshop and Tutorial at Seoul National University in Korea in April 2009, which attracted 60 attendees.

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NCAR is sponsored by the National Science Foundation.

ESSL LAR 2009: RESEARCH CATALOGS

ESSL Staff and Section Profiles By Division

- CGD - The Climate and Global Dynamics Division
- HAO - The High Altitude Observatory
- MMM - The Mesoscale and Microscale Meteorology

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Research Catalog: CGD

CGD 2009 Section Profiles in Science

- Caspar Ammann
- Julie Arblaster
- Julio Bacmeister
- David Bailey
- Gordon Bonan
- Esther Brady
- Grant Branstator
- Bruce Briegleb
- Frank Bryan
- Julie Caron
- Jack Chen
- Aiguo Dai
- Gokhan Danabasoglu
- Clara Deser
- John Fasullo
- Erich Fischer
- Peter Gent
- Andrew Gettelman
- Cecile Hannay
- Kathy Hibbard
- Marika Holland
- Aixue Hu
- James Hurrell
- Markus Jochum
- Jennifer Kay
- Jeffrey Kiehl
- Joanie Kleypas
- William Large
- Peter Lauritzen
- David Lawrence
- Peter Lawrence
- Sam Levis
- Keith Lindsay
- Natalie Mahowald
- Gerald Meehl
- Rich Neale
- Yuko Okumura
- Keith Oleson
- Brian O'Neill
- Bette Otto-Bliesner
- Synte Peacock
- Adam Phillips
- Phil Rasch
- Jadwiga Richter
- Nan Rosenbloom
- David Schimel
- David Schneider
- Dennis Shea
- Christine Shields
- Haiyan Teng
- Robert Tomas
- Kevin Trenberth
- Joe Tribbia
- Warren Washington
- Tom Wigley
- Dave Williamson
- Stephen Yeager

CGD Research Catalog

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HIGH ALTITUDE OBSERVATORY (HAO) RESEARCH CATALOG

- Burns, Alan
- Dikpati, Mausumi
- Fan, Yuhong
- Gibson, Sarah
- Kubo, Masahito
- Lites, Bruce
- Liu, Hanli
- Lu, Gang
- McIntosh, Scott
- Metfalfe, Travis
- Miesch, Mark
- Richmond, Art
- Wu, Qian

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Director's Message

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Imperatives

Research Catalog

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MMM 2009 PROFILES IN SCIENCE

Summary of achievements

169 Refeered Publication(s) for the time period 2008-10-01 to 2009-09-30
(Listed by most recently published first in AMS format)

Author Collaborations Summary:
UCAR Only: 35
UCAR & University: 62
UCAR & Other: 19
UCAR, University, & Other: 53

Sun, J., S. P. Oncley, S. P. Burns, B. B. Stephens, D. H. Lenschow, T. Campos, R. K. Monson, D. S. Schimel, W. J. Sacks, S. De Wekker, C.-T. Lai, B. Lamb, D. Ojima, P. Ellsworth, S. L. Sternberg, S. Zhong, C. Clements, D. J. P. Moore, D. E. Anderson, A. Watt, J. Hu, M. Tschudi, S. M. Aulenbach, E. Allwine, T. Coons, 2009: A multi-scale and multi-disciplinary investigation of ecosystem-atmosphere CO2 exchange over the Rocky mountains of Colorado. *Bull. Amer. Meteor. Soc.*, doi: 10.1175/2009BAMS2733.1.

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2009 Lab Annual Report

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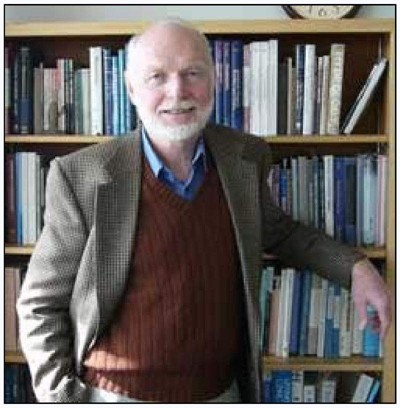
DIRECTOR'S MESSAGE



Brant Foote – RAL Director

Welcome to the Research Applications Laboratory's Annual Report for FY2009. Our mission is to conduct directed research that contributes to the depth of fundamental scientific understanding, to foster the transfer of knowledge and technology for the betterment of life on earth, and to support technology transfer that expands the reach of atmospheric science. We are, at present, an organization with annual expenditures of approximately $37M and a staff comprised of nearly 240 scientists, software engineers, and management/administration personnel.

In 2009 we added a new program to the RAL organizational structure: The Climate Sciences and Applications Program (CSAP), headed by Lawrence Buja, has at its core a number of social scientists formerly associated with the Institute for the Study of Society and the Environment. CSAP has close ties to NCAR's Integrated Science Program (ISP) and numerous connections to scientists throughout NCAR and the university community. CSAP conducts interdisciplinary research on the interactions between society and weather and climate, and works to support decision making and increase societal resilience to the impacts of weather and climate. CSAP's work is highlighted in Section 6 of this Report.

Another significant change in 2009 was the development of new strategic plans at the NCAR and Laboratory levels. RAL's plan is closely allied with the NCAR plan in setting forth programmatic imperatives and frontiers to guide our work in the future. This Annual Report follows the outline of that strategic plan, providing details on our many accomplishments in 2009 and our plan for the future. In thinking strategically about where we believe the needs–and opportunities–for our work will lie over the next decade, we have added several exciting new dimensions to our program. Each of the efforts highlighted below (and described more fully in this Report) is supported both by outside funds and by NSF funding allocated to RAL through the Annual Budget Review process to support the basic research that is critical to the success of these new efforts.

- Renewable Energy: This year we launched a wind prediction program aimed at providing detailed, localized wind forecasts to allow Xcel Energy to more efficiently integrate wind-generated electricity into its power grid
- Water in the West: This work is focused on the pressing problems of water availability and water–related disasters in the Western U.S., with an emphasis on understanding the impact of climate change on water resources. Early efforts are focused on the Colorado Headwaters Project (joint with ISP) and on the application of the Water Evaluation and Planning (WEAP) system to help western water utilities better manage their resources
- Weather, Climate and Health: Human health is inextricably connected to weather and climate. Social and physical scientists at RAL are exploring these connections in a variety of studies aimed at understanding the transmission of diseases like dengue fever and meningitis, the impact of extreme weather events on people who live in cities, and the ways in which the urban environment affects weather and climate

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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).

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NEXT GENERATION AIR TRANSPORTATION

Aircraft Icing

Background

The Next Generation Air Transportation System (NextGen) is now beginning to take shape on the design board of several federal agencies under the auspices of the Joint Program Development Office (JPDO). The JPDO has parsed the complex next generation system into several components and has endorsed the concept of Interagency Working Groups to coordinate the R&D associated with each. One such Working Group 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 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 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.

InFlight Icing

The NCAR icing group has been working closely with developers at NCEP's Model Development Lab and forecasters at the Alaska Aviation Weather Unit (AAWU) to implement and evaluate the Interactive Correction in 4D Workstation. This is being evaluated at AAWU as a means for forecasters to view a 'first guess' forecast of icing from FIP (re–coded for NCEP's North American Model, whose domain includes most of Alaska), and make corrections based on their knowledge and experience. They can consult other data sources such as surface, radar and satellite reports to add additional information to the model fields.

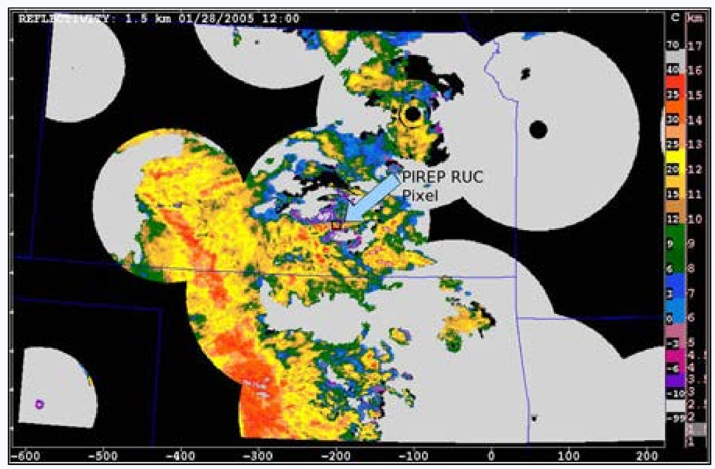

Fig. 1

We have been examining vertical profiles of NEXRAD radar reflectivity in icing conditions reported by pilots via voice reports (PIREPs). These profiles were extracted from the NSSL 3D radar mosaic, which places NEXRAD data into a 1kmx1kmx50m grid over the CONUS. Preliminary findings show that there are distinct profiles for small–drop icing, supercooled large droplets (SLD), (diameters >50 microns) icing, and glaciated regions. Additionally, variability of the reflectivity in boxes surrounding the flight track was found to provide more information on the icing environment. Positive PIREPs tend to be reported where large spreads in the 5th and 95th percentile of reflectivities exist; negative PIREPs tend to occur in areas of uniformly high (> 10 dBZ) REFL where we conclude the glaciated particles have effectively scavenged out any available supercooled liquid water. Our next step is to estimate the benefit of these data to CIP (Current Icing Product), and then to determine how to extract this information and use it as input into CIP to improve icing diagnoses. (Figures 1 and 2 show a case of icing).

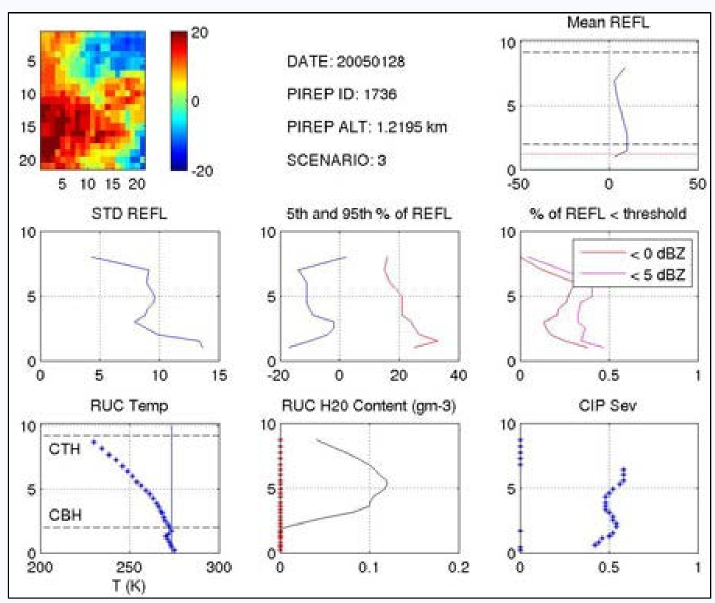

Fig. 2

The NCEP Rapid Update Cycle (RUC) numerical weather prediction model forms the basis for our Current and Forecast Icing Products (CIP and FIP). In June 2010, this will be replaced by the Rapid Refresh version of the Weather and Research Model (WRF–RR). NOAA Global Systems Division has been running a test version of the WRF–RR since late winter 2008 and we have converted FIP to run on the output. Our comparisons with RUC, and with FIP icing

regions running on both models, show very little differences. Our impression is that the condensate fields are more accurate, and we may therefore weigh them more strongly in our FIP fuzzy logic algorithms. Work is underway to convert CIP to WRF–RR and we anticipate similar results (i.e., little difference). Thus, we should be ready to transfer to the WRF–RR in June, on schedule. CIP and FIP run operationally at the Aviation Weather Center, and we will transfer the algorithms to their computers for the transition.

Numerous planning activities for the High Ice Water Content (HIWC) program took place. However, due to cost overruns and schedule slips for the new NASA GRC S3 research aircraft, the field programs to collect atmospheric and engine response data have been delayed at least a year. Another aircraft is being selected (decision will come in mid–fall 2009) and the time and place for the initial field program, originally slated for Puerto Rico in summer 2010, will be decided later in the year. Thus, we have delayed our HIWC warning tool development for a similar period of time. Our intention is to use a combination of satellite data and global numerical weather prediction model output to diagnose areas conducive to production of high concentrations of ice crystals at high altitudes. We have been working with Boeing to look at data from past encounters to establish common factors in these data sets.

Due to procedural problems at the FAA, the FIP–Severity upgrade has seen further delays. The current schedule is for it to be approved for operational use in winter 2009/10. This will allow both FIP and CIP to display severity and probability (instead of an uncalibrated icing potential field) on the operational versions, which have unrestricted supplementary status.

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NEXT GENERATION AIR TRANSPORTATION

Consolidated Storm Prediction for Aviation

Background

The Next Generation Air Transportation System (NextGen) is now beginning to take shape on the design board of several federal agencies under the auspices of the Joint Program Development Office (JPDO). The JPDO has parsed the complex next generation system into several components and has endorsed the concept of Interagency Working Groups to coordinate the R&D associated with each. One such Working Group 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 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 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.

Consolidated Storm Prediction for Aviation

For more than two decades the Federal Aviation Administration (FAA) has funded research and development efforts aimed at improving short–term forecasting of storm hazards affecting aviation. In FY07, the FAA started integrating the wealth of different forecasting tools by focusing on the development of a single authoritative forecast system, the "Consolidated Storm Prediction for Aviation" (CoSPA). This effort brings together researchers from NCAR's Research Applications Laboratory, MIT Lincoln Laboratory, and NOAA's Global Systems Division to create a 0–8 hour forecast for both summer and winter storms. Forecast products from this system are designed to satisfy the current needs of Air Traffic Management (ATM), as well as the future demands of the Next Generation Air Transportation System (NextGen), in which much of the strategic air traffic decision–making will be made utilizing automated decision support tools based on gridded probabilistic forecasts.

FY2009 Accomplishments:

CoSPA reached a major milestone during the summer 2008 with its first experimental real–time demonstration of a prototype CoSPA forecast system focused on the northeastern corridor of the United States (see figure). This past year the domain was expanded to cover approximately two–thirds of the country and within a year we expect to cover the entire continental US (CONUS). The CoSPA forecasts provide now weather outlooks 8 hours ahead and include vertically integrated liquid (VIL) and echo tops (ET). A precipitation phase product will be added in the future. The CoSPA forecasts are generated utilizing an advanced blending technique that merges heuristic–based extrapolation forecasts with output from a high–resolution, mesoscale numerical weather prediction model (i.e., the High–Resolution Rapid Refresh model) that includes radar data assimilation. The blended forecast products are rapidly updating (every 15 minutes) so that the latest model and observational data can be incorporated.

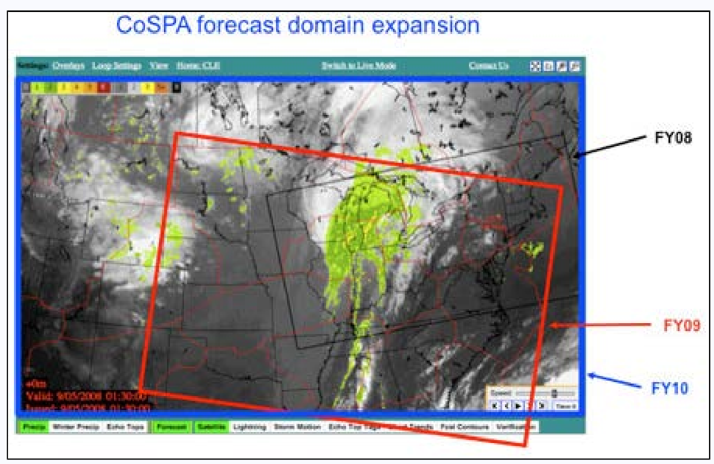

Fig. 1

Research and development (R&D) has continued on all aspects of the CoSPA forecast system, including the establishment of procedures for real–time, network–enabled data exchange and agreement on a common data format, working toward a system architecture with a modular design to foster ease of plug–and–play experimentation with new technologies, improvement of extrapolation techniques for longer lead times, utilization of statistical approaches for assessing the relevance of a myriad of predictor fields in predicting storm initiation and evolution, advancement of radar data assimilation techniques, implementation of sophisticated blending procedures that incorporate a phase correction of the model output, and advanced forecast verification methods.

FY2010 Plans:

The experimental real–time demonstration of the prototype CoSPA forecast system will continue during the coming year, but with an expanded domain to cover the entire CONUS. Thus far, only the developers and FAA sponsor have had access to these forecasts. We are planning for a broader distribution of CoSPA forecasts this coming year with a select group of operational

aviation users getting access to the password–protected website. Work will continue on all of the R&D tasks outlined above.

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NEXT GENERATION AIR TRANSPORTATION

Winter Weather

Background

The Next Generation Air Transportation System (NextGen) is now beginning to take shape on the design board of several federal agencies under the auspices of the Joint Program Development Office (JPDO). The JPDO has parsed the complex next generation system into several components and has endorsed the concept of Interagency Working Groups to coordinate the R&D associated with each. One such Working Group 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 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 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.

See section 5.4 for winter weather R&D focused on hydrometeorology

Winter Weather

Winter weather research and development at RAL has focused on developing two new systems in support of Ground Deicing operations. The Check Time system is a UCAR patented technology for aircraft ground deicing that determines when the fluid is close to failure (Check Time) of an applied aircraft deicing fluid based on temperature measurements and precipitation rates that update every minute. The Check Time is aircraft independent and only requires the end user to know the time that the aircraft was deiced. The Check Time system is based on the LWE system, which determines precipitation rate and type. The LWE system combines a Hotplate and GEONOR snow gauge, a Vaisala PWD–22 precipitation type sensor, a Campbell freezing rain sensor, and a Vaisala WXT wind, temperature, and humidity sensor to estimate a real–time liquid water equivalent precipitation rate in support of the determination of holdover times for de/anti–icing fluids.

FY2009 Accomplishments:

The research and development focus in FY2009 was on testing the LWE and Check Time systems under freezing rain and freezing drizzle conditions. Accomplishments during FY09 include the demonstration of the LWE system at four airports: Pittsburgh, Chicago O'Hare, Denver, and Minneapolis/St. Paul. An additional system was deployed at the Marshall Field site in Boulder, CO, for system verification. Manual snow pan observations (measuring the water equivalent of melted snow every 10–min) were collected at the Marshall site during freezing drizzle events to serve as truth data for the verification. The FAA is using this data to develop a specification for approval of LWE and Check Time systems for operational use at airports in support of ground deicing. We also deployed the LWE system at St. Johns, Newfoundland during April. This site is the site of the climatological maximum of freezing drizzle and rain in North America. Unfortunately, the climate was unusually warm and dry this April, so only limited data were collected.

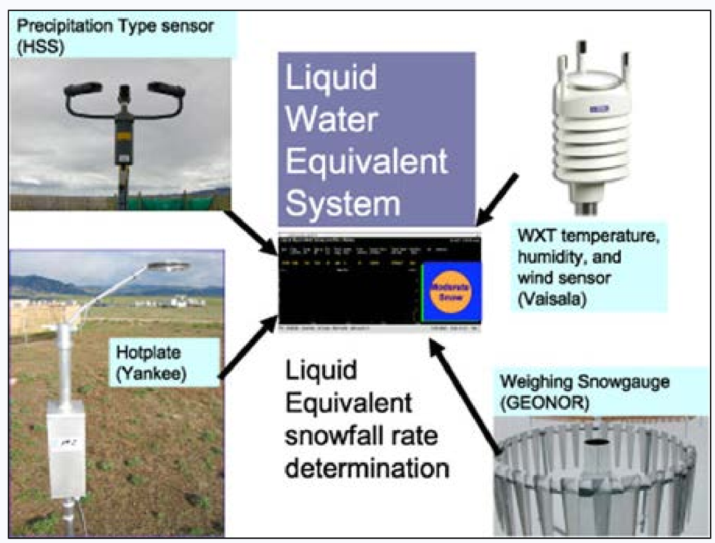

Fig. 1 Schematic of Liquid Water Equivalent (LWE) system

FY2010 Plans:

We plan to deploy in February next year in order to maximize our probability of obtaining the required data. The LWE system was also tested in the cold room of the University of Quebec at Chicoutimi under simulated freezing rain and drizzle.

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NEXT GENERATION AIR TRANSPORTATION

Turbulence

Background

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In situ measurements

Verification of the in situ eddy dissipation rate (EDR, $m^{2/3}/s$) measurements against pilot reports (PIREPs) continued, and International Civil Aviation Organization (ICAO) documentation on the algorithm was completed. Fleet–wide implementation of the winds–based EDR algorithm on the Delta Airlines 737–800 fleet (70 aircraft) was completed. Initial implementation of the algorithm on the Southwest Airlines 737–700 fleet (280 aircraft) was begun and will be completed in FY10. These implementations were based on heartbeat (tied to routine Meteorological Data Collection and Reporting System (MDCRS) reporting) and threshold reports (immediate transmission when one–minute peak or mean above a certain threshold is exceeded), thus substantially reducing communication costs from previous implementations.

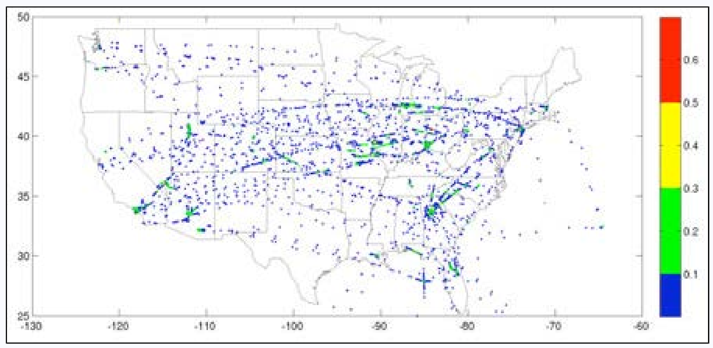

Fig. 1

An example of EDR reports received from the DAL fleet over a 24–hr time period is shown in the figure above. The colors are peak EDR values. We are currently in discussions with United Airlines to implement the algorithm on their Airbus A320 (97 aircraft) and B–777 (52 aircraft) fleets which will provide expanded national coverage as well as some international coverage.

A feasibility study using ACARS–AMDAR wind and temperature measurements to estimate EDR was completed. Initially this was used to construct a global climatology of turbulence, but with expanded data coverage may also allow real–time estimates of turbulence levels. A description of this method was written up and has been accepted for publication in the Journal of Applied Meteorology and Climate (JAMC).

Remote sensing measurements

Development and implementation of the second version of the NEXRAD Turbulence Detection Algorithm (NTDA–2) which provides observations of in–cloud turbulence levels (EDR) continued in response to recent changes to NEXRAD operational modes (super–resolution, phase coding, and new volume coverage patterns), which will provide improved accuracy and coverage. A mosaic of the NTDA–2 product based on 133 NEXRADs over the CONUS has been prototyped and is running operationally at NCAR. An example of the mosaic NTDA display is shown below. Discussions are in progress with United Airlines to provide them cockpit uplinks of flight specific NTDA–derived turbulence, similar to what was done in FY08.

An example of EDR reports received from the DAL fleet

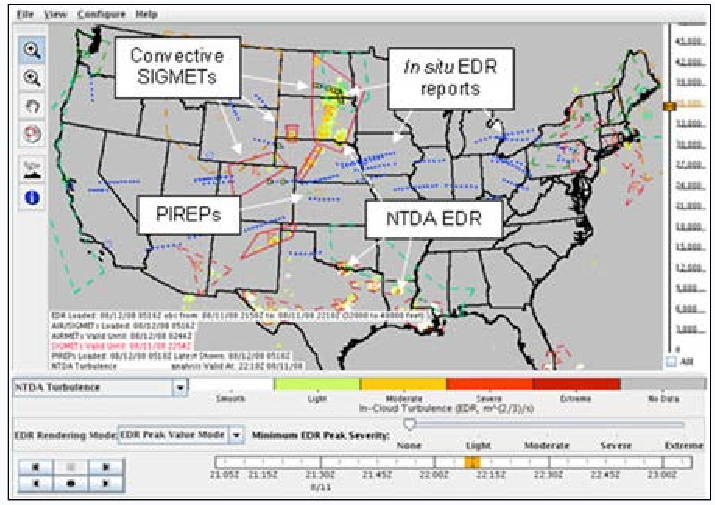

Fig. 2 Feasibility studies of using GPS scintillation measurements continued.

over a 24–hr time period is shown in the figure above. The colors are peak EDR values. We are currently in discussions with United Airlines to implement the algorithm on their Airbus A320 (97 aircraft) and B–777 (52 aircraft) fleets which will provide expanded national coverage as well as some international coverage.

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Nowcasting/forecasting

The Graphical Turbulence Guidance version 2 (GTG2) which provides RUC–based forecasts of turbulence should become "operational" and available on NOAA's Operational ADDS web site (http://adds.aviationweather.gov/turbulence/) in early CY10. It is currently available to users through the Experimental ADDS web site (http://weather.aero/turbulence/). This product produces forecasts of clear–air turbulence sources out to 12 hours, and is updated hourly at 1000 ft increments from 10,000 to 45,000 ft MSL. Work will continue to more efficiently use the high density of in situ EDR measurements within the next version of GTG (GTG3) which will also include all flight levels from the surface to 45,000 ft.

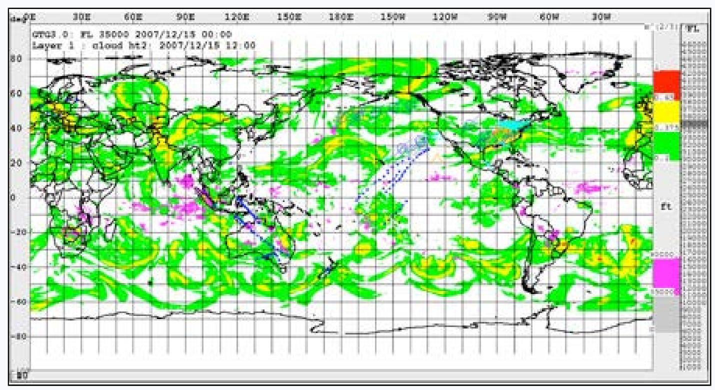

Fig. 3 A WRF–based GTG system was retuned for operational use over the Taiwan airspace.

FY2009 Accomplishments:

Work continued on the GTG nowcast (GTG–N) product, which combines all observations of turbulence (including NTDA–2, in situ EDR, pilot reports, and satellite–based diagnostics) with GTG3 analyses to produce a NAS–wide representation of turbulence updated at 15 minute intervals. The GTG–N product also provides estimates of near cloud convectively–induced turbulence (CIT), and substantial effort has been invested in developing both a better physical understanding of the mechanisms responsible for CIT (two papers have been published on this in FY09 and another is in preparation) and development of an ingredients–based CIT diagnostic algorithm (DCIT).

FY2010 Plans:

An initial version of a global turbulence forecast (Global GTG) product has been developed in FY09 and will continue to be improved in FY10. The global product also provides rapid updates of satellite–derived convection locations and intensities (cloud top heights). These forecasts use Global Forecast System (GFS) model data, which can be used to provide upper–level turbulence forecasts globally out to 36 hours. The figure below is an example of the combined cloud–top (magenta), turbulence forecast (green–yellow–red) product as well as observations from in situ EDR data and pireps.

Juneau Terrain-Induced Turbulence

FY2009 Accomplishments:

RAL continued operation and maintenance of the prototype warning system (JAWS–P). In December 2008 the Executive Council of the FAA approved completion of the system and directed RAL to proceed with implementation of the JAWS–H version (a "hybrid" containing an FAA communications front end and the NCAR developed algorithm and display back end). The JAWS–H architecture was developed, and hardware was procured and installed at the Juneau International Airport. The FAA communications equipment was integrated into the JAWS–H rack and communications paths from mountaintop sensors and from wind profilers was tested. New software was developed for JAWS–H and a prototype version loaded in Juneau for testing.

FY2010 Plans:

In FY10, RAL will continue to operate the prototype warning system. A new JAWS–H software version will be released and loaded early in FY2010, and the JAWS–H system will be evaluated in a side–by–side comparison with JAWS–P to ensure continuity of alerts. Once the evaluation is satisfactorily completed, the JAWS–P system will be shut down and dismantled, and JAWS–H will commence operations. At that point the FAA will start taking over some maintenance activities from NCAR. Documentation of the JAWS–H system will continue and several documents will be delivered to the FAA for inclusion in their technical manuals. The end–state JAWS Operational Ready Date is still on schedule for the end of FY2011.

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NEXT GENERATION AIR TRANSPORTATION

Ceiling and Visibility

Background

The Next Generation Air Transportation System (NextGen) is now beginning to take shape on the design board of several federal agencies under the auspices of the Joint Program Development Office (JPDO). The JPDO has parsed the complex next generation system into several components and has endorsed the concept of Interagency Working Groups to coordinate the R&D associated with each. One such Working Group 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 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 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.

Ceiling and Visibility

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.

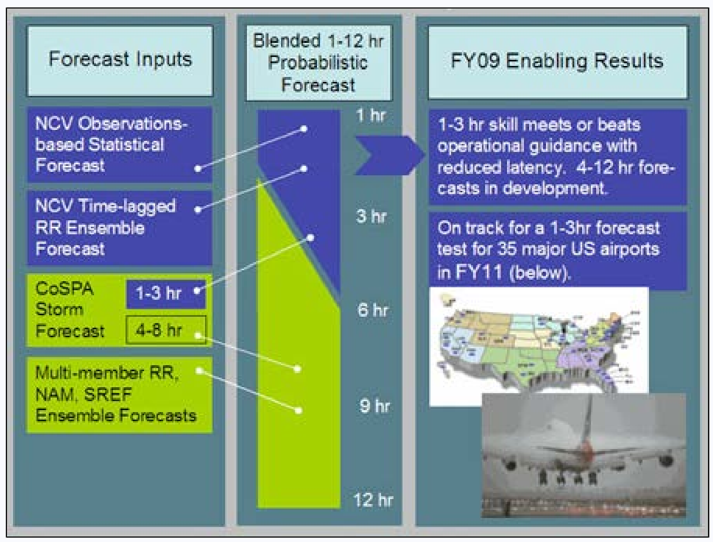

Fig 1. Overview of RAL's probabilistic C&V forecast development concept. Forecast inputs are shown at left. Forecast blending (center) transitions from primarily statistical inputs at 1–3 hr to primarily numerical model inputs at 5–6 hours and beyond. FY09 forecast development has yielded good results and low forecast latency at 1–3 hours (right). A 1–3 hr forecast demonstration in FY11 (right) will provide practical feedback while development of longer–term ensemble forecasts proceeds.

FY2009 Accomplishments:

FY09 work has focused on initial development of elements to comprise a 1–12 hr probabilistic C&V forecast system. The approach taken selectively blends statistical and numerical model forecast methods across the 1–12 hr forecast range as outlined below and illustrated in Fig. 1.

Statistical Forecasting

Observations–based statistical forecast methods play a dominant role in shorter–term forecasts (e.g., 1 to about 3 hr), where the skill of statistical methods operating on current observations exceeds that of numerical modeling. A prototype 1–5 hr observations–based statistical forecast method was developed and tested at selected CONUS airport sites. This method utilizes logistic regression forecast equations trained from 11 or more years of historical data. Customized forecast equations are developed for each site, forecast interval (1 to 5 hr), predictand (C or V) and threshold (e.g., C <3000' or V <3 sm). This approach achieves forecast success by breaking down the forecast process into a large number of focused sub-tasks, each of which can be optimized through automated processes.

Forecast Verification

To enable critical comparison between the prototype method above and current operational C&V forecast guidance, a substantial capability to verify both prototype and LAMP probabilistic forecasts has been developed. Limited verification results to date show the skill of the prototype system to be superior to the operational system at 1 and 2 hours, and to be competitive at 3 hr. As expected, blending of the prototype system with numerical model results is necessary to achieve superior results beyond 3 hr. Work toward that blending is in progress.

Ensemble Forecasting

As shown in Fig. 1, the dominant role of statistical methods at 3 hr duration is tapered to near zero for forecasts of ˜ 5 hr duration and longer, where the role of numerical model ensembles becomes dominant. A method to construct and verify hourly RUC or Rapid Refresh time–lagged ensembles at any airport site has been developed. To allow the flexible selection of sites, forecast parameters and time periods during the development process, ensemble assembly is handled by a MySQL database. Exploratory testing of ensemble forecast methods and resultant skill has used a statistical approach to 'calibrate' the ensemble's relationship to the desired predictand (e.g., C or V). Preliminary forecast results are encouraging, but demonstrate need for a larger verification sample size. Further development and verification using data through 2010 will help address this need.

FY2010 Plans:

The NCV CONUS analysis product will undergo independent evaluation by the FAA in FY2010, and we anticipate that the analysis system will be approved for operational use. Work toward the probabilistic forecast system will focus on the following:

- Continue development of 1–3 hr probabilistic forecast methods and implement a prototype system to support an operational demonstration at 35 CONUS airports in FY11.
- Continue exploration of the utility of CoSPA 1–8 hr forecasts to improve forecasting of regime changes in C&V (e.g., transitions from clear to impacted conditions).
- Better exploit model ensemble skill with longer training, use of additional model fields and selection of improved logistic regression model characteristics through testing. Prepare a prototype ensemble system for production of 4–12 hr forecasts.

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NEXT GENERATION AIR TRANSPORTATION

Integration of Weather Information Into ATM Decisions for Reduced Weather Impact

Background

The Next Generation Air Transportation System (NextGen) is now beginning to take shape on the design board of several federal agencies under the auspices of the Joint Program Development Office (JPDO). The JPDO has parsed the complex next generation system into several components and has endorsed the concept of Interagency Working Groups to coordinate the R&D associated with each. One such Working Group 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 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 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.

Methodologies for translation of weather information into probabilistic information useful to air traffic management decision support tools.

As NextGen moves from planning to implementation, RAL moved from concept to concrete accomplishments toward understanding how weather will be integrated into the future air transportation system. Our focus is on defining alternative methodologies for translating weather constraints to air traffic management (ATM) impact as the first step in weather integration. This offers advantages in terms of integrating weather into decision support tools while allowing the human to remain in and/or over the loop during the decision making process. It further facilitates human intervention when automation fails or is inappropriate.

NASA sponsored an initial RAL study that looked at the translation to ATM impact problem using ensembles for convective weather forecasting. Aviation users need 0 – 12 h forecasts that provide not only details about the likely weather outcome, but also information about storm structure, intensity, organization, and associated forecast uncertainty. This emphasizes the need for short–range (0 – 2 days), high–resolution (<10 km spatial resolution) ensemble weather forecasting systems. Optimization of air traffic management, especially under future scenarios of anticipated increased demand, has to build upon automated decision support tools that integrate probabilistic weather information to estimate airspace capacity and provide guidance for managing air traffic flows under consideration of the associated uncertainties in prediction. This NASA–sponsored research develops and refines new concepts of how probabilistic weather forecasts can be tailored for aviation needs and integrated with automated decision support tools. The novel approach entails a translation of ensemble weather forecasts into probabilistic predictions of the impact on air traffic capacity.

A proof–of–concept was developed during FY2007 and put to work during FY2008 to show how ensemble weather forecasts in the not–too–distant future may be analyzed from an aviation user's point of view and packaged for integration with automated air traffic management decision support tools. The figure shows a 9–hour probabilistic forecast of the likelihood to loose 30% airspace capacity (left panel) compared to the observed traffic reduction (right panel). The focus of this work has been on convective storms primarily because of their disruptive influence on air traffic flows. However, we have also shown that the ensemble–based approach is applicable to other en–route weather hazards, such as turbulence. During FY2009 several additional case studies were carried out that focused on the performance assessments of ensemble–based probabilistic scenario forecasts as a function of lead–time, spatial scale, and magnitude of the weather event. A proper calibration of these probabilistic forecasts requires long–term data, which are not currently available, but the database of six multi–day events reveals dependencies of forecast performance to the type of weather encountered, scale of analysis, and criteria used for evaluation.

FY2009 Accomplishments:

A proof–of–concept was developed during FY2007 and put to work during FY2008 to show how ensemble weather forecasts in the not–too–distant future may be analyzed from an aviation user's point of view and packaged for integration with automated air traffic management decision support tools. The figure shows a 9–hour probabilistic forecast of the likelihood to loose 30% airspace capacity (left panel) compared to the observed traffic reduction (right panel). The focus of this work has been on convective storms primarily because of their disruptive influence on air traffic flows. However, we have also shown that the ensemble–based

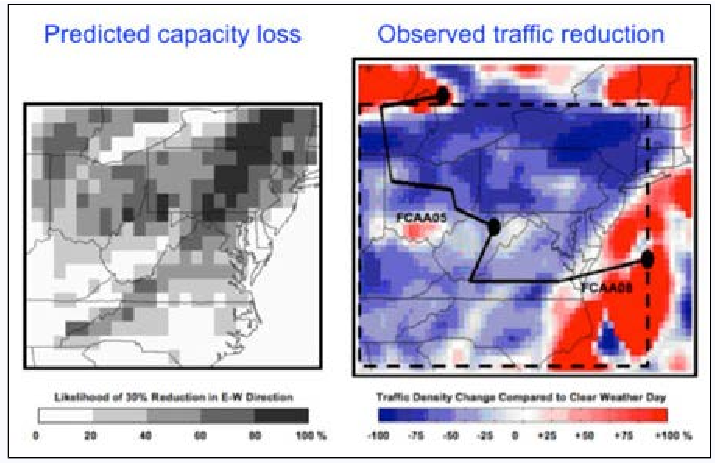

Fig. 1

approach is applicable to other en–route weather hazards, such as turbulence. During FY2009 several additional case studies were carried out that focused on the performance assessments of ensemble–based probabilistic scenario forecasts as a function of lead–time, spatial scale, and magnitude of the weather event. A proper calibration of these probabilistic forecasts requires long–term data, which are not currently available, but the database of six multi–day events reveals dependencies of forecast performance to the type of weather encountered, scale of analysis, and criteria used for evaluation.

Integration of Weather Information into Cockpit Decisions

One of the programs being 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 ATC system collaborative triad (the others being ATC/ATM and airline dispatch or flight operations control). Throughout 2009, 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. Thus the WTIC capability will be harmonized between North America and the European Union, and will include standard weather information to all aircraft flying between the two continents.

ATM/Weather Integration Planning

Planning for implementation is a large step toward realizing an initial operational capability (IOC) in 2013, so for the weather integration problem RAL took the initiative and led part of the effort to consolidate potential tools and methods that were included in the JPDO ATM–Weather Integration Plan. These tools are state–of–the–art algorithms and mathematical techniques 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 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 AWRP and the FAA's Reduce Weather Impact (RWI) program, both part of the FAA's AWO.

Determining the Optimal Sensors and Platforms to Meet the Needs for ATM/Weather Integration

Optimized and relevant weather observation and forecasting capabilities are essential for conducting safe and efficient flight operations in the National Airspace System (NAS). It is imperative, therefore, to ensure that the FAA's weather observing and forecasting capabilities are adequate to satisfy NextGen requirements. Under the Reduced Weather Impact (RWI) program, the FAA has set up a multi–institutional team for conducting an assessment of relevant weather sensors. The FY2009 activities under the RWI weather sensor assessment (also known as "Right Sizing") effort focused on cataloguing relevant weather sensors and platforms. In addition, preliminary gap identification was carried out based on the NextGen functional requirements document available to the team. The corresponding performance requirements will become available for the in–depth gap analysis to be conducted during FY2010. Initial identification of opportunities (i.e., "low–hanging fruits") for demonstrating improved capabilities will also continue into FY2010.

ATM/Weather Integration Activities within NOAA

To further RAL's work to integrate weather R&D and transition to operations across Federal agency lines, a cooperative agreement with NOAA and the National Weather Service was consummated in FY2009. This $5 million CA defines collaboration between RAL and NOAA, and coordinates with the FAA JPDO for the IOC and beyond. Meetings are in progress to detail the collaboration and will initially focus on Alaska weather integration within that region's ADS-B/R environment (this is automatic dependent surveillance, broadcast and rebroadcast), to include human–over–the–loop techniques for forecasters. Further effort will include university involvement while the collaboration moves to populating the CONUS NNEW with gridded weather variables for the IOC. HOTL techniques will be further developed using RAL's AutoNowcaster (ANC) system in place at DFW, and soon–to–be in place in Florida.

ATM/Weather Integration Outreach Activities

RAL participated in most outreach venues available to further weather R&D, harmonization, and integration into ATM decision support tools. Notable additional events include new technology workshops sponsored by the FAA, NASA, and the Air Traffic Control Association. Presentations that were specifically focused on the weather integration problem were given at the FAA/NASA/ATCA New Technologies Workshop in Atlantic City NJ in May 2009, and the AIAA ATIO Conference at Hilton Head SC in September. Both were well received, showing RAL's leadership in this area. Additionally, RAL is participating as a team member in several NextGen systems engineering and planning initiatives being conducted by the JPDO and FAA.

FY2010 Plans:

The accomplishments in 2009 are just setting the stage for 2010 and beyond. Actions established for 2009 will continue as we move more from planning to implementation, looking forward to an IOC in 2013.
Specifically:

- Real–time demonstration of the concept of translation of ensemble forecasts into ATM information is under development utilizing the vertical integrated liquid (VIL) and echo top (ET) output generated by the NOAA/ESRL Global Systems Division (GSD) hourly–updating High–Resolution Rapid Refresh (HRRR) model runs. The VIL and ET forecasts will be combined into a Weather Avoidance Field (WAF), a heuristic approach developed at the MIT Lincoln Laboratory that mimics pilot's deviation around storms. In addition, the impact of such probabilistic scenario forecasts on aviation users will be evaluated using NASA's FACET (Future ATM Concepts Evaluation Tool) software package.
- RAL will continue 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.
- The "Right Sizing" FY2010 effort will include an in–depth gap analysis utilizing the sensor catalogue and other means (e.g., workshops) as appropriate. There have been a variety of gaps identified in FY2009 and they need to be better understood. Moreover, plans will be developed for demonstration experiments in FY2011 that may show improvements that can be made toward meeting NextGen requirements.
- The NOAA Aviation Weather Cooperative Agreement will move from the planning phase to implementation, to include deployment of the RAL ANC to Florida and the evaluation of HOTL applications in Alaska, all contributing to the body of knowledge needed to integrate weather information and the human being into NextGen processes.
- 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.
- RAL is already scheduled for both the 2010 ATCA/NASA/FAA New Technologies Workshop and the 55th ATCA Annual Meeting. Other opportunities this year will include the AMS ARAM Meeting in January, 2010, where we will report our progress to date on translation of weather hazards into ATM impacts.

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NEXT GENERATION AIR TRANSPORTATION

Dissemination of Aviation Weather Information

Background

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Dissemination of Aviation Weather Information

The NNEW Program is developing a new network service based infrastructure for distributing weather data within the FAA and exchanging it with external entities. NCAR is collaborating with MIT/LL, NOAA/ESRL, NOAA/NWS, and MITRE/CAASD to develop software and prototype systems for the NextGen 2013 initial operational capability.

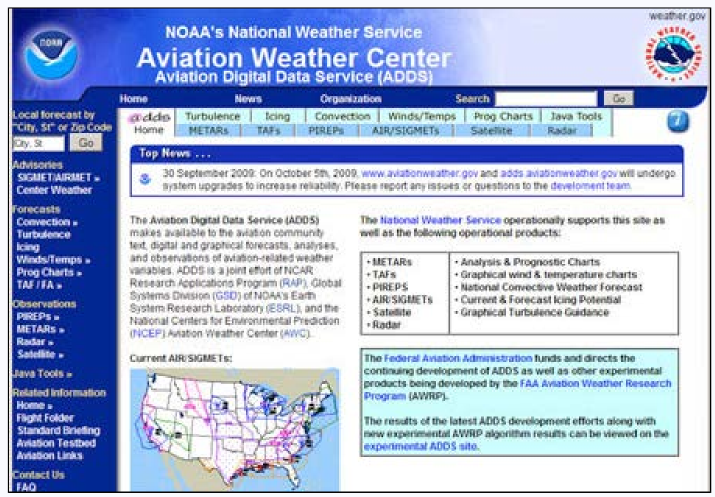

Fig. 1 Operational ADDS http://adds.aviationweather.noaa.gov/

RAL has been developing a web based service to distribute gridded weather data based on the Open Geospatial Consortium's (OGC) Web Coverage Service (WCS) standard. In FY2009, RAL worked with the OGC to extend the WCS standard where necessary to accommodate three and four dimensional gridded weather data sets. Also in FY2009, RAL developed a first generation reference implementation of the FAA WCS server software for weather data. Some of the more notable capabilities of this server are its ability to spatially and temporally subset the weather data as will be required for NextGen weather data queries.

Also in FY2009, RAL worked in conjunction with the European Union's air traffic consortium, EuroControl, to develop weather data format standards for commonly used non–gridded weather data. One of the NNEW collaborators, MIT/LL, developed a reference implementation of a server for WXXM (Weather Information Exchange Model) based on the OGC's Web Feature Service (WFS) standard for non–gridded (feature) data distribution. This emerging standard, WXXM, is XML based and promises to aid in harmonization of weather data exchange between air traffic control systems in the US and Europe.

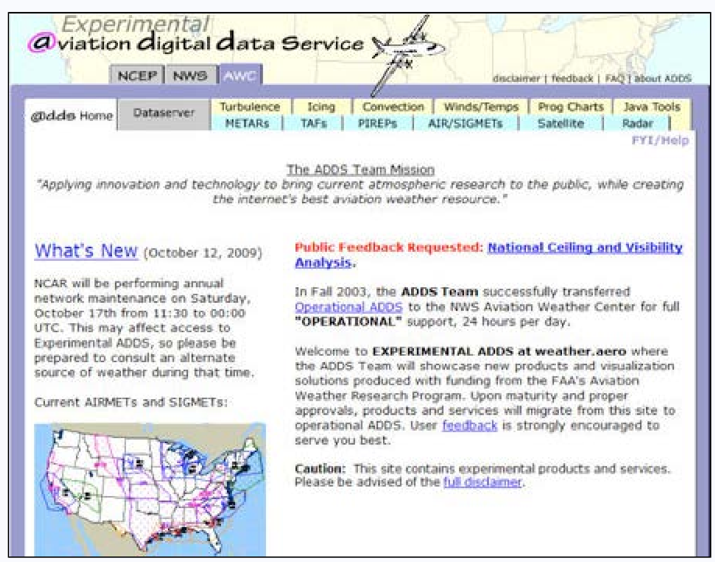

Fig. 2 Experimental ADDS http://weather.aero

The NNEW program periodically schedules capability demonstrations to exhibit the current state of the art in NNEW standards, technologies, software, and test bed infrastructure. For the most recent NNEW demonstration, RAL contributed its WCS reference implementation software, developed demonstration client software, developed the flight weather hazard service and tool, and implemented part of the NNEW test bed to support real–time WCS and WFS servers.

The demonstration client software provided a graphical depiction of data delivery and weather products available from the NNEW test bed.

The Flight Weather Hazard Service (FWHS) and the Flight weather Hazard Tool (FWHT) were developed at RAL in FY2009 to illustrate how a complex aviation weather application can be built on the capabilities and flexibility inherent in the NNEW WCS and WFS servers. The FWHS and FWHT allows a user to specify a flight through the US airspace, retrieve weather hazards that may be encountered along that route of flight, and view a graphical depiction of those composite hazards. The data retrieved and depicted is a four dimension trajectory through the weather hazards customized for the planned path of flight and airplane capabilities. The ability to provide four dimensional trajectories of weather hazards is foundational to the needs of NextGen's air traffic automation tools.

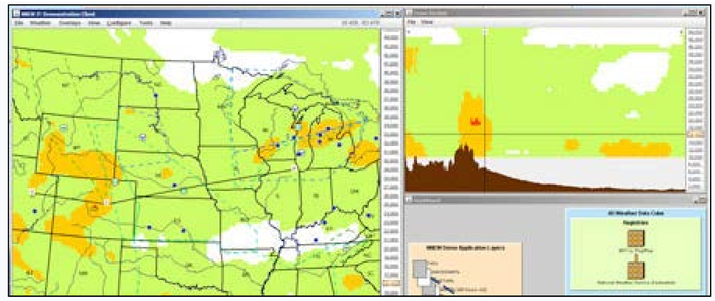

Fig. 3 NNEW Demonstration Client (Click to Enlarge)

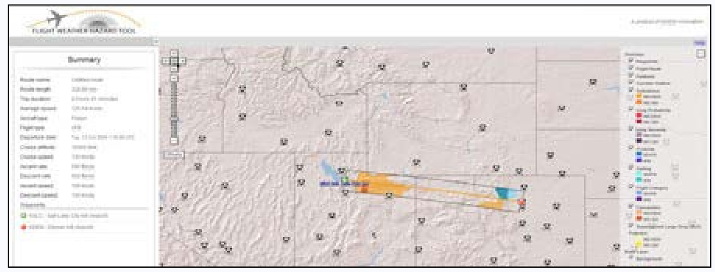

Fig. 4 Flight Weather Hazard Tool (Click to Enlarge)

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NEXT GENERATION AIR TRANSPORTATION

Oceanic Weather

Background

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Convective Nowcasting Oceanic System (CNO)

A comparison of three extrapolation techniques was undertaken that included the current CNO methodology of object tracking via the Thunderstorm Initation, Tracking and Nowcasting (TITAN) software, a statistical technique called Random Forest that utilizes additional observational data sets and model results, and a gridded forecast system that merges model winds, TITAN storm vectors, and satellite–tracked winds. Initial results suggest that the gridded forecast produces superior results at longer lead times with the Random Forest and gridded forecast techniques producing similar results at a 1 hour lead time. Investigation into these techniques will continue into the next year.

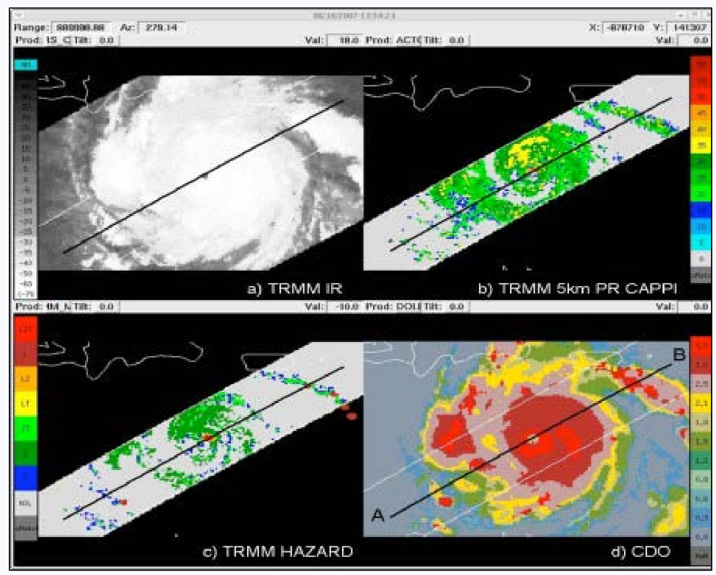

Fig. 1 Four–panel analysis display showing the (a) TRMM infrared brightness temperature (°C), (b) TRMM radar reflectivity (dBZ) at 5 km altitude, (c) TRMM derived hazard product, and (d) CDO interest field of oceanic convective clouds associated with Hurricane Dean on 18 August 2007 at 13:44:11 UTC.. The TRMM derived product denotes regions where our criteria for hazard was observed based on the following designations: T – convective rain, Z – reflectivity >30 dBZ at 5 km altitude, L – lightning, or ZT, LT, LZ, and LZT – combination of the hazard classes. An interest threshold of 2.5 is applied to the CDO interest field to indicate the presence of convective clouds. A cross sectional view of the radar reflectivity and CDO interest values along the black line segment labeled A–B in (d) is illustrated in the second figure. The TRMM PR swath width is 243 km.

Convective Diagnosis Oceanic System (CDO)

Modification of the CDO methodology to partition the calculation based on daytime, terminator or night time conditions has been completed and is being compared to the previous methodology using Tropical Rainfall Measuring Mission (TRMM) low Earth orbit satellite data sets for validation. Investigation into including the World Wide Lightning Location Network (WWLLN) data set within the CDO nears completion; this CDO modification will also be validated with TRMM data sets.

CDO/CNO Domains

The domain of the Convective Diagnosis Oceanic and the Convective Nowcasting Oceanic (CDO/CNO) system was expanded into the Intertropical Convergence Zones covered by the GOES–East, GOES–West and MTSAT–1R satellites. The project web pages were updated with movie loop capability for these new regions.

FY2010 Plans:

This project ends in February 2010. Completion of research goals and writing a final report will be done.

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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

Soil Condition Analysis & Prediction

Wildland Fire Behavior Modeling

Weather Prediction Statistical Optimization

International Aviation Weather Systems

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NEW AND EMERGING APPLICATIONS

Surface Transportation Weather

Background

RAL has a goal to become the central focus for research and development for the weather component of Federal Highway Administration's wireless vehicle technology program called IntelliDrive[SM]. In addition, RAL is supporting the adoption of the winter Maintenance Decision Support System (MDSS) technology across the nation and plans to extend this technology by developing transportation decision support systems focusing on traffic, incident, and emergency management and maintenance beyond snow and ice control. RAL is performing research to seamlessly blend the strategic prediction components of the system with tactical short–term weather and road condition technologies. RAL is also working on improving the quality of the Clarus System observations and examining how the Clarus data can be used to increase safety and efficiency for summer road maintenance operations.

Vehicle Data Translator

During FY09, the USDOT renamed the Vehicle Infrastructure Integration (VII) Program IntelliDrive[SM] to reflect a change in focus from engineering research to more consumer–oriented products. The IntelliDrive[SM] program has three main goals, namely to increase safety, mobility, and 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. 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 FY09 to develop a prototype Vehicle Data Translator (VDT) that 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. This development focused on two key concepts: assessing vehicle probe data quality and developing the road and atmospheric hazard products.

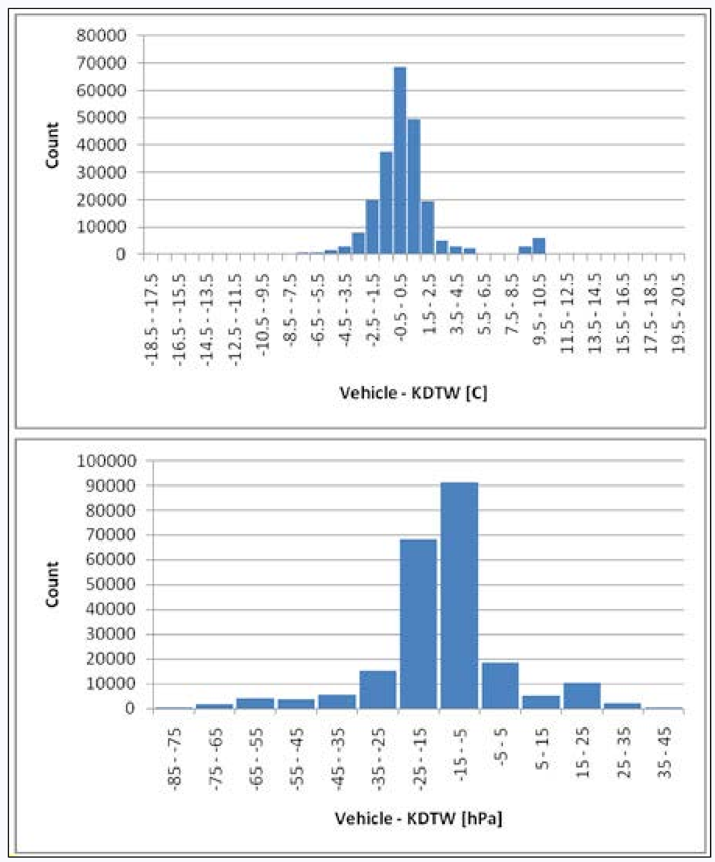

Fig. 1 Histograms of differences between vehicle probe data and KDTW ASOS station for temperature (top) and barometric pressure (bottom).

Questions about data quality focused on determining the accuracy and bias of mobile temperature and pressure observations using data from 11 specially equipped cars NCAR operated within the USDOT testbed near Detroit, Michigan. These cars sensed and recorded more than 500,000 temperature and pressure observations and several million other vehicle data elements – with an emphasis on collecting data during rain and snow conditions – over 11 days in April 2009. Early results suggest that vehicle temperature data are in general agreement with data from the nearby KDTW ASOS station but vehicle pressure data are negatively biased (Figure 1).

The same Detroit–area data were also used to develop the prototype VDT road and atmospheric hazard condition products. As an example, a major hazard for the surface transportation industry is precipitation (liquid or frozen), which lowers friction between the tires and the roadway and increases the probability of

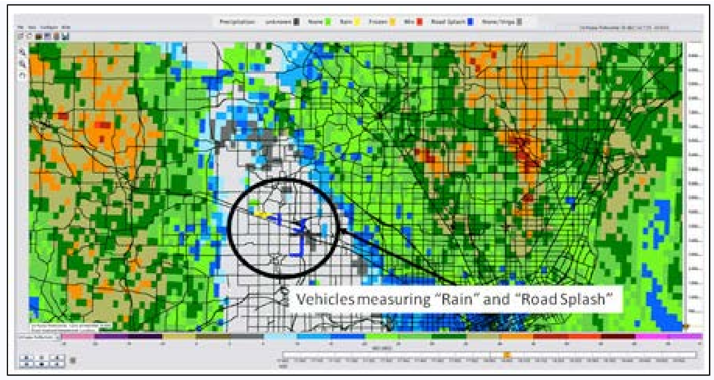

Fig. 2 Example display of the VDT "road precipitation" algorithm and radar data.

accidents. The VDT has a "road precipitation" algorithm that blends vehicle data elements (e.g., wiper status distribution, air temperature) with radar data, nearby weather station data, and weather model and satellite data. The end result is an indication of whether a motorist might encounter various precipitation–related conditions, such as "rain", "frozen precipitation", "mix", "road splash", "none/virga", or "uncertain" (Figure 2). More details on the VDT concept and algorithms are presented in an Intelligent Transportation Society of America (ITSA) conference paper (Drobot et al. 2009a) and an ITS International article (Drobot et al. 2009b).

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.

FY2009 Accomplishments:

In FY09, the bridge and roadway pavement heat balance models, data fusion system, and rules of practice components of the MDSS were refined to improve the overall performance of the system. This culminated in the release of Version 6.0 of the MDSS software. Additions in Release 6.0 include new data sets, such as Automated Vehicle Location (AVL) information, truck camera images, and webcam images from fixed locations, which can now be viewed on the display. The observation processing subsystem has also been enhanced to allow easier spin–up of forecast sites by using weather forecast elements as surrogates for missing Environmental Sensor Station (ESS) observation data. This allows new (and intermittently observing) sites to work more seamlessly within the requirements of the Model of the Environment and Temperature of Roads (METRo). An event playback capability has also been added to view previous weather forecasts and treatment recommendations. This capability requires that previous data be maintained on the MDSS server for an extended period of time. Finally, initial work was performed to transition the source of ESS data from the Meteorological Assimilation Data Ingest System (MADIS) to the new Clarus system. The components of this work are included in Release 6.0, but because of the lack of ESS data available from the Clarus system covering the Colorado demonstration area, these components were not completely interfaced to the MDSS system.

Other highlights included working with Denver International Airport to transition the MDSS to an airport environment and supporting the FHWA's annual MDSS stakeholder meeting, which included numerous participants from the surface transportation community, including State DOTs.

Clarus QCh

The USDOT FHWA Road Weather Management Program, in conjunction with the Intelligent Transportation Systems (ITS) Joint Program Office, established the Clarus Initiative in 2004 to reduce the impact of adverse weather conditions on surface transportation users. The goal of the initiative is to create a robust data assimilation, quality checking (QCh), and data dissemination system that can provide near real–time atmospheric and pavement observations from the collective state's investments in road weather information systems.

FY2009 Accomplishments:

In FY09, RAL focused on improving several of the Clarus QCh algorithms. For the sea level pressure algorithm, NCAR discovered that the primary deficiency of the original algorithm was that it uses a standard (monthly) 700 mb temperature to estimate the density of the lower atmosphere. NCAR recommended using current atmosphere soundings to estimate the 700 mb temperatures near the environmental sensor stations, which led to a better algorithm (Figure 3). NCAR also provided recommendations for the climate range test, and developed a new spatial algorithm test based on using an inter–quartile range rather than a standard deviation, which is how the original QCh algorithm operated.

In late 2009, NCAR began to develop QCh algorithms for pavement surface and subsurface temperature.

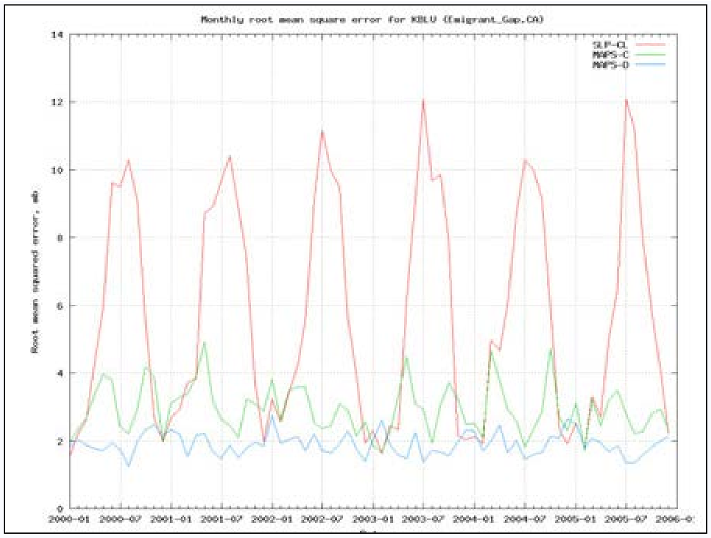

Fig. 3 Monthly RMSE between Emigrant Gap (KBLU) and Beale AFB (KBAB), California METAR stations for 2000 – 2005 for the original Clarus algorithm (SLP–CL), Climatology–based MAPS algorithm (MAPS–C), and dynamic (sounding based) algorithm (MAPS–D).

These QCh algorithms will be incorporated and tested in Clarus in early 2010.

Clarus Regional Demonstration

The USDOT FHWA Road Weather Management Program is conducting multi–state Clarus Regional Demonstrations to highlight progress in developing the Clarus System. These demonstrations encourage state agencies to contribute ESS data, show how Clarus facilitates better transportation system management, and enable the private sector to create improved road weather information business solutions. RAL is participating in one of the two regional demonstrations, focusing on

- Assessing to what extent Clarus data improves numerical weather prediction modeling capabilities to support surface transportation weather
- Developing a non–winter maintenance and operations decision-support system
- Contributing road and weather forecasts for a multi–state regional operational experiment

RAL is teamed with Mixon–Hill and State DOTs in Iowa, Indiana, and Illinois.

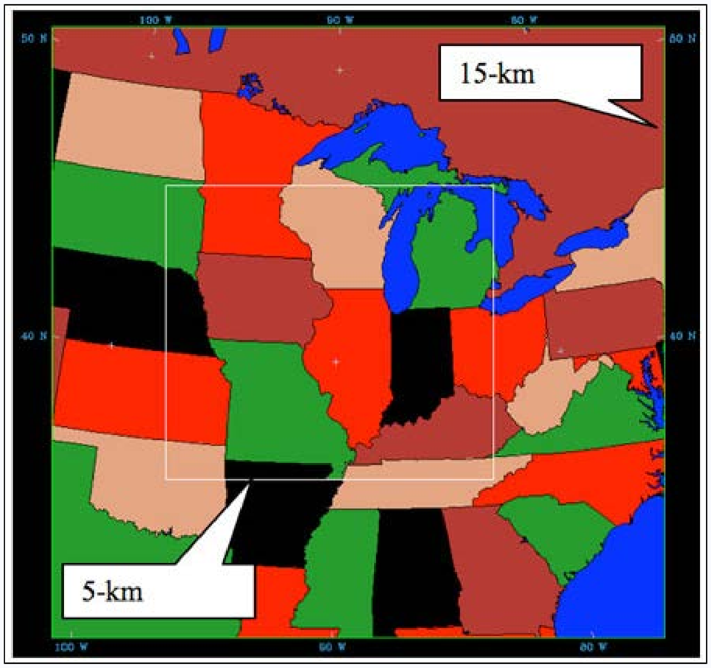

Fig. 4 WRF model sensitivity study domain for the Clarus Regional Demonstration project.

FY2009 Accomplishments:

Research in FY09 centered on setting up the Weather Research and Forecasting Model (WRF) and the Road Weather Forecast System (RWFS)/METRo model for the three states of interest (Figure 4). Five separate meteorological case events, including the 2008 Midwest Floods and the remnants of Hurricane Ike, will be used to assess the value of Clarus data. The results of this research will be reported in 2010.

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NEW AND EMERGING APPLICATIONS

Renewable Energy

Background

NCAR is uniquely qualified to help support our nation's transition to renewable energy due to its breadth of atmospheric science knowledge, experience with technology transfer, and access to university researchers. These capabilities led NCAR to include a new research frontier in the 2009 NCAR Strategic Plan. RAL is collaborating with university researchers, DOE labs, and other NCAR entities to develop methods to more accurately analyze and predict wind energy to support the renewable energy industry. It is anticipated that RAL's renewable energy research will expand to include the prediction of direct and indirect solar radiation and the impact of aerosols and jet contrails on surface insolation.

Xcel Energy Wind Prediction Project

In late December 2008, RAL began a collaborative project with Xcel Energy Services, Inc. to perform research and develop technologies to improve Xcel Energy's ability to increase the amount of wind energy in their energy generation portfolio. The agreement and scope of work was designed to provide highly detailed, localized wind energy forecasts to enable Xcel Energy to more efficiently integrate electricity generated from wind into the power grid. The wind prediction technologies will help operators make critical decisions about powering down traditional coal–and natural gas–powered plants when sufficient winds are predicted, enabling the increased reliance on alternative energy while still meeting the needs of its customers. The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) is also collaborating by developing algorithms to calculate the amount of energy that the turbines generate by winds blowing at various speeds for a broad spectrum of wind facilities. The wind prediction technologies have been designed to cover Xcel Energy wind farms in Colorado, Minnesota, New Mexico, Texas, and Wyoming. It is anticipated that wind energy forecasting companies in the United States and overseas may adopt the developed technologies to help utilities that need more accurate wind predictions to transition away from fossil fuels.

To generate wind energy forecasts, NCAR is incorporating observations of current atmospheric conditions from a variety of sources, including satellites, aircraft, weather radars, ground–based weather stations, and even sensors on the wind turbines. The information is utilized by three powerful NCAR–based tools:

- The Weather Research and Forecasting (WRF) computer model, which generates finely detailed simulations of future atmospheric conditions
- The Real–Time Four–Dimensional Data Assimilation System (RTFDDA), which continuously updates the simulations with the most recent observations
- The Dynamic Integrated Forecast System (DICast®), which statistically optimizes the output based on recent performance

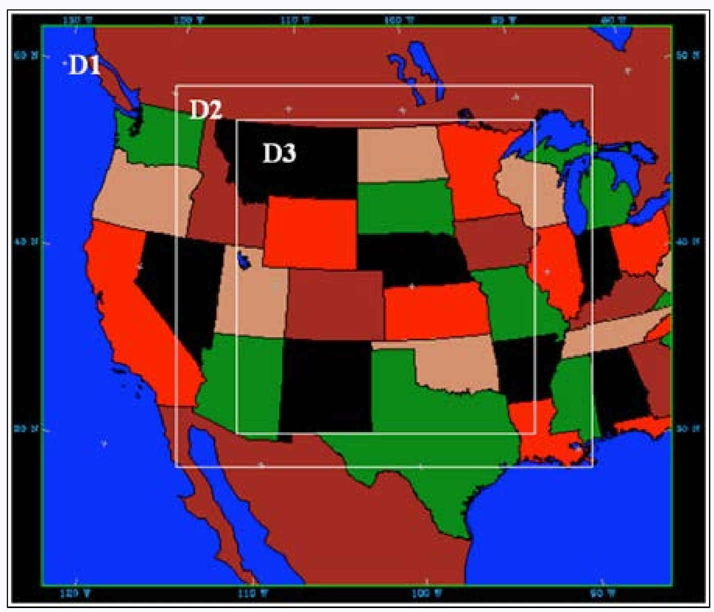

Fig. 1 Diagram of the WRF domains used in the wind energy prediction system. The grid spacings are as follows: D1=30km, D2=10km, and D3=3.3km.

Wind predictions are made for each wind turbine and a sophisticated post–processing algorithm converts the hub–height wind predictions into energy predictions. The energy generation values for each turbine, wind facility and connection node are provided to Xcel Energy.

In the first six months of the agreement, NCAR successfully developed the initial capabilities and began providing wind energy predictions. By late September 2009, all (40+) wind facilities were included. Real–time information from Xcel Energy's largest wind facilities is utilized by the wind energy system to refine the power curve calculations and tune the forecasts.

The Real–Time Four Dimensional Data Assimilation

(RTFDDA) and forecasting system, that has been developed by RAL to satisfy the meteorological needs of Army test ranges, has been adapted for wind–energy prediction. RAL implemented an operational RTFDDA system over the western and central states for supporting wind–power forecasting. This system contains three modeling domains with grid sizes of 30, 10 and 3.3 km (Fig. 1). The 3.3 km domain covers the Rocky Mountains from New Mexico to Montana, the High Plains states, and most areas of the Central Plains. The system runs with a 3–hour cycle. In each cycle, it produces 27–hour forecasts for the innermost domain and 72–hour forecasts for the two coarser domains. The inner domain (3.3 km) generates output at 15–minute time steps.

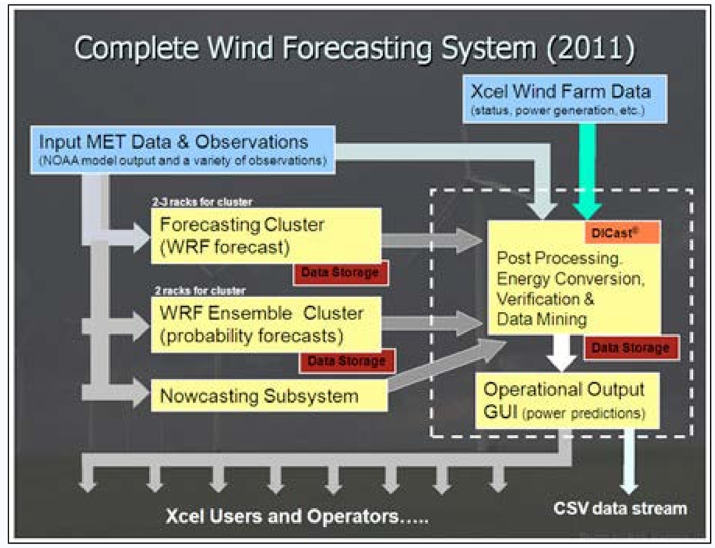

Fig. 2 Conceptual diagram of the wind energy prediction technology components that will be incorporated into the final configuration.

FY2010 Plans:

An ensemble wind energy prediction system will be developed in early 2010 and implemented by midyear. The nowcasting system will be developed in 2010 and should be incorporated in 2011. A final conceptual diagram of the technology components is provided in Fig. 2.

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NEW AND EMERGING APPLICATIONS

Soil Condition Analysis & Prediction

Background

Weather is the critical factor in the success of a harvest and for farmers' livelihoods. Severe weather events, such as hail, high winds, tornados, and flash floods can destroy an entire harvest in a very short period. However, many agricultural decisions simply require more accurate forecasts of the weather and the resultant soil conditions. Precise soil temperature and soil moisture forecasts are critical for the timely application of pesticides, herbicides, seed and fertilizer selection, and for efficient irrigation practices. RAL has been collaborating with industry to develop agricultural decision support capabilities that optimizes the timing of pesticide application and irrigation.

NASA–sponsored Soil Condition Analysis and Prediction Project

This year, NCAR land–surface modelers developed and tested improvements to the High–Resolution Land Data Assimilation System (HRLDAS). The focus has been on improving the modeled surface heat transfer. This seems to be fairly manageable task when operating on a relatively small and homogenous domain. However, as this project covers the eastern United States, a wide variety of land use and soil types are encountered.

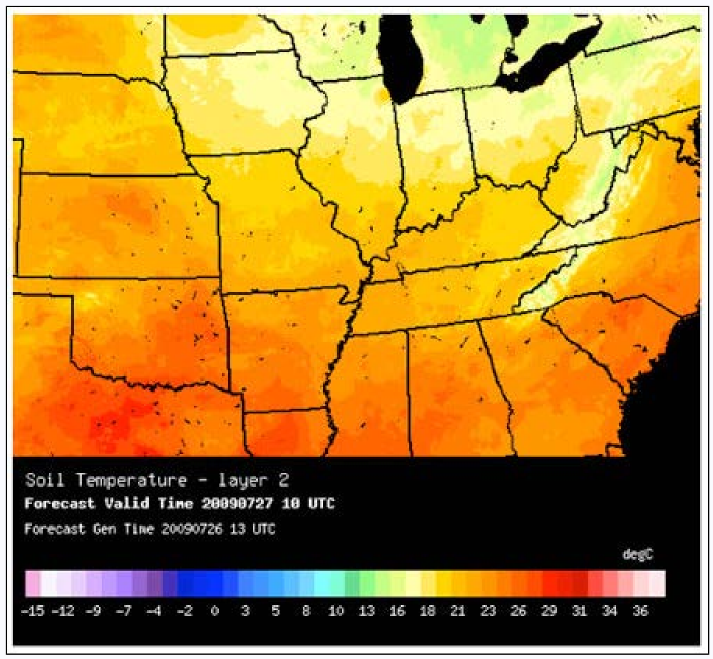

Fig. 1 Soil temperature prediction generated by the RAL soil analysis and prediction system valid on 26 July 2009 at 13 UTC.

The software engineering team upgraded the operational forecasting environment which generates soil temperature and moisture predictions to incorporate the latest versions of HRLDAS. The soil forecast data produced by the system is delivered to Telvent–Meteorlogix, our partners in this project. This system has run continuously since early 2008 and its performance was evaluated again during the 2009 growing season (April–June). Investigations have led to a better understanding of the complexities of land–surface model inputs. Notably, using land–use and vegetation data sets with different resolutions can lead to mismatches which negatively affect model performance.

The control run in this experimental system was initialized using the climatological vegetation state. This is the standard method used by HRLDAS as better estimates of the state of the vegetation are difficult to integrate. A key focus of this project was to evaluate replacing the climatological vegetation state with a remotely sensed vegetation state. The National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) satellite Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation (FPAR) data were used to better capture the current environmental state. The comparison of this variation to the control run was very important to the sponsor, NASA, who was interested in determining the value of the MODIS instrumentation to improved soil prediction. With the current HRLDAS heat transfer scheme, the MODIS data significantly improved the 5–cm soil temperature forecasts in regions east of the Mississippi. These areas are more heavily vegetated than the Central Plains. In the Central Plains, the use of the MODIS data made the forecasts worse for the early months of the growing season. However, as these areas

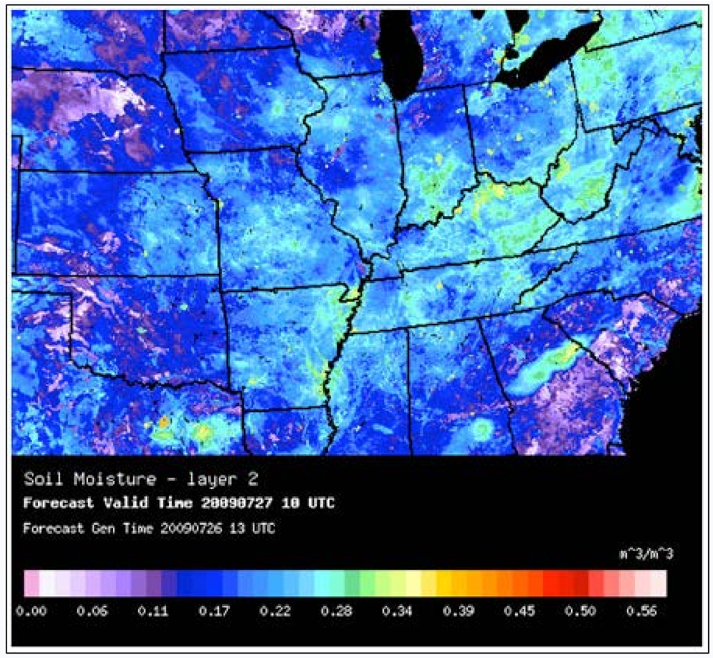

Fig. 2 Soil moisture prediction generated by the RAL soil analysis and prediction system valid on 26 July 2009 at 13 UTC.

became more vegetated, the MODIS data improved the soil temperature forecasts.

Interactions with Televent–Meteorlogix were geared toward designing products oriented towards the agricultural end–user. The Decision Support System, DTN Online, has approximately 80,000 subscribers. Several easy to use summaries of the forecast data were prototyped for potential use in the DSS. The high–resolution soil condition forecasts are now being evaluated by end users.

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NEW AND EMERGING APPLICATIONS

Wildland Fire Behavior Modeling

Background

RAL and MMM have spent several years performing research and development on coupled weather – wildland fire behavior models with the goal of producing public domain models that can be used for research, education, and applications. This presents many substantial scientific, computational, and operational challenges. Although current field tools for diagnosing expected fire behavior are simple algorithms that can be run on calculators, researchers and fire managers alike envision a future when we might rely on complex simulations of the interactions of fire, weather, and fuel, driven by remote sensing data of fire location and land surface properties, as a component of planning, education, evacuation, and wildfire mitigation decision support systems.

Open Wildland Fire Modeling E–Community

NCAR and collaborators at the University of Utah and the University of Colorado at Denver were funded by NSF's Cyber–Enabled Discovery and Innovation program to develop an Open Wildland Fire Modeling E–community. The team's goals are to release open source community models, provide a hub for other models to be plugged and used by the community, and develop forums for fire–weather community collaboration so that diverse, interdisciplinary, geographically–distributed participants can collaborate.

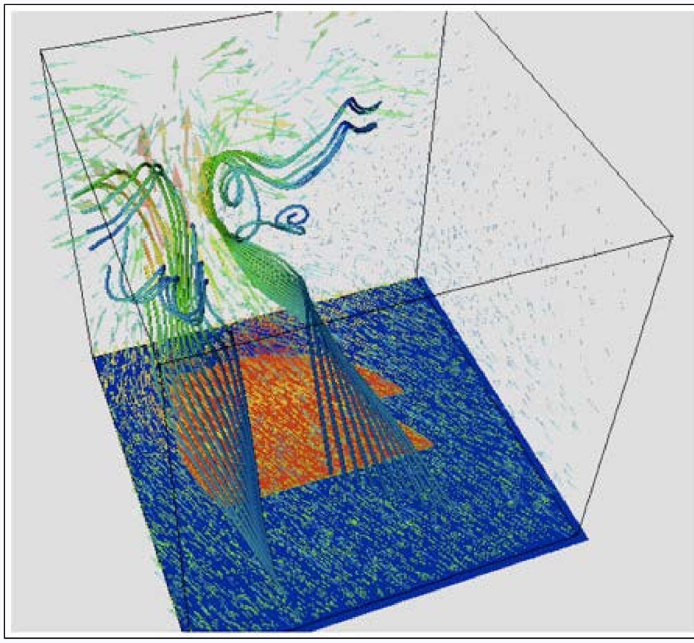

Fig. 1 Streamlines of the flow of air (colored by temperature) drawn into two merging fires (burned out area location shown by darker colors on the surface). The coupled weather–fire model (WRF–Fire) and concurrent visualization (using the SCIRun Problem Solving Environment, for modeling, simulation and visualization of scientific problems) is managed by the VisTrails open–source scientific workflow and provenance management system.

As the first milestone, NCAR and colleagues at the University of Colorado Denver released the open source WRF–Fire module, a wildland fire behavior module coupled to WRF, and are refining it with approximately two dozen test users. A scientific steering committee has been established to identify and prioritize development needs. Drafts of user guides and technical documentation have been produced.

As a second milestone, a basic system prototype enabled users to seamlessly manage the model configuration workflow of adjusting model parameters, running a suite of simulations, and visualizing results using a linked WRF–Fire model, the University of Utah VisTrails collaboration software, and the University of Utah SCIRun Problem Solving Environment visualization software.

The project is establishing a repository for all public domain software output from the project, beginning with the WRF–Fire distribution at Open Wildland Fire Modeling.

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NEW AND EMERGING APPLICATIONS

Weather Prediction – Statistical Optimization

Background

RAL has been 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 this 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.

Intelligent Weather Prediction Systems

DICast® continued to become an integral part of many RAL projects. Amongst the projects relying on DICast® this year are the NASA–Agriculture, Telvent technology transfer, Global Weather Forecasting, Winter Road Maintenance Decision Support System, and Xcel Energy. Each project has a very different focus and requirements. DICast® has been pushed to accommodate and satisfy each of these. The continuing development of these systems has led to a broader set of tools that can be applied to a new problem domain.

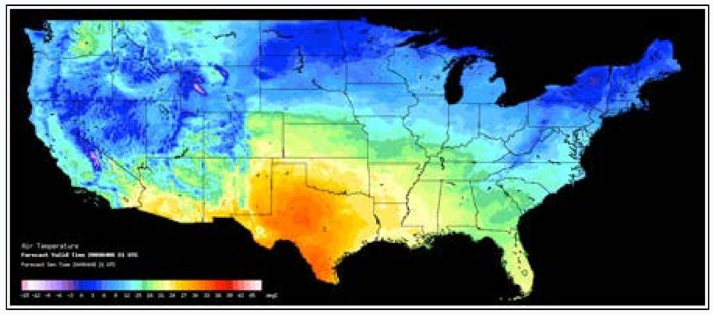

Fig. 1 LOGICast™ generated forecast of air temperature data over the CONUS valid on 6 April 2009 at 21 UTC.

DICast® research topics this year include development of turbine hub height wind forecasts, new Dynamic Model Output Statistics (MOS) techniques, and evaluation of new National Centers for Environmental Prediction (NCEP) MOS products and foreign weather services' NWP models. Software development efforts have explored configuring and evaluating higher resolution forecast systems for the near term (0–12 hours).

DICast® is a point forecast system that makes tuned forecasts typically at observation sites. There is a need however for forecasts where observations do not exist. The LOGICast™ system was refined this year to produce forecasts on a 4–km grid over the CONUS. This satisfies the needs of many users, such as Location–Based Services (LBS). For these applications, a high quality forecast at the specific location is critical. Example of this would be the cell phone market or road paving operations. LOGICast™ is an ideal weather forecast technology for these emerging application domains.

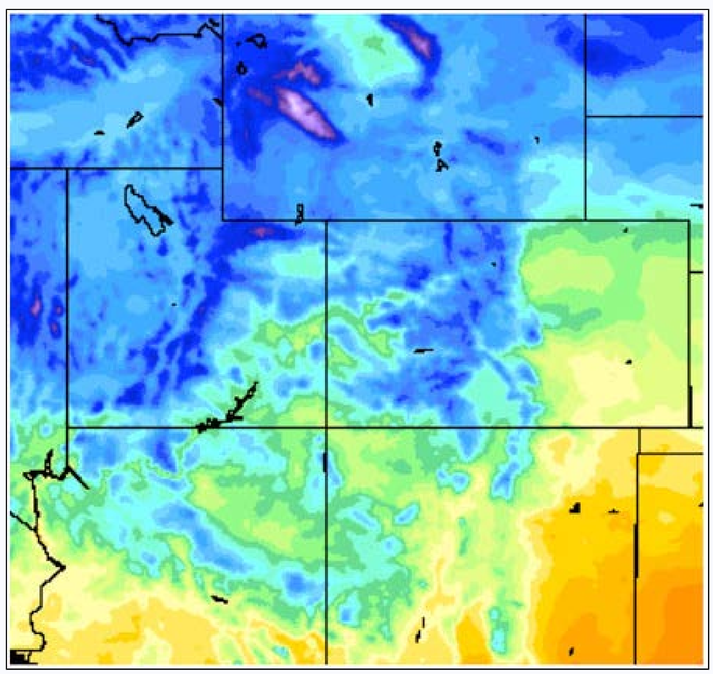

Fig. 2 LOGICast™ generated forecast of air temperature data over the intermountain west valid on 6 April 2009 at 21 UTC.

LOGICast™ generates an initial guess at the forecast using spatially and temporally coarse direct NWP model output. This first guess is downscaled using high–resolution climatology and temporal interpolation techniques. The result is a high–resolution forecast that lacks in tuning. DICast® forecasts are utilized to nudge this high–resolution forecast towards a more accurate solution.

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NEW AND EMERGING APPLICATIONS

International Aviation Weather Systems

Background

RAL has spent the past twenty–eight years addressing and supplying the needs of aviation stakeholders in the U.S. and other countries. This work has yielded fundamental improvements in the scientific understanding of aviation weather hazards as well as a broad array of practical tools and systems that reduce the vulnerability of aviation to such hazards. RAL has worked with international civil aviation authorities to modernize their aviation weather systems. This work includes developing and implementing wind shear and turbulence alerting systems, four–dimensional gridded aviation weather forecasting systems that include guidance products covering in–flight icing, turbulence, winds, temperatures, ceiling visibility, and convective hazards. RAL's international aviation weather research and development leverages the results of RAL's aviation weather research conducted with Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) funding. Advanced aviation weather systems include the Windshear and Turbulence Warning System (WTWS) in Hong Kong and the Advanced Operational Aviation Weather System (AOAWS) in Taiwan. RAL also consults with international aviation authorities on aviation weather hazards, particularly on wind shear and wind shear detection systems.

Advanced Operational Aviation Weather System (AOAWS)

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, airspace capacity and safety at Taiwan's major hub airports. In 2009, NCAR's local Taiwan technology partner became InfoExplorer, Co., Ltd.

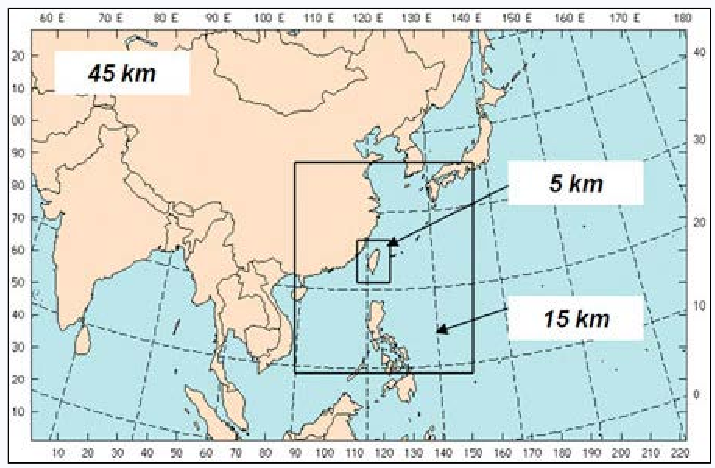

Fig. 1 Illustration of the three WRF model domains and respective grid spacing used by the Central Weather Bureau (CWB) that also support the AOAWS. The Taipei Flight Information Region (FIR) is covered by the WRF 5–km domain.

The AOAWS research and development project is currently focused on improving the WRF modeling system, advancing the WRF data assimilation system (WRF–VAR) to incorporate new data types (e.g., COSMIC GPS, and satellite radiance data, etc.), upgrading the in–flight icing and turbulence algorithms to incorporate the latest advancements developed as part of the FAA Aviation Weather Research Program, and developing new JAVA based display systems.

Major components of the AOAWS include: Low–Level Windshear Alert Systems (LLWAS Phase III) at Songshun and Taoyuan International Airport (formerly known as Cheng Kai Shek International); the WRF model which provides regularly–updated forecasts on three domains with grid spacing of 5km, 15km, and 45km; 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.

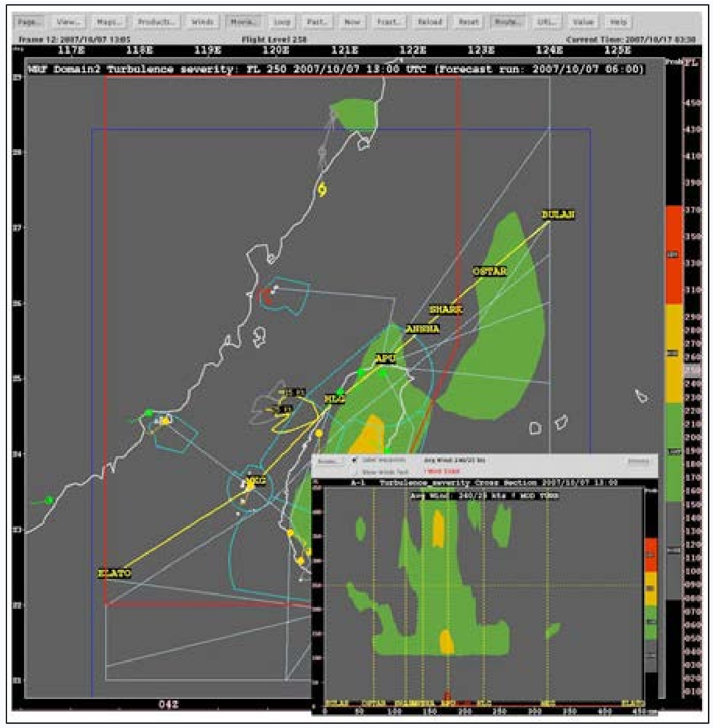

Fig. 2 AOAWS Java based Multi–dimensional Display System (JMDS), which integrates all available aviation weather products (real–time and forecasts) and displays the information automatically in plan view or in vertical cross section form along user–defined flight routes. Image shows predicted clear–air turbulence at 25,000 ft and along a flight route.

FY2009 Accomplishments:

Several system upgrades were accomplished in 2009 including upgrades to the WRF model and the WRF–VAR data assimilation system to Version–3.x. New input datasets were explored including AMSU–A radiance data, and parametric studies were performed to evaluate various physics packages to optimize WRF performance over Southeast Asia. A new AOAWS tropical cyclone bogus scheme was also developed and ported to the Central Weather Bureau's (CWB) WRF model.

Research was also conducted to evaluate the performance of the in–flight icing and clear–air turbulence products operating on the Taiwan WRF modeling system. The in–flight icing algorithm was upgraded to a version similar to the FAA's Forecast Icing Potential Product (FIP) product, and the turbulence product was upgraded to be similar to the FAA's Graphical Turbulence Guidance (GTG) product. Both algorithms were evaluated using a WRF model configuration similar to Taiwan, but run over the continental U.S. where sufficient pilot reports (PIREPS) were available to support the performance verification studies.

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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.

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NATIONAL SECURITY APPLICATIONS

Operational Numerical Weather Prediction and Improved Data Assimilation

Background

RAL has developed and deployed very high fidelity, operational, computer–based weather analysis and forecasting systems for many applications worldwide. For example, new weather–prediction systems have brought the Army Test Ranges and Proving Grounds into the 21st century, in terms of weather services. The improved weather information for Army test planning has saved tax payers millions of dollars. Numerous other domestic projects include providing general weather support for Navy missile launches in California and Hawaii, supporting potential Space Shuttle landings at alternative sites, and forecasting for wind farms. Recently, in collaboration with AirDat LLC, NSAP built a CONUS–scale operational forecasting system that runs with its data–assimilation technology and uses observations from special AirDat weather instruments onboard regional commuter aircraft. Another focus of such operational systems is on urban areas and urban impacts on the weather.

U.S. Army Test and Evaluation Command Four–Dimensional Weather System

Over the past 13 years, the U.S. Army Test and Evaluation Command (ATEC) has sponsored research and the development of the Four–Dimensional Weather (4DWX) system, an advanced, computer-based system for analyzing and modeling weather. 4DWX has two model cores, the traditional MM5 and the state–of–the–art WRF model, and assimilates observations via NCAR's Real–Time Four–Dimensional Data Assimilation (RTFDDA) scheme. 4DWX provides high–resolution mesoscale numerical weather prediction (NWP) products, short–term thunderstorm predictions, multi–dimensional integrated displays, and fine–scale climatological analysis tools, enabling the Army to test materiel under precise conditions across the full spectrum of arctic, tropical, desert, and other natural and controlled environments. The WRF model core of 4DWX was recently upgraded to version 3.1. The 4DWX is accredited for operational use at seven test ranges (Fig. 1).

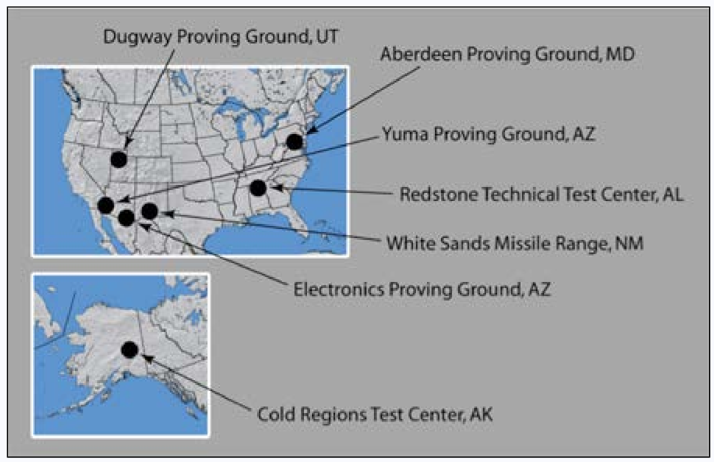


Fig. 1 Army test ranges that use 4DWX.

Data Assimilation

4DWX has traditionally used the RTFDDA scheme to assimilate a multitude of observations from common and specialized sources. RTFDDA involves modifications to an NWP model's predictive equations, which permit the model to be gently adjusted, or nudged, toward observed conditions during the analysis stage. 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. In order to assimilate observations not associated with variables in the model's predictive equations, RAL is combining RTFDDA with a 3–Dimensional Variational Data Assimilation (3DVAR) scheme. A research version of this new, advanced hybrid scheme has been successfully tested, to the overall benefit of 4DWX's performance.

New Datasets

RAL has developed a unique method of creating global, spatial–temporal composites of real–time lake– and sea–surface temperatures (SSTs) derived from the MODIS instruments aboard polar–orbiting satellites operated by NOAA. The resolution of these composites is higher than those of most SST datasets currently used for operational forecasting, and numerous studies have shown that finer SSTs lead to better simulations of the atmosphere. RAL is in the process of including these improved observations in the 4DWX system.

Ensemble Forecasting

RAL continues to operate and improve an ensemble forecast system (called E–4DWX) for Dugway Proving Ground (DPG), one of the army test ranges that use 4DWX. E–4DWX provides a suite of 30 mesoscale forecasts, all valid at the same place and time.

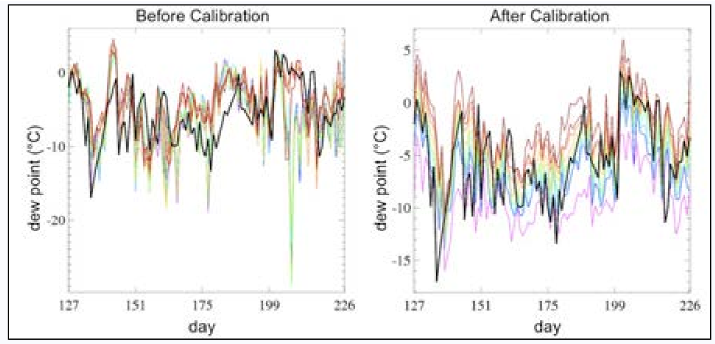


Fig. 2 Example of the benefits of calibrating E–4DWX. Both panels show a series of 42–h forecasts of dew point (°C) for a station at Dugway Proving Ground. Before calibration (left panel) the ten quantile forecasts (colors) from the ensemble are biased high compared to the observations (black), and the spread among quantiles is too small. After calibration (right panel) the spread is larger and the envelope of forecasts generally encompasses the observations.

Differences among members are introduced by varying initial conditions, boundary conditions, model physics, and model cores. RAL has developed and applied an innovative technique, based on quantile regression, for calibrating forecasts of precipitation and near–surface temperature, dew point, and wind, making E–4DWX one of the few calibrated, operational, mesoscale ensembles in use anywhere in the world (Fig. 2).

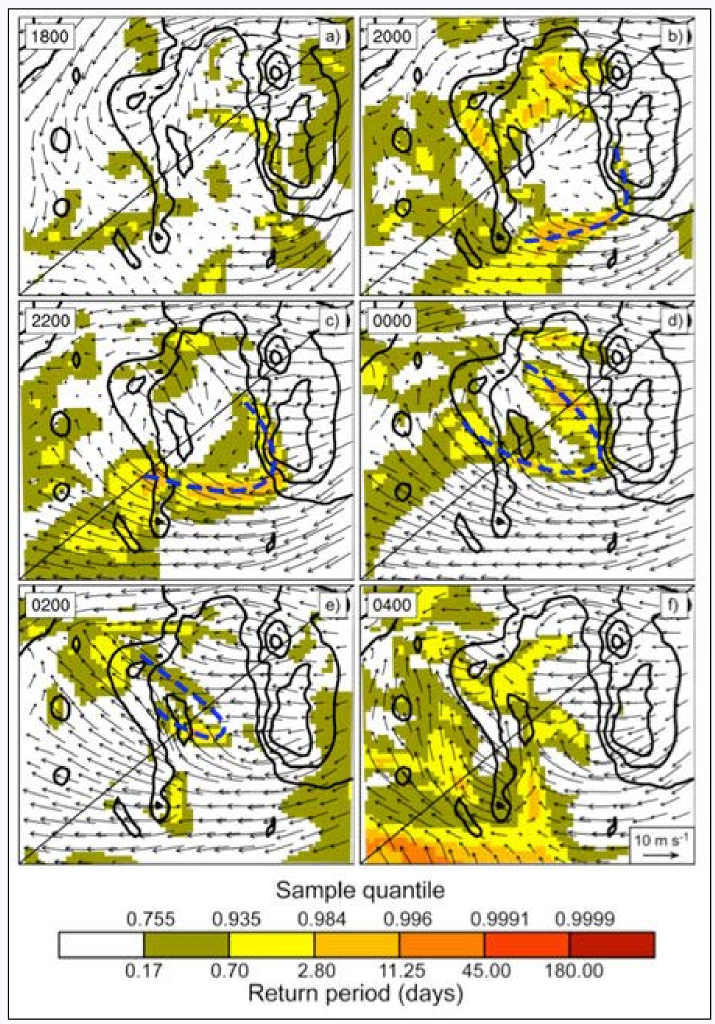
Coupled Applications

The direct weather predictions from 4DWX and E–4DWX are the essence of the forecast guidance used by staff at the ATEC ranges, but substantial value can be added to such predictions by diagnosing how the weather affects other processes and conditions, such as sound propagation and the trajectories of missiles. To achieve this added value, RAL couples analyses and forecasts to secondary models, sometimes called coupled applications. These include:

- Noise Assessment and Prediction System (NAPS)
- Second–order Closure Integrated Puff (SCIPUFF) model
- Lewis Rocket Trajectory Model, and
- Open Burn / Open Detonation Model (OBODM)

While exploring new opportunities in coupled modeling, RAL recently demonstrated that Cn2 (a structure parameter that describes atmospheric refractive index) can be successfully estimated from some configurations of 4DWX. These demonstrations suggest that 4DWX might play an important role in forecasts related to optical imaging, performance of global positioning systems, and communications that are sensitive to atmospheric turbulence.

Model Verification



In FY09, RAL continued development of approaches to model verification that go beyond traditional metrics such as root–mean–squared errors calculated at points. Among these newer approaches to verification is one recently developed that compares the characteristics of temporal changes in observed wind (10 m AGL) with wind simulated by numerical models. Although these changes are defined independently from site to site and grid point to grid point, clusters of changes in observations and simulations are nevertheless highly continuous in space and time (Fig. 3). Such continuity strongly suggests that graphical depictions of these clusters can serve not only as a means for judging a model's skill, but also as a tool that will allow forecasters to mentally adjust for a model's biases in wind forecasts.

Web Portal

RAL completed the transition to the Web Portal as the primary interface to the 4DWX system at all ATEC ranges (Fig. 4). The portal's flexibility, accessibility, modularity, and extensibility have facilitated user acceptance and RAL's rollout of additional capabilities for the 4DWX system.

Climate FDDA (CFDDA)

Expensive, weather–sensitive tests at the Army ranges sometimes must be planned months or years in advance, well beyond the reach of conventional NWP. As a solution to this dilemma, RAL uses a range's observed weather over recent decades to make long–range, probabilistic weather forecasts. Most datasets of weather information from past decades are too coarse, by themselves, to be useful for this approach, so RAL adds detail to these datasets through dynamical

downscaling. During downscaling, gridded climate data from coarse sources are assimilated into a modified version of the RTFDDA system that, when run in this downscaling mode, has been dubbed Climate FDDA (CFDDA). CFDDA re–analyses are stored, studied, and translated into statistical descriptions of a range's regional climate. Forecasters will be able to access these statistics and provide fast, customized, cost–saving, probabilistic, long–horizon estimates of weather conditions to test directors.

NLDN Climatography

Cloud–to–ground lightning strike climatographies are being computed for each of the ATEC ranges in the conterminous U. S. from ˜6 years of National Lightning Detection Network (NLDN) data. These data will be used for long–range strategic mission planning at the ranges, within the model–based lightning forecasts, and within the AutoNowcaster.

Short–Term Lightning Prediction

Total lighting data from the Lightning Mapping Array (LMA) at the White Sands Missile Range (WSMR) are being tested as input into the AutoNowcaster for the purposes of:

Fig. 3 10–m (AGL) wind events for a day when a cold air mass moved through White Sands Missile Range (22–23 April 2005). Simulated winds (arrows) are plotted atop return periods (colors). Corresponding sample quantiles are shown in the label bar. Thick lines show terrain elevation every 400 m. Vector winds are plotted at every fourth grid point. Times are UTC. The thick, dashed, blue line marks a major temporally coherent feature.

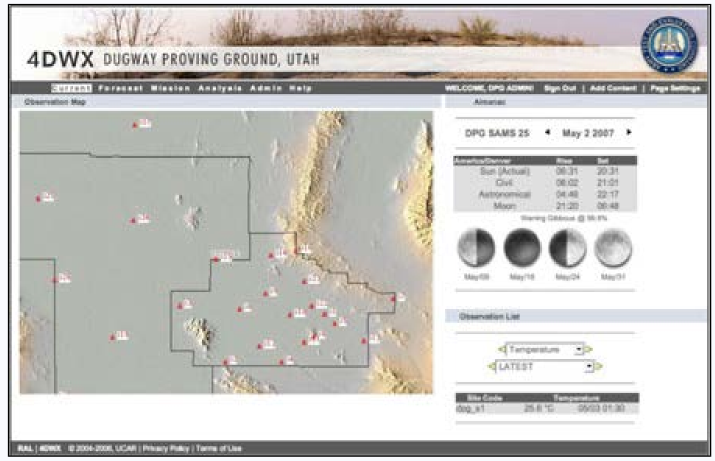


Fig. 4 Front page of the 4DWX Portal at Dugway Proving Ground. From this page, forecasters can access model output, current and historical observations at the stations shown in red on the map, a tool for issuing weather warnings, and more.

1. Improving short–term forecasts of moist convection's growth and dissipation
2. Producing a short–term forecast of total lightning potential

Preliminary results for the first goal are promising.

Model–based Lightning Forecasts

Lightning potential forecasts, out to a 48–hour lead time, have been developed using the 4DWX system at WSMR. From the model output, lightning amounts are computed in each grid cell using an empirical relationship for lightning–ice–water path and lightning–updraft volume. A fuzzy logic algorithm combines these two parameters, plus the cloud–to–ground lightning strike climatography, to compute a single lightning potential. Validation was accomplished with the LMA at WSMR.

FY2010 Plans:

RAL is collaborating with Unidata to integrate 4DWX with the Integrated Data Viewer (IDV), a sophisticated, flexible, Java–based application for analyzing and displaying geophysical data. IDV will become one of the primary means by which range forecasters display weather analyses and forecasts.

Web Portal development will also continue and will emphasize making enhancements that are prioritized based on feedback received from range users.

RAL will continue to develop a hybrid data assimilation scheme that combines the best attributes of RT–FDDA and 3DVAR, with the eventual goal of full operational implementation. RAL also will continue to explore methods for assimilating radar data into 4DWX. The approach being pursued is a coupled cycling of RTFDDA and the Variational Doppler Radar Assimilation System (VDRAS).

4DWX is currently run on Linux computers distributed among the test ranges and at NCAR. In 2010, RAL will begin a multi–year consolidation of 4DWX hardware. One cluster, to be located at DPG, will run the primary configuration of 4DWX for all ranges. A second cluster, to be located at another range to be determined, will run a back–up configuration of 4DWX for all ranges, thus providing complete redundancy in the event that operation of the primary 4DWX system is interrupted.

RAL will finish developing, and will release, an interactive GUI that permits forecasters and other users of model output to customize reporting of verification statistics. Output will include two–dimensional maps and time series of verification statistics, both in terms of forecast hour and time within the diurnal cycle. Statistics for 4DWX will be compared with those of other operational models, such as those from the National Centers for Environmental Prediction (NCEP).

RAL will complete installation of a unique method of dynamically correcting the WRF Model's bias in near–surface temperature, humidity, and wind over full computational domains, even where observations are unavailable.

NCAR will optimize, test, and implement the Variational Doppler Radar Analysis System (VDRAS) for a mobile X–band radar and a fixed C–band radar at DPG. VDRAS assimilates series of real–time radar observations (radial velocity and reflectivity) from single or multiple Doppler radars, and then uses a fast numerical model to make frequently updated, short–term forecasts of dry flow in the planetary boundary layer.

Model for Advanced GENeration of 4D Weather (MAGEN) for Government of Israel

MAGEN is a 3–year project to apply and improve the RAL Real–Time Four–Dimensional Data Assimilation (RTFDDA) and forecasting system for operational forecasting over the Eastern Mediterranean region, centered over Israel. The system will 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 NCAR RTFDDA system with several improvements that are applicable to the weather regimes, the data availability, and the operational needs of the sponsor in this unique geographical region.

Preliminary numerical experiments illustrate that it is necessary to use high–resolution grids in order to resolve the major forcing factors that control the mesoscale weather processes. For example, a 10 km grid–increment model tends to erroneously shift the winter precipitation from the coastal mountains to offshore areas. To maximize the use of computing resources, the MAGEN modeling system is configured with three nested grids, with 30, 10 and 3.3 km grid intervals. The 3.3 km fine–mesh domain is movable so that it can provide simulations for different regions. Fig. 1 shows a map of the model domain configuration.

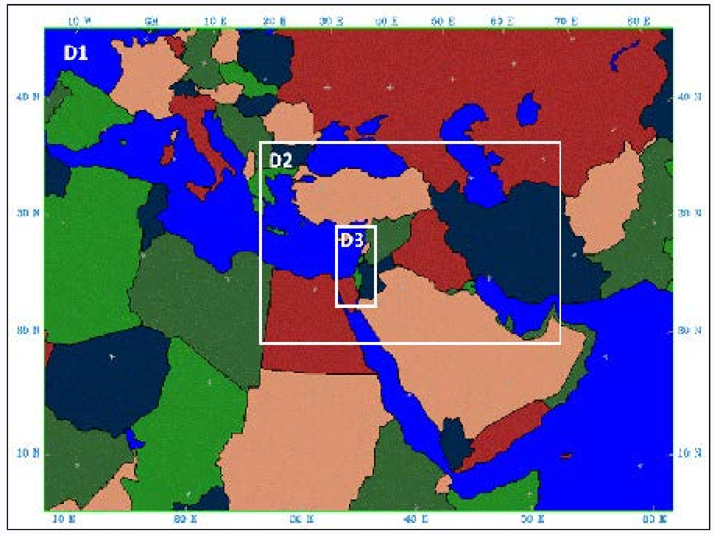


Fig. 1 MAGEN model domain configuration.

RTFDDA is a continuous–cycling data assimilation and forecasting system, which performs optimally in areas where rich conventional weather observations are available, such as in the US, Europe, and Eastern Asia. To take advantage of the data–assimilation scheme for data–sparse regions in the Middle East, a hybrid data assimilation scheme employs the 3DVAR (3 Dimension VARational) assimilation of satellite remote–sensing data. The 3DVAR analysis is integrated into RTFDDA through a "grid-nudging" approach. The hybrid data assimilation permits improved synoptic–scale weather forecasts, and provides a large–scale constraint for the finer meshes. Figure 2 describes the concept of the RTFDDA–3DVAR hybrid data assimilation approach proposed for the MAGEN system.

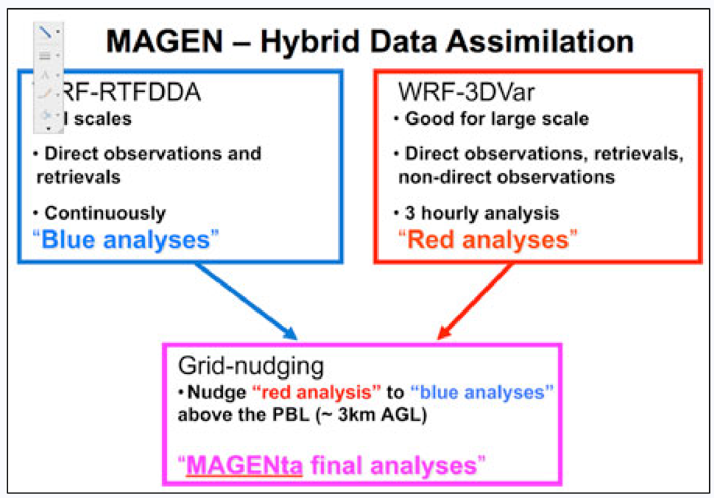


Fig. 2 Concept of RTFDDA and 3DVAR hybrid data assimilation for MAGEN.

Another key scientific aspect of the MAGEN system is the model–physics and model–configuration optimization. We are studying the performance and characteristics of different WRF physics schemes and their combinations by conducting numerical experiments for a case–study testbed made up of prevailing and high–interests weather cases. In addition to the model physics, the model dynamical algorithms, positions of vertical levels, the nesting strategy, and data–assimilation weighting functions are being studied. Forecast cycling algorithms are also being customized for different fine–mesh regions, to account for the data density and the complexity of local terrain and land–surface features.

The MAGEN project began in the second half of FY2009. A demonstration forecasting system, built upon the off–the–shelf basic RTFDDA technology, has been set up at NCAR and is providing real–time weather forecasts to the sponsor. Baseline numerical experiments for two selected cases have been carried out. Progress has been made regarding the processing and analysis of observation data from the Middle East countries.

FY2010 Plans:

FY10 will be a critical year for developing the advanced data assimilation algorithms and optimizing various model components. The FDDA and 3DVAR hybrid data assimilation scheme will be further designed and implemented. Testing and optimization of data–assimilation algorithms will be conducted. Model physics and domain configurations will be optimized through the use of case studies and on–line parallel testing with real–time semi–operational models. An optimized MAGEN modeling system will produce forecasts for the Middle East users.

RTFDDA Operation for Wind Energy Forecasting

The effective combination of mesoscale weather modeling systems with diverse weather observations can provide high–resolution forecasts for many weather–critical applications. At RAL, such a system has been developed by enhancing the MM5 and WRF models with a four–dimensional data assimilation (FDDA) capability, namely the RTFDDA (Real–time Four–dimensional Data Assimilation) and forecasting system. In the last few years, the RTFDDA has been deployed to provide multi–scale (meso–

gamma to meso–alpha), rapid–cycling (1 – 6 hours), fine resolution (0.5 – 3 km grid intervals) real–time weather information for many weather–sensitive missions and field experiments, several US government agencies, public and industrial sponsors, and foreign governments and institutes. The RTFDDA data assimilation technology is also the core engine for the RAL regional current–climate downscaling capability. In FY09, in addition to providing continuing support to a few existing projects, the RTFDDA system has also been deployed for several new operational applications, including renewable energy.

Xcel Energy Project

Accurate weather forecasting is critical for wind energy production and management because the wind speed can change rapidly in a short time period, and the associated wind power variability represents a challenge with respect to managing the power grid. Being able to accurately predict wind power allows power companies to save substantial amounts of money. So, in December 2008, NCAR, in collaboration with Xcel Energy, began to design and implement a version of the RTFDDA forecasting system. In June 2009, an Initial Operational Capability (RTFDDA–IOC) started running, and currently provides real–time prototype products to Xcel Energy.

Operational forecasting for wind energy faces many challenges. First, the forecast accuracy requirements are much greater than for typical weather forecasts. Second, surface and lower–level winds are highly variable in space and time because they are the product of multi–scale interactions, and complex terrain can greatly magnify this challenge. Third, there is a very limited understanding of the modeling requirements for representing the wind at turbine hub heights, and across the turbine blades. To address these difficult issues, the RTFDDA modeling effort includes basic model–physics parameterization optimization, optimal use of the wind farm measurements, and advanced model output post processing.

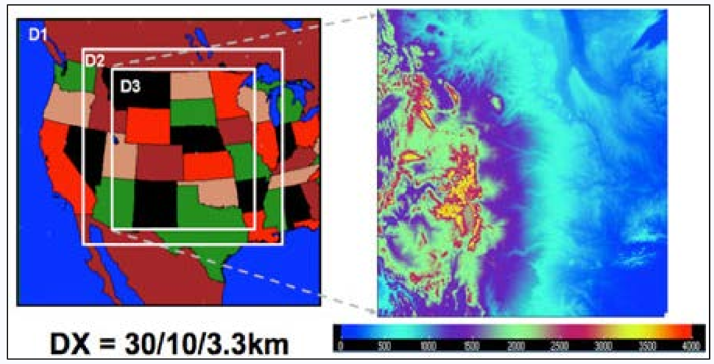


Fig. 1 Domain configuration of the RTFDDA–IOC system for Xcel Energy wind power prediction. The terrain height is plotted for the innermost Domain 3.

To address the dominant effect of the Rocky Mountains on the weather in the Front Range area where the major Xcel wind farms are located, the operational RTFDDA system was set up with a large fine mesh, with 3.3 km grid increment, to cover the major forcing of the Rocky Mountains (Figure 1). The RTFDDA–IOC system provides real–time forecasts for the Xcel Energy sponsor, and serves as an experimental testbed for development of model improvements.

Figure 2 presents RTFDDA forecasts for an episode with a significant wind ramp–up and ramp–down at Cedar Creek, a large wind farm with 274 turbines within a 10 km x 15 km area. The RTFDDA–IOC captures the major ramp up and ramp down reasonably well. However, the capabilities of the RTFDDA–IOC for forecasting the detailed features of the ramps need to be improved.

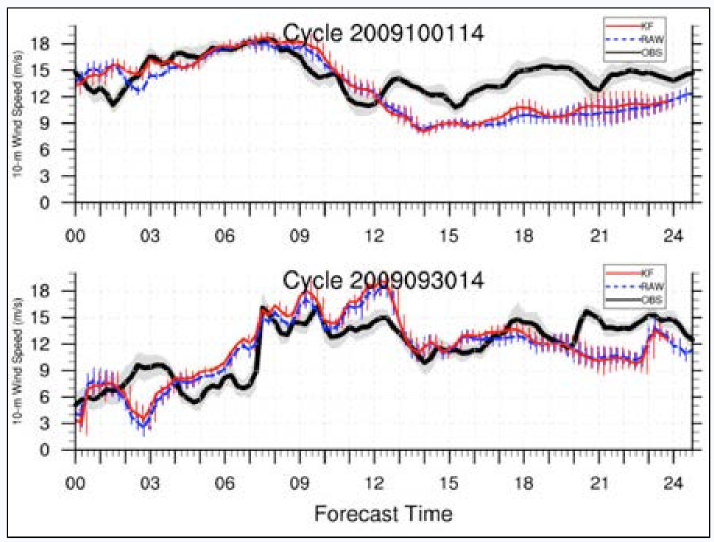


Fig. 2 RTFDDA-IOC wind forecasts for a strong-wind event. Two RTFDDA-IOC forecast cycles, the 14Z cycle on September 30 and the 14Z cycle on October 1, 2009 are presented.

To study the RTFDDA–IOC performance, a careful analysis of the bias of the RTFDDA forecasts under different weather regimes was conducted using the RTFDDA–IOC output archive. Many numerical experiments were performed for selected weather cases, to study the behavior and performance of the boundary layer and land surface schemes within WRF. Wind farms provide meteorological tower reports, and clusters of dense wind–speed measurements from the turbines, which offer a new opportunity for data assimilation. Analyses of these high–frequency wind farm observations were carried out, and statistics were computed for intra–farm wind variations.

The WRF model exhibited systematic biases, especially in the surface variables. The wind biases should be removed for power conversion. An advanced Kalman–filter(KF)–based bias correction scheme is applied to the RTFDDA forecasts to remove the biases of the surface wind and temperature forecasts. Furthermore, the KF scheme is adapted for regression–based downscaling of the RTFDDA wind forecasts to the power forecasts.

Wind farm data analyses indicate large intra–farm wind variations across a few tens of kilometers distance. The current knowledge about such microscale wind variability is very limited. The RTFDDA was extended to model microscale flows using nested grids to simulate the multiple scale weather, from the synoptic scale to the microscale, with grid sizes varying from 30 km to 123 m. Realistic high–resolution terrain from the NASA Shuttle Radar Topography Mission (SRTM) was used for the fine grids. This 6–nest WRF–RTFDDA–LES model was used to simulate a two–day event over a large farm located in northern Colorado. For this case, data assimilation was activated on the four coarse mesoscale grids, and Large–Eddy–Simulation (LES) settings were specified for the two finest meshes. This study found that the WRF–RTFDDA–LES reproduced many realistic intra–

farm flow features, thus providing encouragement about its possible use in future operational real–time modeling. The result also illustrates that the vertical profiles of wind speed in the lower boundary layer vary dramatically with different grid sizes, even through the same boundary layer parameterization scheme was used for all mesoscale grids.

FY2010 Plans:

Despite the advances represented by our model applications for wind–energy forecasting, great challenges and the need for improved wind–forecast accuracy remain. The modeling work carried out in FY09 will continue. Land surface processes and boundary layer physics will be studied to address the surface wind and temperature forecast biases.

Considering the inherent limitation of weather predictability, especially over complex terrain, a version of the RTFDDA ensemble prediction system will be set up to provide probabilistic forecasts for the same areas served by the deterministic system. Optimization of the ensemble system to produce reliable probabilistic information about wind power will be important. Methods for ensemble perturbation sampling, model output calibration, and derivation and presentation of uncertainty information will be explored. Specific attention will be focused on wind energy ramp events because of their special importance for Xcel operations.

The methods for Kalman–filter–based bias correction and turbine–site wind and power downscaling will be refined. Specific factors to be explored include:

- Analog–based training – only making use of similar historical scenarios to define bias correction gain
- Taking into account recent observations for 0 – 3 h nowcasting
- Making use of cluster analysis

Research and exploration of the WRF–RTFDDA–LES capability will be pushed forward. More observational and modeling case studies for different geographical locations and weather regimes will be conducted. The research will be aimed at understanding the complex microscale flows, and improving the WRF LES modeling capability.

AIRDAT 4–Km CONUS RTFDDA Forecasting System

AirDat LLC deploys and operates an airborne weather measurement system called TAMDAR – Tropospheric Airborne Meteorological Data Reporting. TAMDAR systems are installed on the aircraft of numerous regional airlines to measure temperature, pressure, winds, moisture, icing, turbulence, and GPS heights during the flights. In recognition of the ability of the RAL Real–Time Four–Dimensional Data Assimilation (RTFDDA) and forecasting system for effectively assimilating weather observations that are highly variable in space and time, such as the airborne observations, AirDat collaborates with NCAR on evaluating the use of the TAMDAR data for short–term operational numerical prediction. We also are exploring the use of data assimilation algorithms to optimize the TAMDAR–data's impact on forecast quality.

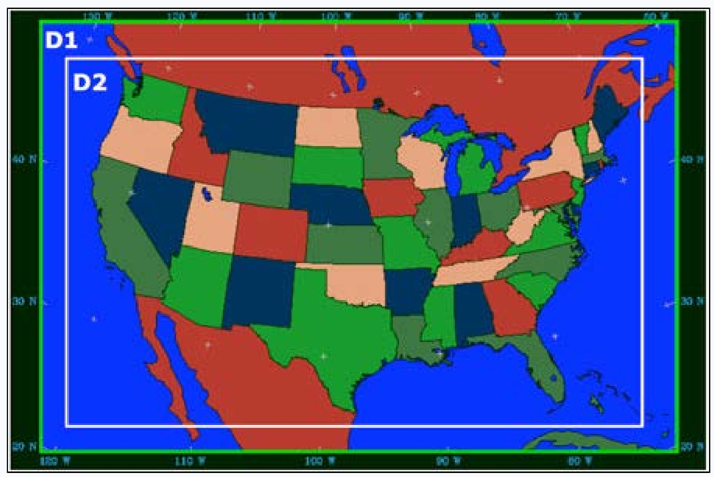


Fig. 1 The NCAR–AirDat RTFDDA–WRF domain configuration for CONUS forecast operations. (D1: DX=12 km, 441 x 303 x 36 and D2: DX= 4 km, 1192 x 766 x 36).

In the summer of 2009, AirDat purchased a 1280–node computing cluster and worked with NCAR to develop a CONUS–scale explicit (with a 4–km grid increment) operational RTFDDA system, called NCAR–AirDat RTFDDA–WRF. This system was configured with two one–way–nested domains, with 12 and 4 km grid sizes (Fig. 1). The system assimilated observations from both NOAA/MADIS (Meteorological Assimilation Data Ingest System) and all TAMDAR fleets. The MADIS data feed is made up of both WMO/GTS (World Meteorological Organization, Global Telecommunications System) data sources as well as observations from NOAA wind profilers, cooperative agency wind profilers, satellite cloud–drift winds, GPS, and a large number of mesonets across the US. TAMDAR data sets provide ˜5000 daily soundings in North America at more than 360 locations.

The NCAR–AirDat RTFDDA–WRF uses a 6–hour forecasting cycle, associated with 4–D continuous data assimilation. In each cycle, the system generates 6–hour final analyses from–6 h to the current hour and 72 hour forecasts. NOAA GFS operational forecasts are used for lateral boundary conditions, and at cold–start times (once a week) for initial conditions. The system began operation in July 2009. Verification of the system performance for the summer season is being carried

out. The research objectives include evaluation of the benefit of the explicit forecasting of convection, investigation of the impact of the TAMDAR data on forecast skill, comparison with NOAA NCEP operational forecasts, and studying the impact of cumulus parameterization and microphysics schemes.

Figure 2 compares NCAR–AirDat RTFDDA–WRF short forecasts of convective systems on the 12 km and 4 km grids with NCEP STAGE 4 precipitation analysis. It can be seen that the explicit convection forecast on the fine mesh produces better agreement with observations in terms of the convection morphology and the locations of convective bands and cells.

FY2010 Plans:

NCAR–AirDat RTFDDA–WRF research will focus on three major areas. The first is to continue to evaluate and optimize the operational forecast system's performance, and develop necessary model–output post–processing components. The second is to expand the current Domain 1 (12 km) to cover a larger region of North American. Due to the sparse observation availability over the oceans, a RTFDDA–3DVAR hybrid data assimilation approach is proposed to assimilate TAMDAR data as well as satellite radiance data over the oceans. And thirdly, optimizing the existing data assimilation scheme and the development of new algorithms for optimal use of TAMDAR data will be explored.

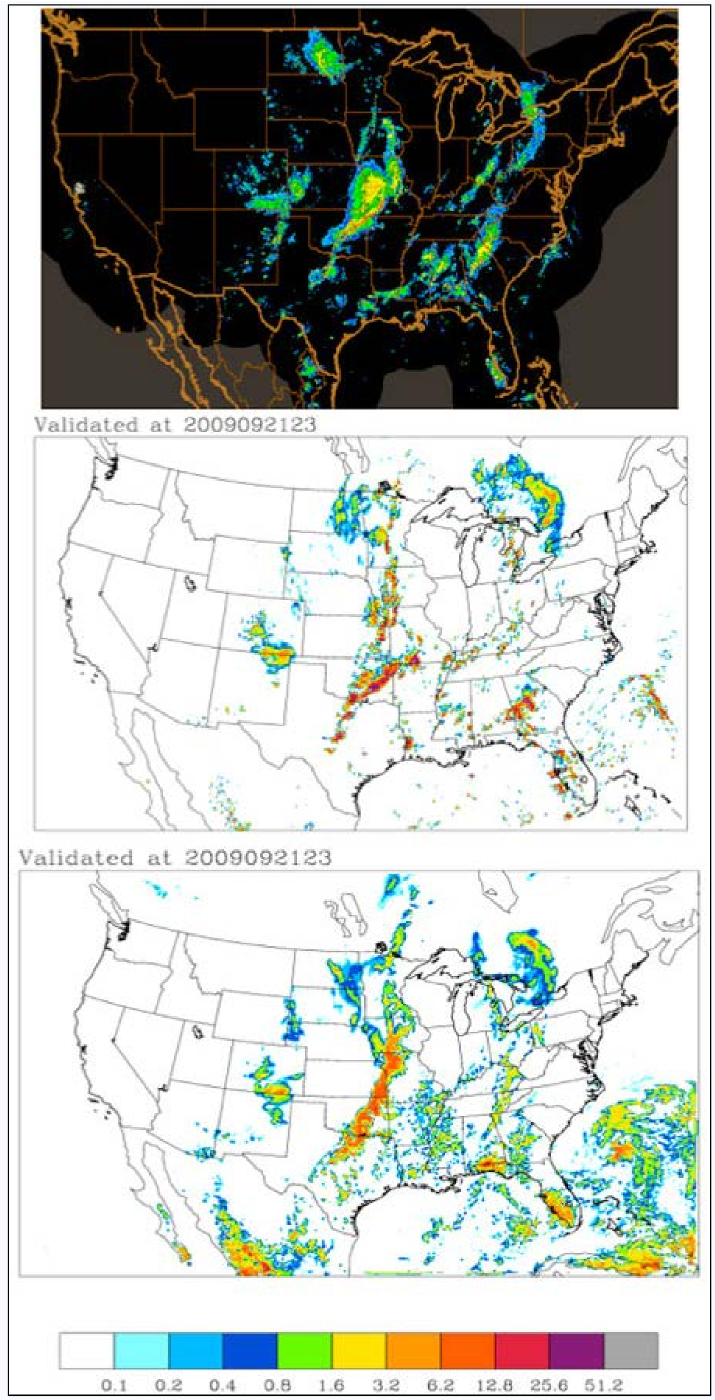


Fig. 2 Comparison of RTFDDA 5 h forecasts of 1–h rain from Domain 2 (4 km grid, middle) and Domain 1 (12 km grid, bottom) and NEXRAD radar reflectivity (top).

Development of Next–Generation RTFDDA Forecasting System

The goal of the next–generation RTFDDA development is to advance the RTFDDA data assimilation technology by developing an effective hybrid data–assimilation framework that uses ensemble–based data assimilation (EnKF), and radar and satellite data assimilation. The goal also includes expanding the RTFDDA capabilities for advanced mesoscale ensemble prediction and coupled mesoscale–LES modeling.

The concept of incorporating the NCAR DART (Data Assimilation Research Testbed) EnKF into the RTFDDA framework has been formulated. The incremental development is divided into three phases:

1. Testing/evaluation of DART-EnKF
2. Development of RFDDA-EnKF hybrid data assimilation
3. Development of an ultimate 4–dimensional EnKF data assimilation system

The DART–EnKF has been ported and evaluated with a case study using the output archive of the real–time ensemble RTFDDA operational forecasts for the US Army Dugway Proving Ground.

Progress has been made on the development of a hybrid RTFDDA–3DVAR data assimilation algorithm for assimilating radar radial winds and reflectivity, and satellite radiances, into RTFDDA. The RTFDDA–3DVAR hybrid radar data assimilation is an approach to incorporate radar data into the RTFDDA system to improve the analysis of cloud and precipitation, and achieve improved nowcasts of moist processes. In FY09, the RTFDDA–3DVAR radar data assimilation study was extended from the single case study to continuously cycling re–forecasts for a seven–day IHOP–2002 period in which different convection regimes occurred. The result confirms the advantages of the hybrid scheme over both 3DVAR forecasting and the RTFDDA forecasting, for 0 – 6–hour prediction of convection systems. The development of the hybrid system for semi–operational forecasting experiments for the US Army Aberdeen Test Center is underway. The RTFDDA–3DVAR hybrid data assimilation method was also employed for assimilation of satellite radiance measurements, with the aim of improving the analyses and forecasts of synoptic–scale weather in regions where the conventional data are too thin, such as over the oceans, Africa and the Middle East. The key approach of the RTFDDA–3DVAR hybrid data assimilation method is the use of "grid–nudging". High–frequency 3DVAR analyses for radar data assimilation and satellite radiance data assimilation are assimilated by the RTFDDA prognostic equations.

Many applications critically rely on mesoscale and microscale weather. Mesoscale and microscale weather predictions are limited by many factors, one being the inherent low predictability at these scales and another is inadequate representation of the fine scale local forcing. Complex terrain plays a critical role in both. To take advantage of increasing computing power, RTFDDA has been expanded for ensemble probabilistic prediction, and dynamical downscaling for LES applications on the microscale. Both E–RTFDDA and RTFDDA–LES are described in detail in the other sections of this report. Briefly, in FY09, a 30–member Ensemble–RTFDDA system has been operating at the US Army Dugway Proving Ground, supporting routine tests and decision–making. Several new ensemble systems were developed and tested:

1. A real–time demonstration forecasting project for the Army Aberdeen Test Center for a 2–month period
2. An air–quality modeling study for the Salt Lake Valley, in collaboration with Dugway Proving Ground and the Utah Department of Air Quality
3. A project in support of the NASA Airspace Terminal Management (ATM) probabilistic decision system development

The research related to E–RTFDDA includes ensemble member refinement, statistical verification, and ensemble forecasts calibration. On the downscaling front, the RTFDDA–LES model was used to model the microscale flows over a wind energy farm in northern Colorado. The verification of simulations against the dense observations available from the wind farm is encouraging, but additional work is needed related to the formulation of the subgrid–scale mixing scheme, and the internal boundary condition specification for the nested grid.

FY2010 Plans:

The need for the development of a seamless ensemble data–assimilation and probabilistic prediction system has recently been articulated at the National Mesoscale Probabilistic Prediction Workshop (Sept 23–24, 2009), organized by the WRF DTC at NCAR. The RAL approach for developing a seamless E–RTFDDA probabilistic prediction and data assimilation system is to integrate the NCAR DART–EnKF into E–RTFDDA. E–RTFDDA provides a framework for developing an ensemble–based flow–dependent Kalman–Filter data–assimilation system. In FY10:

1. Systematic testing and evaluation of the DART–EnKF will be completed
2. Hybrid E–RTFDDA and EnKF will be tested, where the E–RTFDDA ensemble forecasts will be used for the DART–EnKF background error covariance estimation
3. The DART/EnKF perturbation members will be integrated to enhance the sampling of the probability distribution functions of E–RTFDDA perturbations

In addition, a 4–D EnKF scheme, a hybrid nudging–EnKF FDDA system, will be formulated that makes use of the Kalman gain to define the spatial weighting factors used in observation–nudging data assimilation.

Using E–RTFDDA for producing, understanding, and presenting concise, intuitive, and informative probabilistic forecasts will remain an important scientific and technological goal. For example, an E–RTFDDA operational system for wind energy forecasting will be developed in FY10 for Xcel Energy. Calibration of ensemble bias and uncertainties, and derivation of probabilistic information for wind–power ramp events, will be explored.

In order to successfully achieve the goals of RTFDDA–3DVAR hybrid data assimilation, the first step is to produce accurate 3DVAR analyses with radar and satellite data. The second step is to define proper coupling weights to absorb the 3DVAR analyses into RTFDDA. FY10 research will focus on both areas. 3DVAR radar data assimilation and 3DVAR satellite radiance data assimilation will be evaluated and optimized separately through individual case studies and semi–operational tests. The grid nudging coefficients in the RTFDDA–3DVAR hybrid scheme will be studied.

The WRF–RTFDDA–LES will be further studied and refined for simulation of mesoscale and microscale interactions, and microscale local forcing. Test and evaluation of the WRF IBM (Immerse Boundary Method) technology for modeling steep terrain and natural and/or artificial obstacles (e.g. wind turbines, buildings) will be conducted.

Improving Data Assimilation by Newtonian Relaxation

This project, subcontracted through Penn State University (PSU) and sponsored by the Defense Threat Reduction Agency, has the objective of enhancing data assimilation in the community WRF model by improving observation and analysis nudging algorithms. The ultimate objective is to produce a complete, multi–scale, end–to–end FDDA system for use in research and

operations by the entire WRF community.

Observation nudging developed at NCAR and analysis nudging developed at PSU have been implemented in the latest community WRF model, with enhanced capabilities and flexibility in the data assimilation code. The data assimilation has been integrated into WRF to form a complete end–to–end multi–scale system, as shown in Fig. 1.

FY2010 Plans:

The objective of the project in FY10 is to continue the construction of the WRF–based multi–scale end–to–end FDDA system, and to enhance its capability and flexibility for the broad community. One of the foci is to develop the planetary boundary layer regime–dependent nudging algorithm for the end–to–end FDDA system. A thorough testing with multiple configurations in both idealized and real–data cases will be conducted to refine the FDDA system for its public release at the end of the project.

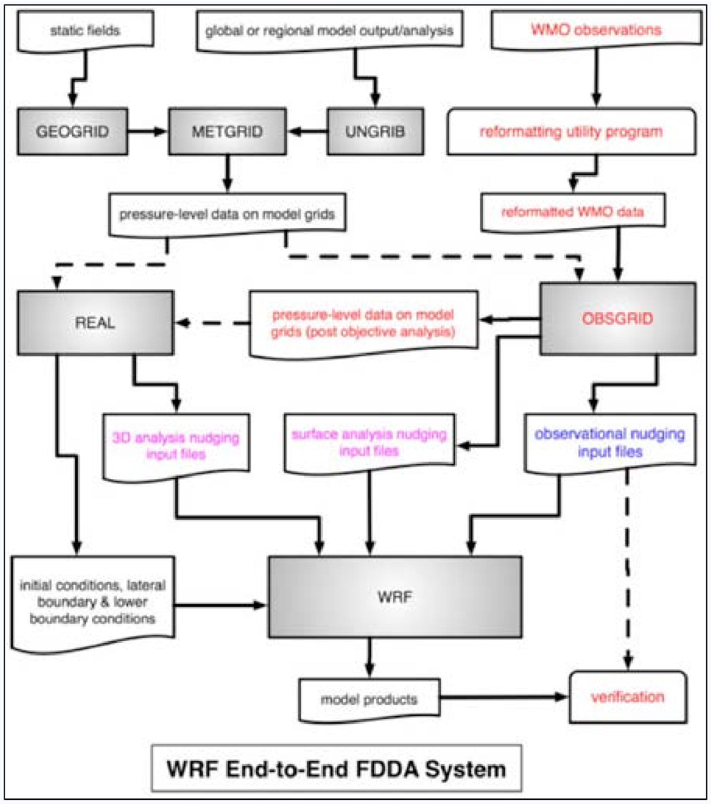


Fig. 1 WRF end–to–end FDDA system.

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NATIONAL SECURITY APPLICATIONS

Understanding, Modeling and Forecasting Urban Atmospheres

Background

Atmospheric processes are influenced by urban complexes over a wide range of scales. The larger metropolitan area produces an aggregate effect on the mesoscale atmosphere, and RAL is developing improved urban–canopy parameterizations for representing the bulk dynamic and thermodynamic effects of buildings for use in the community version of WRF. On the smaller scales of neighborhoods, a variety of models and measurement systems have been used to define boundary–layer structure.

Modeling Coastal Urban Atmospheres (DTRA sponsored)

An international collaborative effort has been undertaken to develop an integrated, cross–scale urban modeling capability for the community WRF model. The goal is not only to improve WRF weather forecasts for cities, and thereby improve air–quality prediction, but also to establish a modeling tool for assessing the impacts of urbanization on environmental problems. This will provide accurate meteorological information for planning both mitigation and adaptation strategies in the changing climate. The WRF urban–modeling system consists of:

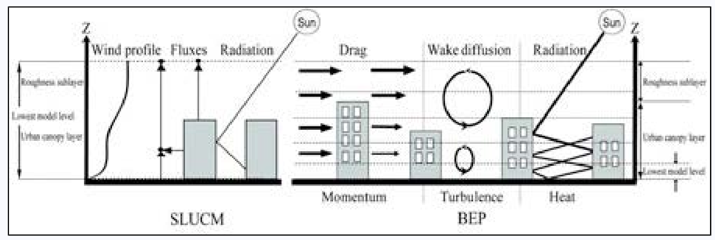

Fig. 1 A schematic of the Single–Layer UCM (SLUCM, left side), and the multi–layer model (right side).

1. A suite of urban parameterization schemes with varying degrees of complexity
2. A capability for incorporating in–situ and remote–sensing data about urban land use, building characteristics, and anthropogenic heating and moisture sources
3. Companion fine–scale atmospheric and urbanized–land data assimilation systems
4. The ability to couple WRF/urban to fine–scale urban T&D models and to chemistry models (Fig .1)

Evaluations and applications of this newly developed WRF/urban modeling system have demonstrated its capability for studying air quality and regional climate. Preliminary results that verify the performance of WRF/UCM for several major cities are encouraging. They show that the model is generally able to capture the influences of urban processes on near–surface meteorological conditions and on the evolution of atmospheric boundary–layer structures in cities. Also, recent studies have demonstrated the value of this model for investigating urban and street–level plumes (Fig. 2), for predicting the impacts of urbanization on our living environments, and for anticipating urban environmental risks in the context of global climate change. This project ended in FY09.

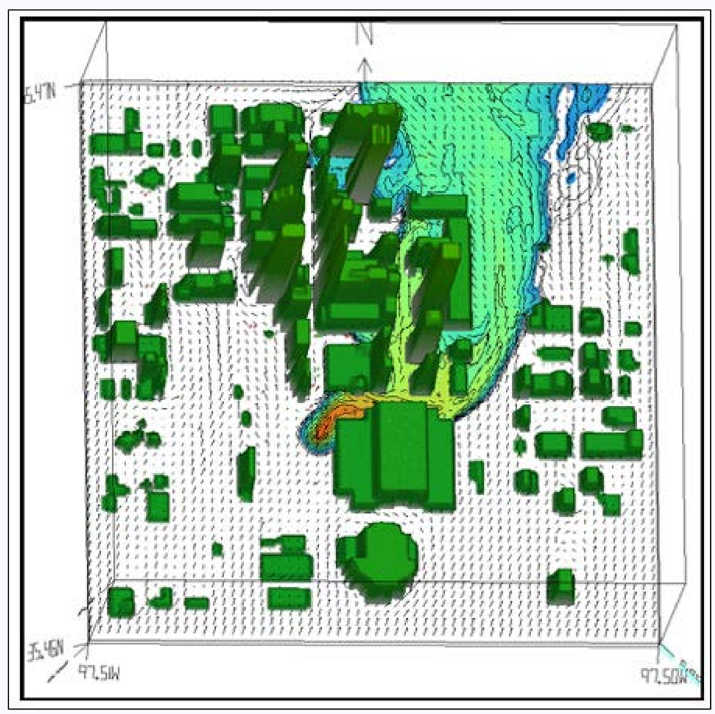

Fig. 2 Dispersion footprint for IOP6 0900 CDT release from source located at Botanical Gardens (near Sheridan & Robinson avenues, Oklahoma City, Oklahoma) calculated with WRF/EULAG.

Mesoscale Modeling for New York City (NASA sponsored)

The goal for this three-year project is to use NASA Earth–science datasets within the WRF model to improve the quality of meteorological forecasts for New York City and the surrounding area. Routine forecasts were produced using NCAR's WRF–based RTFDDA weather analysis and prediction system. Four 36–h forecasts were produced each day, with the first initialized at 0000 UTC, and a new one initiated every 6 h thereafter. The meteorological forecasts were directly input into decision support systems (DSS) used by emergency managers within the New York City (NYC) area, enabling them to provide more accurate information about the transport and dispersion characteristics of airborne releases of toxic material. Local stakeholders in the NYC area include the Office of Emergency Management, the Police and Fire Departments, and the Port Authority. These agencies use one of two DSSs: the Department of Energy (DOE) National Atmospheric Release Advisory Center's (NARAC) system, and the Hazard

Prediction and Assessment Capability (HPAC) developed and operated by the Defense Threat Reduction Agency (DTRA).

A major accomplishment this year is the development of a simple method of creating daytime and nighttime composites of lake–and sea–surface temperature based on observations from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua and Terra satellites. The composites are constructed from data typically available nearly in real time; are applicable anywhere on the globe; have a significantly higher spatial resolution than do many other operational SST products; perform well near coasts; and together are capable of roughly representing the diurnal cycle in skin temperature.

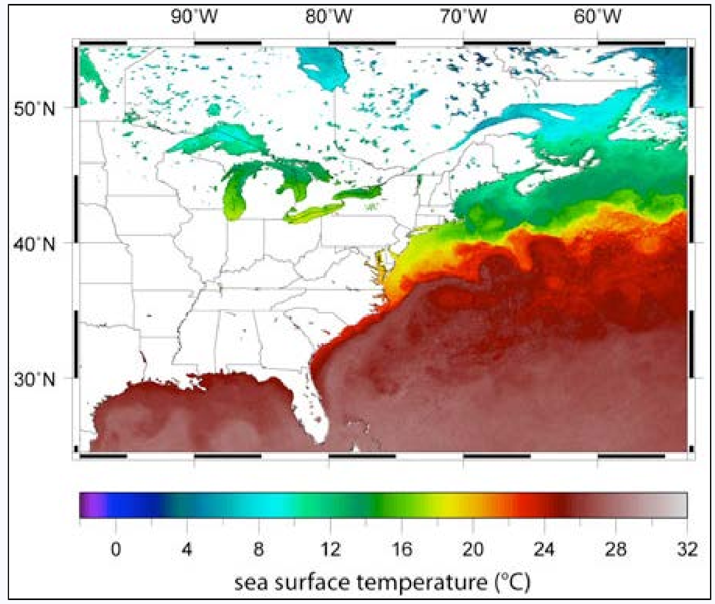

Fig. 1 Example of the 12–day composite of MODIS SST data from Aqua and Terra. Our research shows that the improved specification of SST sometimes results in significant differences in the simulation of near–surface atmospheric flows, as shown in Fig. 2.

Numerical simulations of the atmosphere above and near large bodies of water are sensitive to how the water's skin temperature is specified. Various methods of specifying skin temperature exist, each involving trade–offs in qualities such as spatial and temporal resolution, timeliness, ease of access and processing, precision, accuracy, global coverage, and lifetime of the dataset. The relative importance of each quality depends on the purpose of the numerical simulations. For example, studies of global climate benefit from datasets that are stable over large areas and over long periods of time without artifacts such as biases from instruments and other sources that can significantly corrupt physical signals. On the other hand, for operational mesoscale numerical weather prediction (NWP), this study's emphasis, the most important qualities in an SST dataset include ease and efficiency of access and processing, temporal and spatial resolution, and timeliness. For an operational system that needs to be re–locatable, applicability anywhere on the globe is also advantageous.

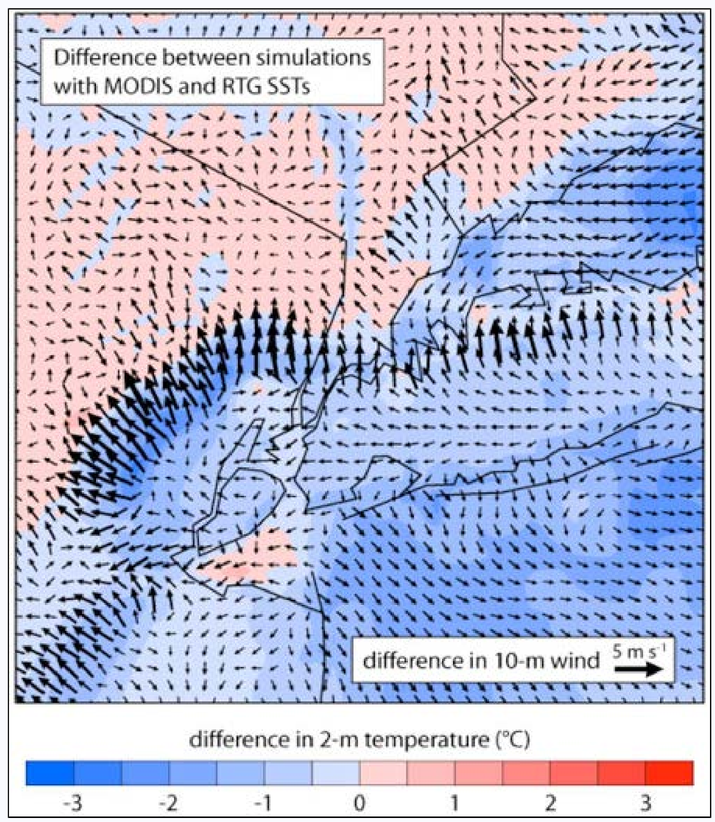

Fig. 2 Difference in wind at 10 m AGL between simulations based on the 12–day MODIS composite and the 1/12°–RTG daily file at 1800 UTC on 12 May 2007. The longest vectors represent a difference of approximately 4 m s–1. The figure is a close–up of the part of the computational area that is over NYC.

In the first step of creating the composite SST field, each day's Level 3 data from Aqua and Terra are merged into a two–satellite, daily array of skin temperature. Where data from both satellites are available for a given location, the average is used; otherwise, an available datum from one of the two satellites is used. Second, the daily files from the prior N days are combined into a multi–day composite. This step is necessary because daily files of IR–based retrievals suffer from large areas in which clouds cause missing data, even when the files include retrievals from both Aqua and Terra. For the part of the Atlantic Ocean within the domain used for this study to us, N=12 days is long enough to capture most recent valid satellite retrievals (Fig. 2), yet short enough to retain most of the physical structure in the ocean's skin temperature, as represented by the autocorrelation of temperature on the MODIS grid. In the third step, we apply one additional layer of quality control beyond the layers that are part of NASA's Level 3 processing. Detection of clouds in IR data is imperfect, particularly near cloud edges and where clouds are thin or low over water at night, so even the heavily processed Level 3 data are occasionally corrupted by cirri, low stratocumuli, and the like. This produces 24–h changes in SST that sometimes are large and non–physical. Observations and simulations with simple models strongly suggest that 24–h changes in skin temperature greater than 6° C over large regions of open ocean are not physical. In the fifth and final step, we compensate for the fact that using N=12 days of daily merged files (that is, today's merged file plus the files from the last 11 days) to create the composite SST fields means that it will lag the seasonal fluctuations in SST nominally by 5.5 days (half of the past 11 days). Even such a relatively short lag can equate to nearly 1° C during times of the year when SSTs change most rapidly. To compensate for this lag, we:

- Calculate the spatial and temporal mean SST from the 12–day composite of RTG data
- Subtract that value from today's spatial mean of RTG data

- Add the difference between the results of steps a and b, which is the negative of the mean lag, to every pixel of the 12–day composite MODIS SST field

The additional quality control in the third step removes some pixels, and there are inevitably still some holes in SST owing to persistent cloudiness Accordingly, in step 4, holes in the MODIS–based composite are filled with the 12–day mean of NCEP's 1/12° Real–time Global SST analysis (RTG), after removal of any systematic difference between the domain–wide means of the RTG and MODIS data.

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2009 Lab Annual Report

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NATIONAL SECURITY APPLICATIONS

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 easily fit within a single rack (standard 42U) of equipment. Pushing even further into the Teraflop environment provided by GPUs (graphical processing units), RAL is aiming for a desktop platform that provides climate and weather simulations previously only possible on super computers.

GPU Climate Laboratory

RAL's Climate Four–Dimensional Data Assimilation (CFDDA) system uses WRF–based downscaling of historical global analyses. CFDDA has the capability to generate hourly atmospheric analyses at a horizontal resolution down to the sub–kilometer scale for any meteorological situation or time period in the past 30 years. However, generating 30–year model climatographies can be an exceptional computational challenge. Thus, a GPU-based simulation facility was proposed in FY09 and funded in FY10. The effort, to be undertaken in cooperation with CISL staff, is examining the efficiency gains to be realized from the use of Graphical Processing Units versus conventional CPUs.

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NATIONAL SECURITY APPLICATIONS

Modeling Plumes of Hazardous Material

Background

A core RAL technology is the measurement and prediction of plumes of hazardous material in the atmosphere, and also reverse–locating the source(s) in the event of a release. A variety of models is used across a range of space scales, for both forensic analysis and real–time operations. For historical, forensic analysis, very–high–resolution research–grade models can be used to assess plume properties and the exposure of personnel and materiel. For real–time operations, the DoD SCIPUFF/HPAC plume model, soon to be transitioned to the Joint Effects Model (JEM) system, has been used for some applications.

Boundary–layer Basic Research Sponsored by Defense Threat Reduction Agency (DTRA)

Predictability experiments with the WRF model as a proxy for the atmosphere are analyzed to quantify the spatial and temporal scales of the boundary–layer (BL) wind response to land surface perturbations. Soil moisture is chosen as the land surface variable subject to uncertainty because the atmosphere is known to be sensitive to its state. A range of experiments with spatially correlated, small–amplitude perturbations to soil moisture lead to results that show the dependence of predictability on atmospheric conditions. The primary conclusions are as follows:

1. Atmospheric conditions, including static instability and the presence of deep convection, determine whether large errors and local loss of predictability are possible in response to soil moisture errors
2. The scale of soil moisture uncertainty determines scales of BL wind predictability when the atmosphere is resistant to upscale error transfer, but when the atmosphere is sensitive the scale and magnitude of soil moisture uncertainty are not important after a few hours
3. Nonlinear error growth is present whether or not the atmosphere is relatively sensitive to soil moisture uncertainty, leading to doubling times of minutes to hours for finite–sized perturbations

Similar results could be expected from other land surface variables or parameters that exert time–dependent forcing on the atmosphere that is similar in magnitude and scale to that of soil moisture. This project ended in FY09.

Sensor Data Fusion Project Sponsored by DTRA

Since late FY04, RAL has been sponsored to develop tailored meteorological decision–support applications for the military and domestic emergency–response communities. In particular, these applications are used to enhance 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 JEM. RAL's work has two primary objectives: Development of an operational algorithm which can both estimate an unknown CBRNE source and predict a refined downwind hazard from that source, using available CBRNE and meteorological sensor observations; and integration of this algorithm into the HPAC/JEM hazard–prediction toolsets. To support testing and evaluation of this product, RAL is developing a virtual testing and evaluation environment (VTHREAT) which will enable simulation of a physically realistic CBRNE release scenario, placement of CBRNE and meteorological sensors, and extraction of the resulting synthetic sensor readings. These synthetic observations can then be used by the evolving algorithms to evaluate their ability to recreate the CBRNE event.

Virtual Test and Evaluation Toolset (V-THREAT)

- The graphical interface has been slightly enhanced/improved so it can run under Mac OS X as a native application
- A new capability has been added, which allows the user to save synthetic sensor readings into NBC4 Messages. These messages can then be read by a number of warning and reporting software packages, such as the Joint Warning and Reporting Network (JWARN) and Joint Effects Model (JEM)
- Several VTHREAT simulations of FFT07 Trial 54 were completed and analyzed, before being sent to the Institute for Defense Analysis (IDA) for further independent evaluation

Variational Sensor Data Fusion (SDF) Algorithm

- Prototype
    - A preprocessor has been added to the prototype which attempts to identify whether the source release was continuous or instantaneous, based on the sensor measurements. This information is needed as an input into the current algorithm and was originally input manually by the operator using their best guess about the release type
    - Improvements were made to the meteorological preprocessor configuration to better diagnose the ambient atmospheric conditions, over the computational grid, based on the available meteorological sensor data
    - The algorithm was rerun for the FFT07 evaluation trials, provided by IDA, and the results sent to IDA for evaluation

- V1.0
  - We began discussions with SAGE, DTRA, and the JEM Program managers about the integration of V1.0 into the JEM model. The JEM PMs have sent us information on the JEM coding standards, which we are currently reviewing
  - As a first step, we are working with SAGE to integrate the prototype algorithm into HPAC 5.0 SP1 for demonstration purposes. We plan to demonstrate the capability, within HPAC at the November JSTO CBD conference in Dallas

FY2010 Plans:

VTHREAT will be a key element of the CBRNE Contamination Avoidance System Evaluation Tool (CASET) being developed for DTRA. RAL plans to continue the refinement of the VTHREAT prototype application during FY10 to support this effort. Current plans call for the enhancement of the meteorological sensor (towers, rawinsonde, and LIDAR) and chemical/biological sensor emulation, implementing the ability to dynamically place grids of chemical sensors, and development of an improved GUI application tailored for the CASET program.

A primary activity of the SDF program during FY10 will be the continued development of the variational sensor data fusion algorithm. The Phase II SDF algorithm will be enhanced to discriminate between, and identify, the source parameters of instantaneous, continuous, and limited–duration chemical and biological weapon releases. Current plans call for the development of the capability to include observations taken at multiple times and the ability to identify the source locations from multiple release scenarios.

MDS Environmental Science Research and Development Sponsored by DTRA

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:

1. Continue to develop and operational 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.

Tasking in FY 2009

The project focus for FY09 was to simplify and make the operational system easy to maintain. All work and associated accomplishments were focused on the following primary objectives:

1. Simplify System Maintenance/Operation/Troubleshooting – The MDS simplified various aspects of the end product. This helps the onsite MDS administrators with day–to–day support along with making long–term code maintenance easier
2. Make application access more secure and comply with DTRA's security requirements – Provide required patches/updates, which meet DoD DIACAP requirements and allow for the final Authority To Operate (ATO) to be granted to the MDS systems
3. Implement new functionality and enhancements as requested by DTRA – MDS fixed high–impact bugs and implemented new functionality as requested
4. Improve Documentation – Provide documentation, which will aid the ongoing operation, maintenance, troubleshooting, and further development of the MDS systems by the DTRA Operations and Maintenance group
5. Increase Stability – Provide updates, which will improve the reliability of the systems, ensuring 24/7 continuous operations and availability
6. Improve Performance – Provide system/software enhancements, which improve the system's ability to handle high user request volumes. As such, over the course of FY09, RAL developed and deployed 5 new MDS releases to meet the above objectives. A substantial amount of this effort was streamlining/simplifying the MDS system, enhancing the security of the system, and developing the final MDS User's Manual. Additionally, RAL successfully delivered MDS API source code updates and required documentation to the JEM program office

FY2010 Plans:

In FY10, RAL will continue with developing new features that help with the operation and overall maintenance of the system. RAL will work with the DTRA Operations Division to upgrade the OS and deploy new hardware. RAL will implement new features to provide ease of access to the MDS data to more users. The focus will be to develop and deliver a comprehensive set of documentation and associated training.

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NATIONAL SECURITY APPLICATIONS

Mesoscale Climate Modeling: Past, Present and Future

Background

To provide high–resolution current–climate information in data–sparse regions, which contains valuable information for decision makers, RAL has developed the Climate Four Dimensional Data Assimilation (CFDDA) system. This capability was originally based upon the MM5 model, and now has been transitioned to WRF. CFDDA uses global–scale data from long term reanalyses (such as the NCEP/NCAR Reanalysis, or the European Center for Medium Range Weather Forecasting Reanalysis); standard surface and upper–air observations; and satellite–derived estimates of winds, temperature, and humidity to downscale the global climate to the local region, while fully accounting for topographic variations and surface characteristics.

Construction of a Global Reanalysis using CFDDA

A 21–year global reanalysis has been created with NCAR's Climate Four Dimensional Data Assimilation (CFDDA) System, based on the PSU/NCAR Mesoscale Model (MM5) and using a grid spacing of 40 km (the new version is based on NCAR's WRF model). The reanalysis covers the 1985–2005 period. The dataset is used to quantify the global distribution and characteristics of diurnally–varying low–level jets (LLJs). Low–level jets with substantial diurnal variability have traditionally been difficult to study from a global perspective because of the lack of spatial and temporal resolution of available global analyses. A unique characteristic of the reanalysis used in this study is the availability of hourly output in three dimensions. This allows the full diurnal cycle to be analyzed. Furthermore, with a horizontal grid spacing of 40 km, many topographic features are better resolved than in widely used global datasets such as the NCEP–NCAR Reanalysis (NNRP). Thus, the diurnal variation of nocturnal LLJs (NLLJs), as well as the local forcing, is well represented in our analysis. This makes possible a detailed examination of the systematic onset and cessation of the jets, including time–height representations of the diurnal cycle. Understanding the nature of the NLLJs and the environmental factors important for their formation has important implications for quantitative precipitation forecasting and hydrological studies, as well as the transport of dust and other atmospheric constituents.

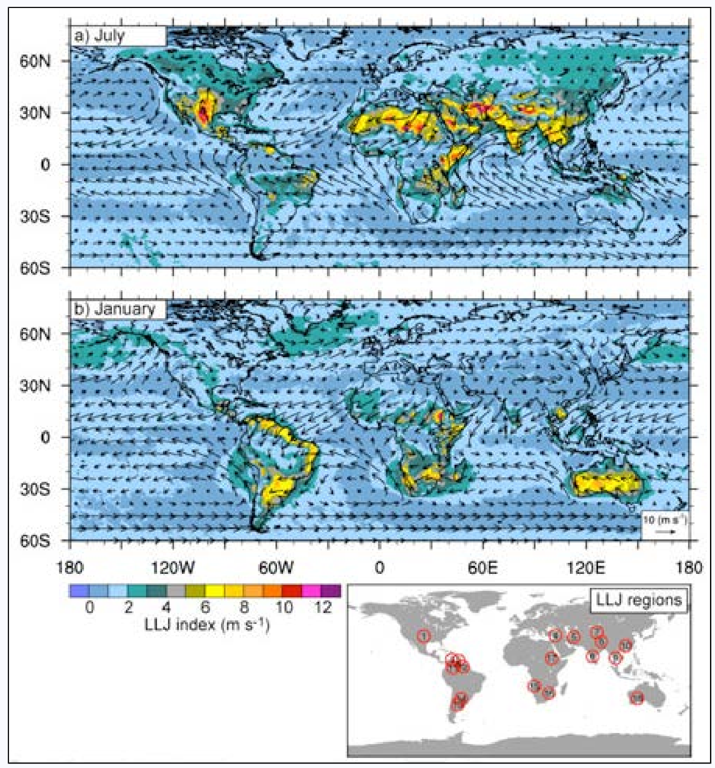

Fig. 1 Mean NLLJ index (colored) and 500 m AGL winds (arrows) at local midnight for 1985–2005 for (a) July and (b) January calculated from the CFDDA hourly global analyses. The inset shows the locations of NLLJs studied. Vector winds are plotted at approximately every twentieth grid point.

The first quantitative global maps of NLLJs were created for this study, using a new index of NLLJ activity that is based on the vertical structure of the wind's temporal variation. A database of daily NLLJ index values for the entire 21–yr period was generated, and then used to form composite global maps of NLLJ activity that highlight not only the locations for recurring jets, but also their mean strength and direction, horizontal extent, geographic orientation, and amplitude of diurnal variation. This technique was shown to resolve all the known NLLJs reported in previous studies, but also a number of newly identified jets. The new NLLJs include those recurring over Ethiopia, Venezuela, Guyana, Syria, Iran, Tarim Pendi, Tibet, the Brazilian Highlands, the Great Rift Valley in Africa, and Maracaibo. Our analysis indicates that NLLJs tend to be at their maxima

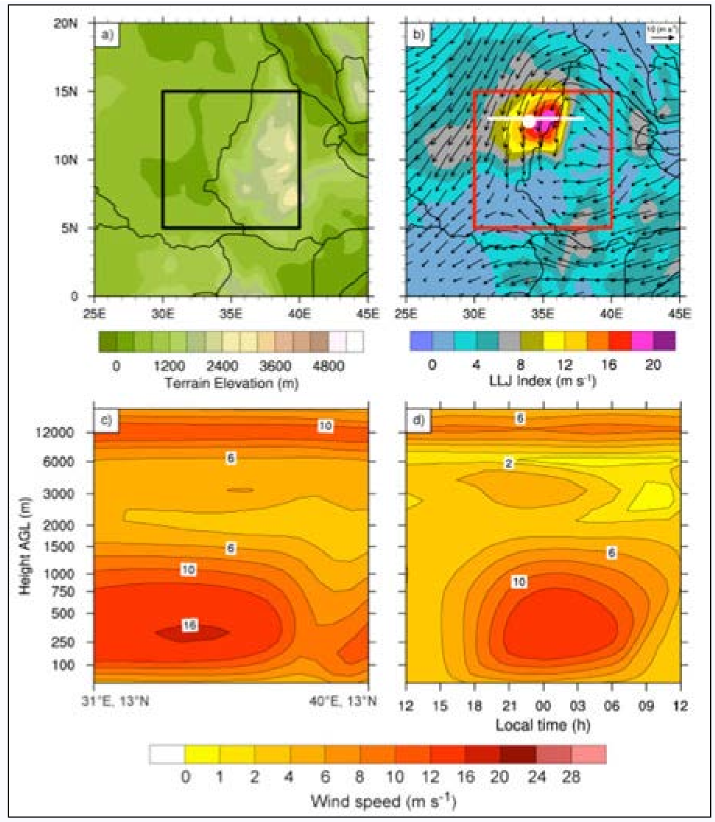

Fig. 2 Composite characteristics for strong (>= 90th percentile) NLLJ events for the Ethiopia NLLJ events for January 1985–2005. (a) Terrain elevation within the region (m AMSL). (b) Mean NLLJ index (shaded) and 500 m AGL winds (arrows). Vector winds are shown at local midnight at each point, and are plotted at approximately every third grid point. The thick white line denotes the location of the cross–section shown in panel (c), and the white circle denotes the point at or near the jet core, and marks the location of the time–height plot shown in panel (d). (c) Cross–section of the mean wind speed along the white line in (b). (d) Mean time–height of wind speed within the jet core, denoted by the white circle in (b). Thick black and red lines in (a) and (b) show the visually defined box centered on the 21–year average NLLJ core.

near local midnight with the height of the jet core ranging from 300–600 m AGL. The diurnal cycle of the jets varied greatly from location to location. The orientation of NLLJs included all four primary directions (north, south, east and west), with the mean direction in each region depending strongly on the geographic orientation of the adjacent physiography, and the underlying horizontal heat contrasts.

Our research indicates that there are fundamental differences between the various NLLJs, many with distinguishing characteristics. An example of a diurnally varying low–level jet is found over western Ethiopia. This jet occurs in Northern Hemisphere winter, although the latitude is around 10°N.The major topographic feature of the region is the Ethiopian Highlands which extend to about 3000 m MSL (Fig. 2a). The composite analysis during the time of maximum nocturnal jet strength indicates that the northerly jet forms as southeasterly flow traverses the northern slopes of the Highlands (Fig. 2b). We also note that this phenomenon appears to blend with the strong and relatively persistent Harmattan, the dry northeastly flow that covers much of the Sahara in winter. An interesting aspect of the northeasterly flow is that it varies diurnally near the Highlands, but not farther west. This jet rapidly accelerates around 2100 local time (Fig. 2d, Fig. 3c) and lasts through the night, then rapidly decelerates after sunrise.

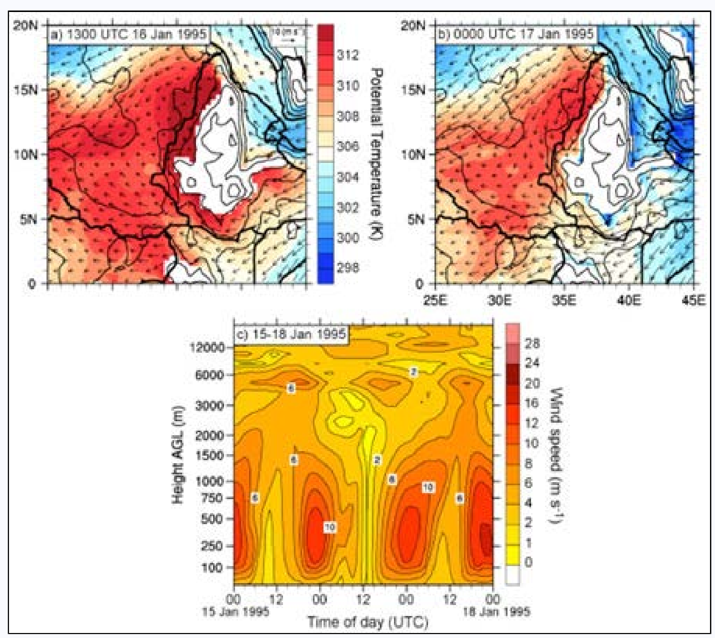

Fig. 3 Characteristics of the Ethiopian NLLJ for a multi–day episode during 15–18 January 1995. (a) Potential temperature (shaded) and winds (arrows) at 850 hPa for 1300 UTC 16 Jan 1995. Thin black lines show terrain elevation in increments of 500 m. Vector winds are plotted at approximately every third grid point. (b) same as (a) but for 0000 UTC 17 Jan 1995. (c) Time†height of mean wind speed within the jet core, whose position is denoted by the white circle in Fig. 2b.

The diurnal variation would not seem to result simply from the decoupling of the flow in the evening because the nighttime flow is broadly similar over a large region of the Sahara, yet maximizes its diurnal variation only near Highlands (Fig. 1). A key to the diurnal variation is the formation of a cyclonic lee vortex on the west side of the Highlands (Fig. 2b, Fig. 3b). The mechanism of formation may be related to the formation of other lee vortices, and the nocturnal occurrence appears because of an acceleration of the easterly flow impinging on the Highlands. A similar, nocturnal vortex mechanism has been discussed in the context of lee vortices in the bight region of California. The single cyclonic vortex is characteristic of the response to large mountains where the Rossby number (U/fL) is less than, or of order, unity. Ro in the present case, with L the cross–flow length scale of the topography, is about unity (for L=500 km, $f=2.5\times10^{-5}$ s^{-1}, U=10 ms^{-1}). At moderate Ro (and low-Froude number), the effects of rotation are important even though the region is near the equator.

Climate Downscaling with MM5/WRF: The Climatological Four Dimensional Data Assimilation (CFDDA) System

The Real Time Four–Dimensional Data Assimilation System developed at RAL generates a mesoscale re–analysis that is

consistent with both observations and model dynamics. Even though it was originally developed for dynamic initialization of mesoscale forecasts with gridded data sets that contained fully developed mesoscale processes, the continuous data–assimilation process in RTFDDA is also ideal for generation of mesoscale climatographies. The RTFDDA technology, when applied in this way, is called the Climate–FDDA (CFDDA) system.

The previous CFDDA infrastructure, which involves performing model simulations, computation of statistical products, and model validation, has been modified in a number of ways:

- An upgrade in the cluster architecture allows the U.S. National Ground Intelligence Center (NGIC) to generate a 30–year climatography for one month within a couple of days, about 16 times faster than what was possible last year
- The core NWP engine was upgraded from MM5 to WRF
- A Self Organizing Map (SOM) pattern recognition post–processor that identifies the various climate patterns and pattern members within the CFDDA output was implemented. We also use this technique to define typical days for case studies and define climate–pattern–related statistics for hazardous–material transport and other applications
- A coupled ensemble transport and dispersion capability with SCIPUFF was added

We continue to work with self–organizing map (SOM) techniques to identify climate patterns and their associated frequencies, and this year we will specifically focus on the sensitivity of the analysis to the classification variables. We also plan to implement a SOM analysis capability for the ensemble SCIPUFF climatography, and investigate the feasibility of using 1–24 month climate forecasts to identify likely climate patterns for transport and dispersion consequence assessment.

SHOM CFDDA Sponsored by the French Ministry of Defense

RAL is devising a regional climatology toolkit that will enable the French Ministry of Defense to generate a high–resolution model–based climatology anywhere in the world. The CFDDA technology is applied with the WRF model to downscale the coarse global weather analyses available from the NCEP/NCAR reanalysis project or from the European 40 year analysis project (ERA40) to generate 30 years of high resolution (˜ 3 km) WRF hourly output files over 200 km x 200 km domains.

Secondary applications, in the form of numerical models, are applied to the WRF generated historical weather data to derive properties of the atmosphere not readily available from weather models. Those properties are visibility, turbulence, and refractivity. The refractive properties of the atmosphere, which impact the propagation of visible and electromagnetic waves, are estimated by application of an electromagnetic propagation model.

The WRF model will be coupled to the wave height community model WaveWatch III within the CFDDA framework.

Seasonal Rainfall Prediction in Israel Sponsored by the Israel Hydrological Service

Major weather centers, such as NCEP and ECMWF produce operational inter–seasonal weather predictions that extend 6 – 9 months ahead. However, the products from these centers have ˜200 km grid sizes, which are too coarse for regional applications. For hydrological applications, such as flood forecasting, watershed control, and water resource planning, detailed spatial and temporal distributions of precipitations are very critical. In collaboration with the Israel Hydrological Service (IHS) and the Israel Institute for Biological Research (IIBR), RAL is developing approaches for downscaling the coarse grid global model seasonal precipitation predictions. Two downscaling algorithms are under study for this project, statistical downscaling algorithms (SDA) and a dynamically enforced statistical downscaling algorithm (DESDA). SDA makes use of the information of historical rain–gauge observations and global model seasonal re–forecasts to build weather and precipitation patterns, and then downscales the current seasonal forecasts to each raingage station according to the occurrence frequency of each weather and precipitation pattern. DESDA makes use of the NCAR Four–Dimensional Data Assimilation (FDDA) modeling system, built upon the WRF model, to produce 2–km gridded climatological precipitation–distribution analyses and then uses the same algorithm built for SDA to derive high–resolution gridded downscaled seasonal precipitation for the WRF model domain.

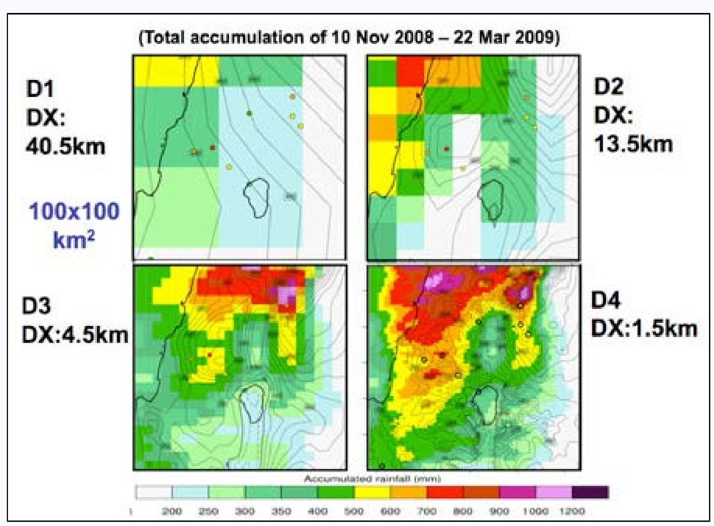

Fig. 1 Comparison of WRF–FDDA seasonal rainfall over the Sea of Galilee and the surrounding areas.

As a preliminary study for testing the WRF–FDDA capability of reconstructing the high–resolution precipitation climatology, WRF–FDDA was configured with four nested domains with grid increments at 40.5, 13.5, 4.5 and 1.5 km. The model system was run for 4 months from November 2008 to March 2009. The model makes use of boundary conditions derived from the NOAA GFS (Global Forecasting System) 0–6 h forecasts, and assimilates conventional WMO/GTS observations. It is found that for the Eastern Mediterranean region, where there are strong ocean–land contrasts and very complex terrain, a high–resolution model (grid size < 4 km) is necessary for constructing the regional precipitation climatology. In particular, a 1.5 km WRF–FDDA model reproduces the seasonal precipitation pattern and amounts, nicely agreeing with rain gage measurements, whereas the coarser grids can displace the main precipitation areas from the on–shore mountains to the off–shore seas. Figure 1 compares simulated seasonal precipitation from different grids, and indicates the verification against the rain–gage

measurements.

The SDA and DESDA seasonal precipitation downscaling algorithms will be developed for Israel and surrounding areas. Dense range–gage data (˜100+ stations) will be processed and quality–controlled for developing the SDA, and used to verify and calibrate the local high–resolution precipitation distribution produced by the WRF–FDDA model. About 5 – 10 years of WRF–FDDA runs will be conducted with a 2 km–grid domain that covers the main forcing for the local orographic precipitation and hydrological processes. The initial downscaling will be bases on the NOAA/NCEP CFS (Climate Forecasting System) model forecasts. The ECMWF and UK Met–Office seasonal forecasts will be integrated into the final products.

Support for the Missile Defense Agency

The probability of occurrence of precipitation – rain, snow, and graupel – is assessed using a combination of satellite remote sensing data, 1–min rain gauge data and climate downscaling. Maps of the global probability of precipitation occurrence have been generated by combining two satellite–based precipitation estimates, from the Climate Prediction Center Morphing Technique (CMORPH) for latitudes between +– 60 and the Global Precipitation Project (GPCP) for latitudes poleward of 60 deg. This dataset was developed for use in ATAC to generate specifications for materials used in the production on nose cones of high speed projectiles such as missiles, rockets, and the space shuttle. It may also be used for evaluation of reanalyses or simulation of present–day climate. Figure 1 show the precipitation rate that is exceeded only 0.1% of the time during the summer (JJA) over Florida and surrounding areas. As one might expect for the Florida peninsula, there are large seasonal variations in the likelihood of heavy precipitation, with winter and fall being very similar.

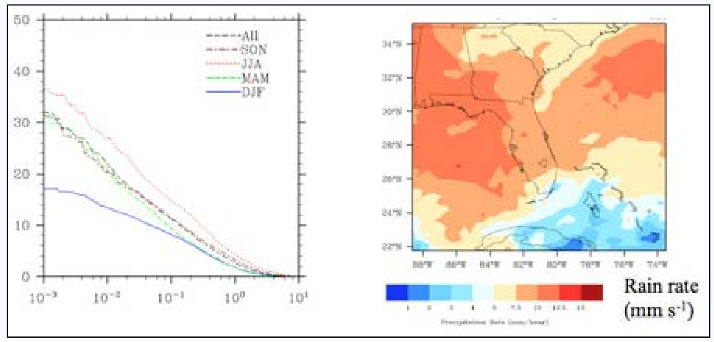

Fig. 1 The precipitation rate (mm s–1) that is exceeded only 0.1% of the time during the summer (JJA) over Florida and surrounding areas.

Dynamical downscaling analyses have been performed using WRF CFDDA at 3 km resolution centered on Cape Canaveral, FL over a 10 year period from 1999–2008. Several different metrics are used to rank the severity of the weather for a given realization. Examples of the total condensed water variable are shown in Fig. 2 for the Cape for JJA, along with a representation of the variability in the distribution across the domain for a given season. Compared with the map above it is seen that the WRF CFDDA better depicts the spatial variability in precipitation intensity (or vertically integrated precipitation) than can be obtained from satellite data. Note the sharp gradient in intensities as one moves off the peninsula. This project was essentially completed in FY09.

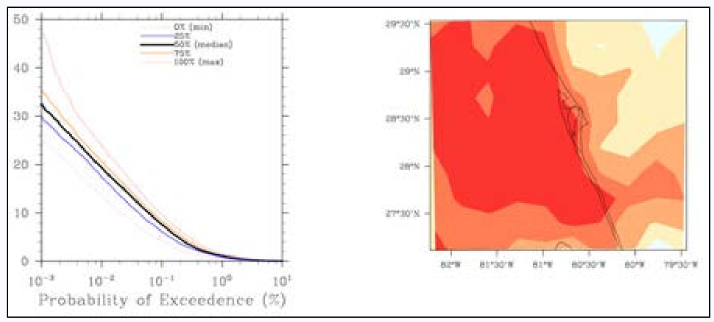

Fig. 2 Vertically integrated condensed water (kg m–2) for the Cape for JJA, along with a representation of the variability in the distribution across the domain for a given season.

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NATIONAL SECURITY APPLICATIONS

Mesoscale Ensemble Prediction

Background

The decisions made by RAL sponsors, based on mesoscale–model forecasts, can be improved through the availability of probabilistic information. Thus, mesoscale ensemble prediction systems are being developed, and prototype systems are now in 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. This work is being conducted through the sponsorship of the Army Test and Evaluation Command and Xcel Energy projects, whose broader objectives and progress are discussed elsewhere in this annual report.

FY2009 Accomplishments:

One of the most important new capabilities added to the RAL Real–Time Four Dimensional Data Assimilation (RTFDDA) and forecasting system is the ensemble RTFDDA analysis and forecasting capability. Unlike most other mesoscale ensemble systems, ensemble RTFDDA is a multi–approach, multi–model, and multi–scale cycling data assimilation and prediction system. In FY09, a 30–member Ensemble–RTFDDA system has been continuously operated at the US Army Dugway Proving Ground, supporting routine tests and decision–making for test planning. In addition, the ensemble RTFDDA system was also implemented for demonstration studies for several projects. A two–month real–time demonstration forecasting operation was conducted for the US Army Aberdeen Test Center; case studies for two week–long pollution episodes were carried out to support a Salt–Lake Valley air–quality modeling project, with the collaboration of the Dugway Proving Ground and the Utah Department of Air Quality; and ensemble modeling of several convection events was performed for the NASA Airspace Terminal Management (ATM) probabilistic decision system development. Currently, a new operational ensemble RTFDDA system is being designed for wind energy forecasting for Xcel wind farms located in Colorado, Minnesota, Texas and New Mexico.

The scientific research on E–RTFDDA includes ensemble–member refinement, statistical verification, and ensemble–forecast calibration. Refinements of E–RTFDDA members include improving individual member forecasts and enhancing ensemble member perturbations. E–RTFDDA is built upon WRF and MM5. To incorporate the advances associated with the evolution of the community WRF model, the E-RTFDDA WRF members have been upgraded in accordance with each community WRF release. In addition, modifications have been put into the WRF YSU and MYJ PBL schemes to improve the PBL modeling. New WRF physical–process parameterization schemes are included in E–RTFDDA physics–perturbation member pools. Operational E–RTFDDA systems are tuned to the perturbation members that provide the best modeling of seasonally evolving weather regimes. For example, extra PBL and land surface model perturbations were added for cold air damming modeling in the wintertime over the eastern states and wintertime cold air pooling in the mid–western and inter–mountain areas, whereas extra perturbation members for modeling moist convections were included for summer weather prediction.

E–RTFDDA verification was carried out using the model output archived for the Army DPG and ATC ensemble model runs. For the 2–month ATC runs, the verification focus is on identifying the best WRF member to provide guidance for modifying the operational high–resolution deterministic forecasting system. Therefore, the verification computation was done for each member individually, and the skill statistics were compared. It was found that for the two months of winter forecasts:

1. Overall the WRF members performed better than MM5 members
2. Using the GFS model as the lateral boundary conditions resulted in better wind prediction, while using NAM led to better low–level moisture fields
3. The YSU, non–local PBL mixing scheme performs better than MYJ, a TKE based PBL mixing scheme
4. The costly, sophisticated microphysics schemes gain very little
5. Appropriate cumulus–parameterization schemes can be beneficially used in 3.3 km grid domains for modeling moist processes, together with a microphysics scheme

Another significant achievement with E–RTFDDA is the development of an ensemble forecast calibration module. Ensemble calibration is a statistical post–processing approach to improve the statistical accuracy of forecasts, as measured by reliability diagrams, rank histograms, etc. Furthermore, calibration allows statistically transferring/downscaling model forecast (1st and 2nd moments) from the raw grid–box–mean model forecasts to station–specific properties. The calibration developed for E–RTFDDA is based on the Quantile Regression (QR) approach. Specifically, the

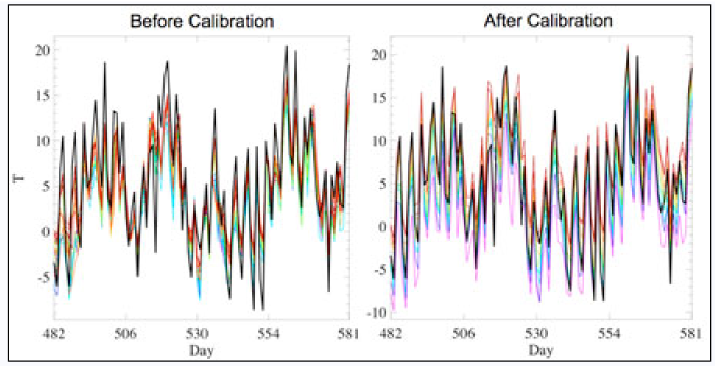

Fig. 1 comparison of the calibrated and raw 36 h forecasts of the surface temperature for the 30 E–RTFDDA members (colored lines). The Solid black line denotes observed temperature.

scheme computes a weighted ensemble mean derived by weighting each ensemble–model based on its error variance. One year of E–RTFDDA hourly forecasts for each member were processed using the Dugway Proving Ground SAMS (Surface Automatic Meteorological Station) observations. These model data and the corresponding observation records at each station are processed and fitted to quantiles using QR conditioned on the ensemble mean, median, spread, and persistence. For a given forecast, the scheme segregates model forecasts into differing ranges of ensemble dispersion, refits the models, and thus achieves calibrated forecasts. Figure 1 compares spaghetti plots of the calibrated and raw 36 h forecasts of the surface temperature for the 30 E–RTFDDA members. It can be seen that the calibrated members better enclose the observation (solid black lines) and correct the under–dispersed ensemble spread.

FY2010 Plans:

The ensemble RTFDDA framework adequately supports the development of the seamless ensemble data assimilation and prediction paradigm. With the development of the next–generation RTFDDA data assimilation capability, by integrating the NCAR DART–EnKF tool, E–RTFDDA will gain more accurate initial conditions and more robust perturbations that will improve the sampling of the uncertainties in the initial conditions. Development and evaluation of the impact and performance of the seamless E–RTFDDA data assimilation and prediction capability will be the focus for the E–RTFDDA in FY10–11.

One of the major new E–RTFDDA applications in FY10 is to support wind energy forecasting for Xcel Energy wind farms in Colorado, Minnesota, Texas, and New Mexico. The low predictability of boundary layer winds and high sensitivity of the wind power to wind variations imply the possible great benefit obtainable from ensemble–based probabilistic predictions. An ensemble RTFDDA system will be set up with 30 members and nested–grid domains at 30 and 10 km grid intervals. This system will provide uncertainties in wind speed forecasts with an emphasis on providing probabilistic information for wind–power ramp events.

Ensemble forecasts produce large amount of output that contain too much information to be easily used by either novice or sophisticated users. Extracting, processing, and displaying those quantities that are most relevant to specific users and applications are critical steps for making use of ensemble model predictions. Thus, RAL will continue to explore ensemble post–processing technologies and refine the ensemble–calibration algorithms.

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NUMERICAL SYSTEMS TESTING & 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.

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NUMERICAL SYSTEMS TESTING & EVALUATION

WRF Developmental Testbed

Background

The WRF Developmental Testbed Center (http://www.dtcenter.org/), which is 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 Systems 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. The goal of these activities is to accelerate the rate at which new technology is infused into operational weather forecasting. The WRF 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.

Community Codes

Community code is a free and shared resource with distributed development and centralized support. Periodic public releases include the latest developments of new capabilities and techniques. The DTC's community code efforts are collaborative activities with developers at NCEP, NCAR's Mesoscale and Microscale Meteorology (MMM) Division, and NOAA/ESRL/GSD. In addition to periodic releases of new versions of the models and other software, the DTC provides user support for these packages in the form of Users' Guides, email helpdesks, and online and on–site tutorials. During 2009, the DTC supported the following software packages to the community: Weather Research and Forecasting (WRF; http://wrf-model.org/index.php), which is a NWP model with pre–and post–processing components; and Model Evaluation Tools (MET; http://www.dtcenter.org/met/users/), which is a verification package that includes standard verification techniques, as well as more advanced techniques. In September 2009, the DTC expanded the packages it supports to the community to include the Gridpoint Statistical Interpolation (GSI; http://www.dtcenter.org/com-GSI/users/) data assimilation system. Work is also well underway to add coupled model capabilities (atmosphere, ocean and wave) to the DTC community codes in 2010 in support of tropical cyclone forecasting.

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 the operational systems. Testing and evaluation undertaken by the developers of new NWP techniques from the research community is 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 experiments. These forecasts can either be generated by the DTC or provided by external modeling groups. The DTC's evaluation includes standard verification techniques, as well as new verification techniques when appropriate. All verification statistics undergo statistical significance assessment when appropriate. During 2009, the DTC performed the analysis for a variety of testing activities ranging from retrospective experimental tropical cyclone forecasts to experimental real–time near–cloud resolving convection forecasts.

High–Resolution Hurricane Intensity Test

In the last 10 years, the errors in hurricane track forecasts have been reduced by about 50%, whereas little progress has been made during this period toward reducing forecasted intensity errors. To address this shortcoming, NOAA established the Hurricane Forecast Improvement Project (HFIP) in 2007. The 2008–09 staging of the HFIP High Resolution Hurricane (HRH) test focused on quantifying the impact of increased horizontal resolution in numerical models on hurricane intensity forecasts. For this test, distributed modeling groups generated forecasts for 69 selected cases corresponding to 10 tropical cyclones from 2005 and 2007 (see Fig. 1). These forecasts were provided to the DTC for objective evaluation; the evaluation was based on a comparison of progressively higher resolution forecasts from the same model. This objective evaluation was performed by assembling a state–of–the–art evaluation system for tropical forecasting that incorporated available software (GFDL Vortex Tracker

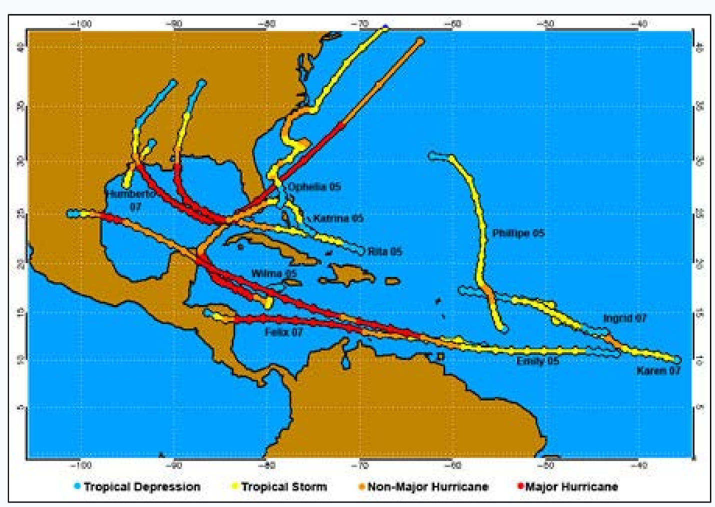

Fig. 1

and the NHC Verification System), as well as new components developed by the DTC. This evaluation showed that the use of higher resolution in the participating models did not lead to an overall benefit in tropical cyclone forecasting as measured by the metrics used in this study (e.g., see Fig. 2). Improvement was noted for some metrics, lead times and models but the majority of results showed no statistically significant difference as a result of using high resolution.

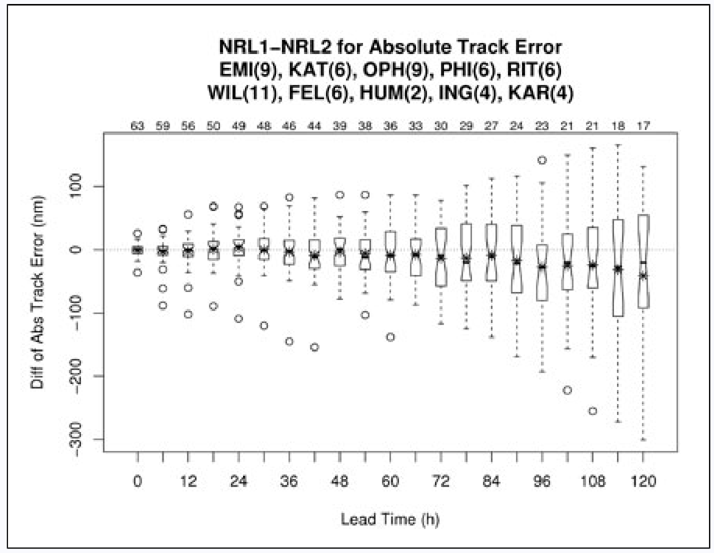

Fig. 2

NOAA Hazardous Weather Testbed Spring Experiment

The main focus of the NOAA Hazardous Weather Testbed (HWT) Spring Experiment is to gain an understanding of how to better use the output of near–cloud resolving configurations of numerical models to predict convective storms. The DTC became involved in this experiment at the request of the organizers in 2008 and continued its participation in 2009. The purpose of the collaboration is to help evaluate the performance of experimental real–time runs by computing objective verification statistics using MET. For 2009, the DTC evaluated three models using both traditional verification approaches and an object–based verification technique called the Method for Object–based Diagnostic Evaluation (MODE). This evaluation provided insights into the impact of radar data assimilation of short–term forecasts (i.e., radar data improved skill for first six hours, but skill improvements exhibited a remarkable drop–off after the first hour of the forecast) and provided an opportunity to compare the subjective evaluation of the forecast, which are part of the experiment, with object–based verification.

FY2010 Plans:

In the coming year, the DTC will continue to support various community codes, including the WRF model and post–processor, MET, and GSI, and will initiate support of coupled model capabilities. Several new model tests will be undertaken, including a test of a new boundary layer scheme and a comparison of precipitation forecasts from a global and a regional model. The DTC will also help organize and support tutorials on WRF, MET, GSI, and hurricane models.

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NUMERICAL SYSTEMS TESTING & EVALUATION

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 the forecasts, or that can be used by end users (including forecasters) for decision making. Moreover, it is possible for forecasts that are quite useful – including high resolution forecasts – to have very poor scores when evaluated by using these standard metrics. 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 object–based evaluation of precipitation and convective forecasts and other approaches (e.g., distribution–based) that can provide more meaningful information – for forecast developers as well as forecast users – about forecast performance; and the development and application of methods (e.g., confidence intervals) to estimate the uncertainty associated with verification measures. 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.

Spatial verification method inter–comparison project

The Spatial Forecast Verification Methods Inter–Comparison Project (ICP; (http://www.ral.ucar.edu/projects/icp) was initiated in February 2007 to help clarify the capabilities, as well as similarities and differences of new approaches for verification and evaluation of spatial forecasts (e.g., for fields like precipitation that are characterized by identifiable coherent features). Many of the researchers who had proposed new methods have participated in the project and have applied their techniques to a common set of test cases. The four types of methods that are included in the evaluation are shown in Fig. 1. The test cases include simple geometric examples and a perturbed quantitative precipitation field which allow the new strategies to be tested on fields with known errors. To make comparisons on realistic fields, nine samples of the WRF 24–h accumulated precipitation forecasts from three different model versions (ARW, NMM and WRF 2–km CAPS) were also included in the evaluation. Traditional forecast verification metrics and subjective evaluations were applied to these test cases in order to provide a baseline of comparison. Results from this first round of test cases have been gleaned, and a special collection of papers for the journal Weather and Forecasting will appear beginning in volume 24 number 5 (most papers are already available at early online release). The collection can be viewed at http://ams.allenpress.com/perlserv/?request=get-collection&coll_id=35). NCAR hosted a workshop http://www.ral.ucar.edu/projects/icp/Fall2009workshop.php on the ICP in August 2009 during which participants discussed results of the ICP and plans for future activities. The project is jointly led by Eric Gilleland (RAL), David Ahijevych (RAL and MMM), Barb Brown (RAL), and Beth Ebert (Bureau of Meteorology, Australia).

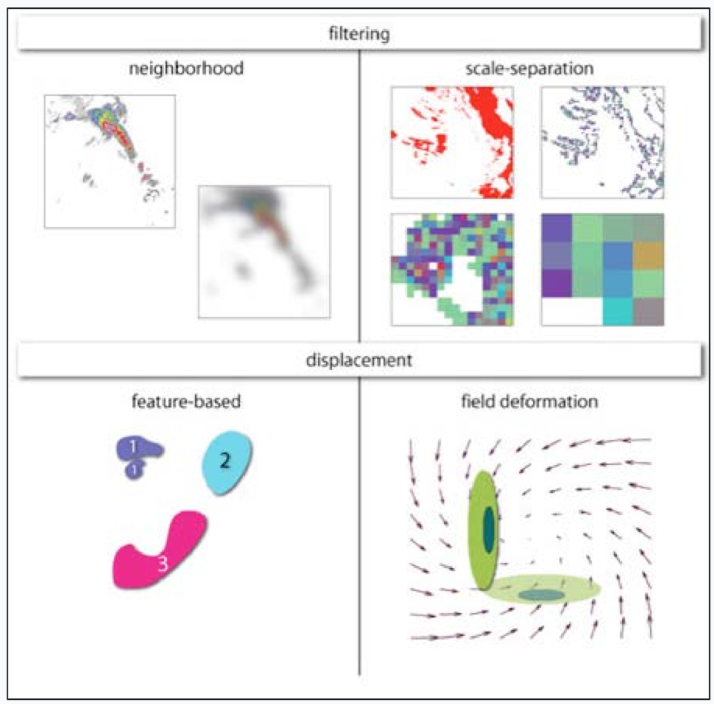

Fig. 1

Method for Object–based Diagnostic Evaluation (MODE)

One of the cornerstones of verification technique development in the RAL Verification Group is the Method for Object–based Diagnostic Evaluation (MODE).

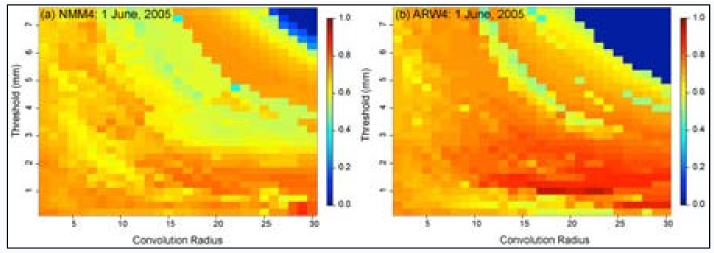

Fig. 2

This object–based spatial verification method was one of the methods included in the ICP (see above). Development of MODE has been supported by the STEP project. MODE was also included in a demonstration of verification capabilities as part of the Hazardous Weather Testbed Spring Experiment (see above). An important MODE development in the past year was the development of a new MODE tool that includes the time dimension, which allows evaluations of timing errors in forecast objects. This addition, which was requested by forecast development groups, will allow the separation of spatial and temporal errors in model forecasts. A second important MODE development was the definition of a summary verification measure that provides an overall assessment of model performance based on MODE evaluations, and makes it possible to directly compare the performance of two or more models. This summary measure, the so–called MMI (medium of maximum interest) is illustrated in Fig. 2 for a forecast by two models included in the ICP.

Model Evaluation Tools

Version 2.0 of the Model Evaluation Tools (MET) http://www.dtcenter.org/met/users/, developed by Developmental Testbed Center (DTC) staff in the JNT/RAL, was released to the community in April. This updated set of model evaluation tools includes traditional verification methods as well as new methods that have been developed for spatial forecasts. Basic methods for evaluation of probabilistic forecasts are a new capability included in MET v.2.0. Another new forecast evaluation method included in MET is the intensity–scale decomposition which was developed by Casati et al. (2004). This method uses wavelet decompositions to examine forecast performance as a function of scale.

MET has been widely implemented by the university community and by government and commercial users. Currently there are more than 650 registered MET users.

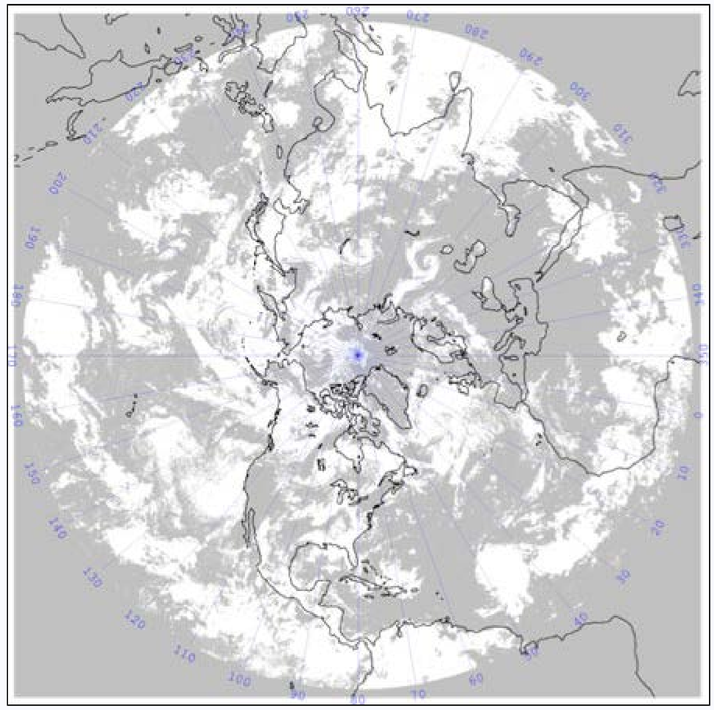
Fig. 3

The DTC Verification Group also organized and hosted a workshop on ensemble and cloud verification methods in August 2009 http://www.dtcenter.org/verification/dtcworkshop2009.php, with participation by international verification and numerical weather prediction experts. Shortly after completion of the workshop, the MET team developed software to use and graph a hemispheric cloud analysis product, shown in Fig. 3.

FY2010 Plans:

Version 3.0 of MET will be released in winter 2009. The new version will include methods for ensemble forecasts, new data formats, and cloud verification approaches. A workshop will be held to identify new methods that should be included in future MET versions, for example, to facilitate the evaluation of spatial features of ensemble forecasts.

The application of object–based verification approaches for fields other than precipitation (e.g., wind–based quantities) is in progress and will continue into the next fiscal year. New diagnostic methods will be developed to summarize wind forecasts. Potential measures of forecast consistency through time are also being investigated. The MODE time–domain tool will be extended and applied to precipitation forecasts associated with the HWT spring experiment.

The ICP will evolve to consider additional test cases and forecast variables. Participants are particularly interested in wind fields, which have very different properties from the precipitation fields. The ICP also will expand to address other verification issues, such as spatial ensemble methods, spatio-temporal approaches, and extremes verification.

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NUMERICAL SYSTEMS TESTING & EVALUATION

Data Assimilation Testbed

Background

The Data Assimilation Testbed Center (DATC) collaborates with the WRF Developmental Testbed Center (DTC) and NCAR/MMM in community support and testing of community data assimilation systems.

Community Support

The DATC continued to work with the DTC and NCAR/MMM on providing bi–annual WRF Data Assimilation (DA) Tutorials. The data assimilation lectures have been extended to include topics on both NCAR's WRF Variational Data Assimilation System (WRF–Var) and the NCEP Gridpoint Statistical Interpolation (GSI) system. The DATC staff also worked with the DTC to prepare GSI for community release and support during this task year http://www.dtcenter.org/com-GSI/users/).

Testing and Evaluation

The DATC continued to work on the AFWA (Air Force Weather Agency) Testbed to access various data assimilation techniques and systems. Some of the activities that were undertaken include the following:

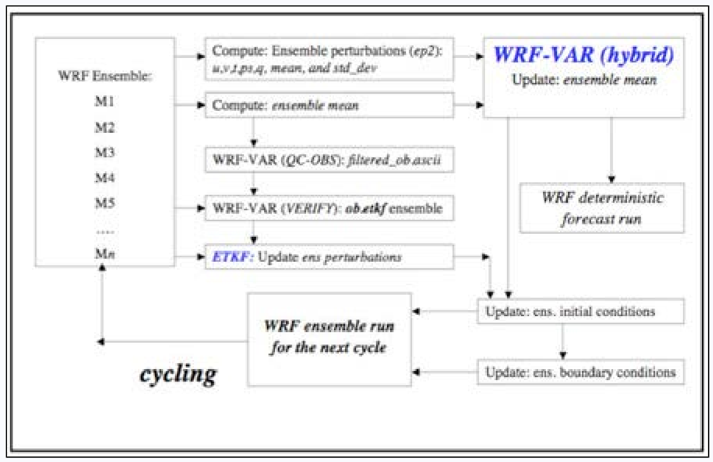

Fig. 1

1. The DATC designed an AFWA rapid update cycle system using the hybrid variational/ensemble data assimilation algorithm coupled with WRF–Var (as shown in Figure 1) and a digital filter. This new system was implemented and evaluated, and testing results were presented in various conferences and meetings.
2. The DATC also collaborated with NCAR/MMM on evaluations of WRF–Var and the ensemble data assimilation system with a focus on surface observation assimilations. The conventional observations and the surface observations from the National Weather Service (NWS) surface network were assimilated using the WRF–Var and ensemble systems at 5–km resolution over a month–long period for winter and summer. In order to provide good mesoscale features in the lateral boundary conditions, the WRF–ARW model was configured in 45–, 15–, and 5–km nests. The results generated by the two systems are being evaluated.
3. The DATC continued to conduct the baseline test for AFWA to evaluate the latest development of the WRF–Var system. A one–month retrospective run was conducted in a Caribbean domain and the results were evaluated and presented at various meetings.
4. The DATC also started to include the NCEP GSI data assimilation system into the AFWA testbed. The DATC has set up an end–to–end system including the NCEP's operational version (2009) of GSI for the baseline tests. The tests are being conducted in a Caribbean domain as in (3) for the period of August 15 – September 15, 2007. The capability and robustness of the WRF–ARW and GSI system in regional applications and the forecast impacts of the radiance data were evaluated by comparing the results from the experiments. This test is being extended to consider the performance of different cycling schemes (e.g., full cycling and limited cycling) of the WRF–ARW and GSI systems.

FY2010 Plans:

The DATC will continue to work with other partners on providing community support for data assimilation systems and techniques. The DATC will also continue to conduct test and evaluation (T&E) activities through the AFWA Data Assimilation Testbed to access the latest development of the AFWA DA systems and evaluate observation impacts on short range weather forecasts.

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NUMERICAL SYSTEMS TESTING & EVALUATION

Tropical Cyclone Modeling Testbed

Background and 2009 research and development

In 2009, RAL's Joint Numerical Testbed formed a new entity called the Tropical Cyclone Modeling Testbed (TCMT) (http://www.ral.ucar.edu/jnt/tcmt/). The focus of this testbed is testing and evaluation of experimental models for tropical cyclone forecasting. The current primary sponsor of work in the TCMT is NOAA's Hurricane Forecast Improvement Project (HFIP). The main TCMT effort for 2009 focused on collection of forecasts from the HFIP 2009 Demonstration Project. In coordination with the HFIP teams, the TCMT developed a plan for collecting tropical cyclone track forecasts from the participating modeling groups and created a web site for making the track data available to other HFIP participants. Plans are also underway for collecting and making available specific sets of model forecast fields that can be used for diagnostic studies in the future. The TCMT is putting in place verification tools that will be used to evaluate the forecasts collected during the HFIP 2009 demonstration, and will provide guidance on improved methods for evaluation of tropical cyclone forecasts.

FY2010 Plans:

In 2010, tropical cyclone track and intensity forecasts collected during the 2009 HFIP demonstration will be evaluated using consistent tools and approaches for all models. Statistical approaches will also be developed and implemented for the evaluation of other relevant attributes of tropical cyclone forecasts, such as forecast consistency. Plans will be developed for a focused test during the 2010 hurricane season, as well as relevant retrospective studies.

The TCMT and JNT staffs are collaborating with agencies associated with other tropical cyclone basins in the Bay of Bengal, Pacific and Indian Oceans and expect T&E initiatives to be initiated in FY2010 and FY2011.

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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.

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HYDROMETEOROLOGICAL APPLICATIONS

Short Term Explicit Prediction

Background

The Short Term Explicit Prediction (STEP) Program (http://www.mmm.ucar.edu/STEP) is a multi–NCAR Laboratory activity to improve the short–term forecasting of high–impact weather such as severe thunderstorms and hurricanes. The STEP Program is being stimulated by the significant advancement in a number of fields that are required to make progress in this area. These include the ability to observe the four–dimensional structure of the atmosphere, the development of new data assimilation techniques, the continuing development of numerical modeling systems and automated nowcasting systems. The program includes research into basic understanding of high–impact weather systems, development of forecast techniques, real–time testing of forecast systems, verification, and interaction with users. This collaborative effort incorporates national and international scientists, engineers, and operational personnel from universities, government institutions and the private sector.

The primary activity for STEP this year was the continued collaborative effort on the International H20 Project (IHOP) retrospective study that started in 2008. STEP scientists specializing in various topics, ranging from mesoscale observation analysis, automated nowcasting, high–resolution data assimilation, high–resolution WRF–ARW (Advanced Research WRF) modeling and physical parameterization schemes, and convective precipitation verification, participated in the study. A workshop was conducted in January 2009 to report on the final results for each project and to discuss collaborative publications. Several journal papers are being prepared. Major themes for the FY10 and FY11 funding cycle were also discussed in the workshop. In FY09, five out of the ten STEP projects are led by RAL scientists. The major contributions from the RAL projects include participation of the international field program TiMREX (Terrain–influenced Monsoon Rainfall Experiment), development of nowcasting techniques, improvement and verification of microphysical schemes, impact of land–surface modeling on short term precipitation forecast, and development of object–based verification technique. The major accomplishments from these projects are summarized below.

TiMREX activities

TiMREX is an international collaboration of scientists from Taiwan, Japan, U.S. and Korea. The two overarching goals of TiMREX are:

1. To investigate the multi–scale effects on the formation, development, maintenance and regeneration of heavy rain events in southern Taiwan
2. To advance the 0–36 hr QPE/QPF skills in complex terrain

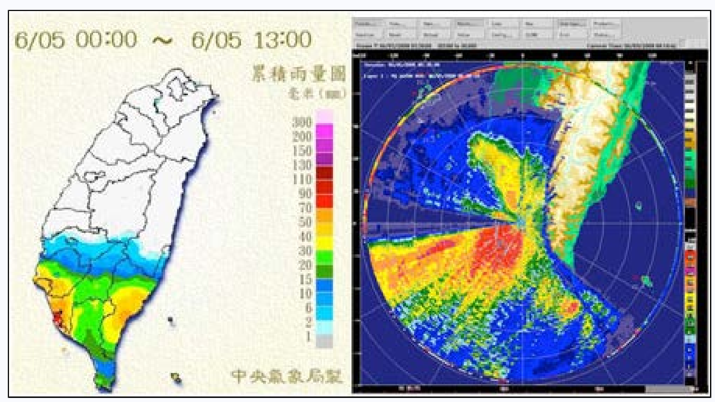

Fig. 1 Heavy rainfall over southern Taiwan on 5 June 2008 as measured by the dense rain gauge network (left panel) and from precipitation accumulation measurements retrieved using the NCAR S–Pol dual–polarization radar data (right panel).

Figure 1 shows the heavy rainfall that occurred over southern Taiwan on 5 June 2008 that resulted in significant flooding. Jim Wilson, Rita Roberts and Jenny Sun participated in the TiMREX field phase, in follow–on scientific workshops and have been heavily involved in discussions with the Taiwan Central Weather Bureau on the development of a Taiwan nowcasting system. RAL hosted two Taiwan visitors at NCAR for one month for training on the NCAR Auto–nowcaster (ANC) system and the 4–D Variational Doppler Radar Analysis System (VDRAS) and for establishing scientific collaborations.

Demonstration of nowcasting system

The ANC and VDRAS ran in real–time during the Beijing 2008 Forecast Demonstration Project (B08FDP) over a domain that was centered on Beijing. This was a culmination of 4 years of scientific and engineering collaboration with the Beijing Meteorological Bureau in the transfer of nowcasting knowledge and short–term nowcasting systems. Sun, Wilson and Roberts participated in the B08FDP. Scientific analysis and a draft journal paper by Wilson is nearly completed on several case studies from 2006–2008 of storm initiation and evolution over the Beijing urban area and the performance of the ANC nowcasts during these high impact weather events. VDRAS post–processed fields of low–level cold pool (perturbation temperature over horizontal mean), CAPE/CIN, low–level wind shear, and horizontal temperature gradient were calculated. These fields revealed good correlations with convective initiation, strength, and longevity.

The ANC and VDRAS were run over the IHOP domain for the one–week STEP retrospective study. This involved significant effort

to collect and format all the relevant data sets for ingest into and tuning of these systems. The VDRAS stability, wind, and thermodynamic fields showed quite good correlations with observed storm initiation and evolution. ANC 60 minute thunderstorm nowcast fields validated very well. Convergence boundary locations were critical to the accuracy of the ANC forecasts for storm initiation.

Improvement of microphysics parameterization

The project on microphysics parameterization led by Ed Brandes had three major foci:

1. Describing particle size distributions (PSDs) in storms
2. Demonstrating the consequences of improper particle size distributions in models
3. Establishing observational constraints for numerical microphysics schemes

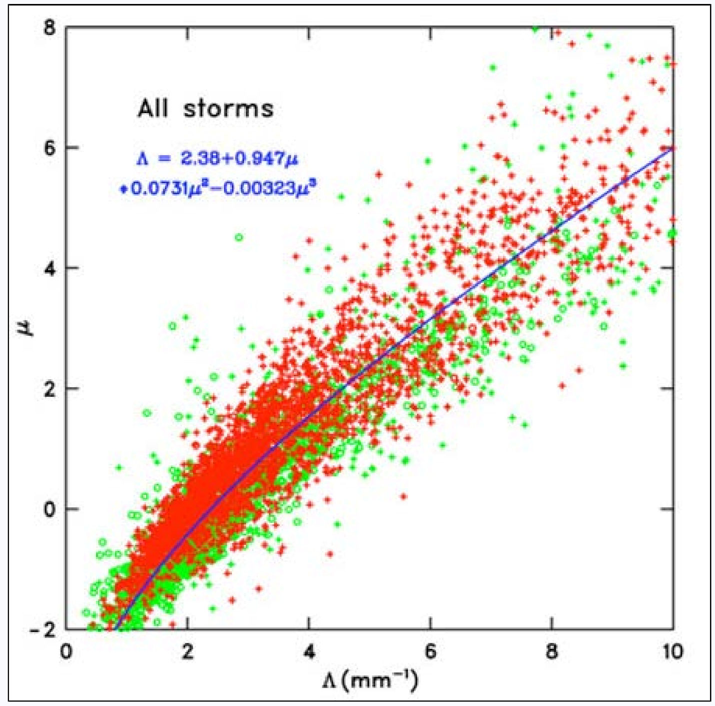

Fig. 1 The slope (Λ)/shape (μ) relation for an assumed gamma raindrop size distribution. Observations from stratiform (red) and convective storms (green) are shown. Observations with rain rates ≥ 5 mm h−1 are shown by circles.

This work is essential for understanding precipitation processes and improving microphysics parameterizations in numerical weather prediction models. Polarimetric radar and disdrometer measurements were used to examine particle size distributions in summer and winter storms. Analyses of convective storms determined that drop distributions can be represented by a constrained–gamma (CG) model in which the shape (μ) and slope (Λ) parameters of the three-parameter gamma distribution are related. An example of the relationship is shown in Fig. 2. Both convective and stratiform rain storms are well represented by the relation.

Using a large dataset of disdrometer observations collected in Oklahoma, the necessary statistics were obtained for a Bayesian approach for retrieving drop size distributions (DSDs). The Bayesian approach, which does not use deterministic coefficients, performs better than empirical relations developed earlier. The Oklahoma dataset is also being used to determine constraints and verification procedures for forecast models. Time histories of drop size distributions and their descriptive parameters have been examined. Early and late stages of convective storm development are dominated by gravitational size sorting, while heavy rains in the storm interior are dominated by broad distributions with equilibrium drop size distributions. Statistical descriptions of the gamma distribution governing parameters, drop median volume diameters, and maximum drop diameters have been determined.

A preliminary study with 2–D simulations of squall lines using bulk and detailed microphysics models revealed sensitivity to assumed hydrometeor size distributions. Simple bulk parameterizations produced short–lived storms that did not propagate, whereas detailed microphysics schemes produced long–lived and relatively organized storms. The improvement with detailed microphysical models was attributed to bin–wise handling of particle terminal velocities and variable size distributions for species, particularly graupel.

Impact of land–surface/atmospheric interaction on summer convection

The land surface modeling work led by Fei Chen examined effects of surface and PBL (Planetary Boundary Layer) processes on warm season precipitation and their impact on WRF precipitation forecasts. Using IHOP retrospective period data, AmeriFlux data, and simulations by the WRF/Noah model, it was found that land–atmosphere coupling (e.g., surface fluxes) has a major influence on PBL structure and precipitation development. Its representation in WRF/Noah could be improved with modifications to the Czil parameter used to obtain the roughness lengths for heat and moisture. Mechanisms influencing convective precipitation in 12–day IHOP WRF simulations using different soil wetness and land surface models have been studied. The primary focus during Y09 is on the effects of surface exchange processes including the detailed specification of vegetation in WRF and land–atmosphere coupling strength on prediction of convective precipitation in 0–24 h WRF forecasts during the 10–16 June STEP IHOP retrospective period. The timing of convection initiation and QPF amounts are

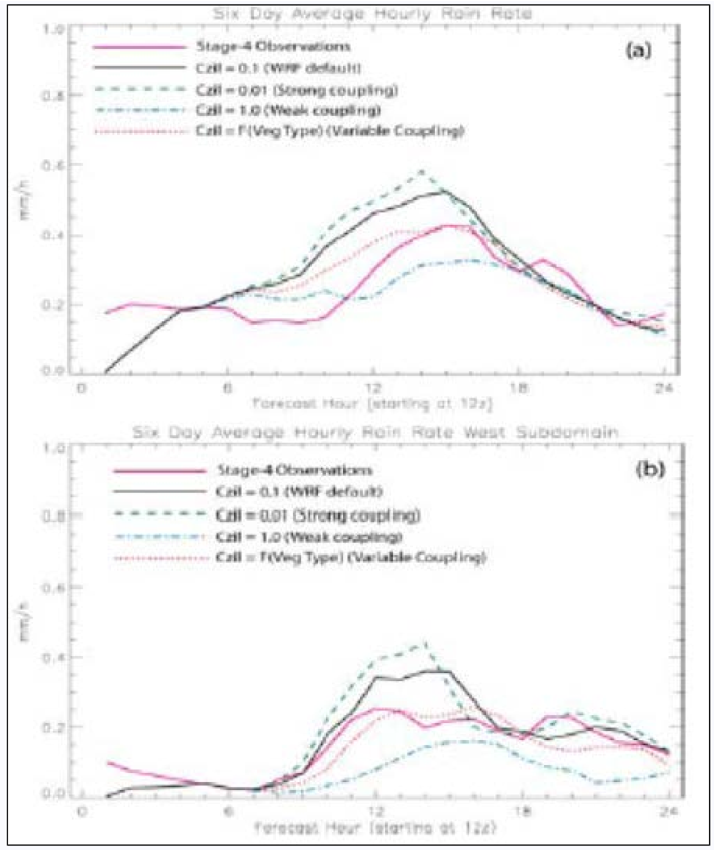

Fig. 3 Six–day averages of hourly precipitation rate over (a) the 750 x 750 km IHOP subdomain, and (b) the 375 x 750 km western half of the above domain.

sensitive to the land–atmosphere coupling. Figure 3a presents six–day averaged hourly rain rates spatially averaged over a 750 by 750 km subdomain of the simulation centered over the IHOP area. Both timing and amounts of heavy rainfall are influenced by the strength of the coupling. For instance, daytime precipitation in the strong coupling run begins several hours earlier and has maximum amounts that are nearly twice as large compared to the weak coupling run. Over the west half (~100-105°W) of this subdomain, where local formation of precipitation dominates (as opposed to propagating convection originating from upstream), the simulations with variable Czil produce the best overall agreement with Stage–4 precipitation observations (Fig. 3b). We have begun preparing a journal article on results from simulations with differing coupling strengths.

Object–based verification

FY2009 Accomplishments:

The object–based verification effort led by Barb Brown had a number of accomplishments in FY09:

1. Participation in the spatial verification method inter–comparison project (ICP)
2. Extension of NCAR's object–based verification tool – the Method for Object–based Diagnostic Evaluation (MODE) – to include the time dimension (MODE–TD)
3. Application of MODE and MODE–TD to the IHOP cases that were central to the STEP program in the last cycle
4. Initial steps to apply MODE to evaluate forecasts from the Beijing Olympics (B08FDP)

Since the latter work is in its early stages, we will not focus on it here.

Participation in the ICP (http://www.ral.ucar.edu/projects/icp/index.html) involved the application of MODE to a specified set of mesoscale forecasts from the 2005 SPC/NSSL Spring Experiment and to a set of geometric cases to assess the tool's abilities to capture and represent particular types of errors. This work led to development of a MODE summary measure (the so–called MMI) which summarizes the relative skill of a forecast field to match an observed field. A manuscript was prepared that will appear in Weather and Forecasting as part of a special collection on the ICP (Davis et al. 2009b).

MODE–TD is an extension of MODE to three dimensions – two spatial dimensions and one temporal dimension. Inclusion of the time dimension 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

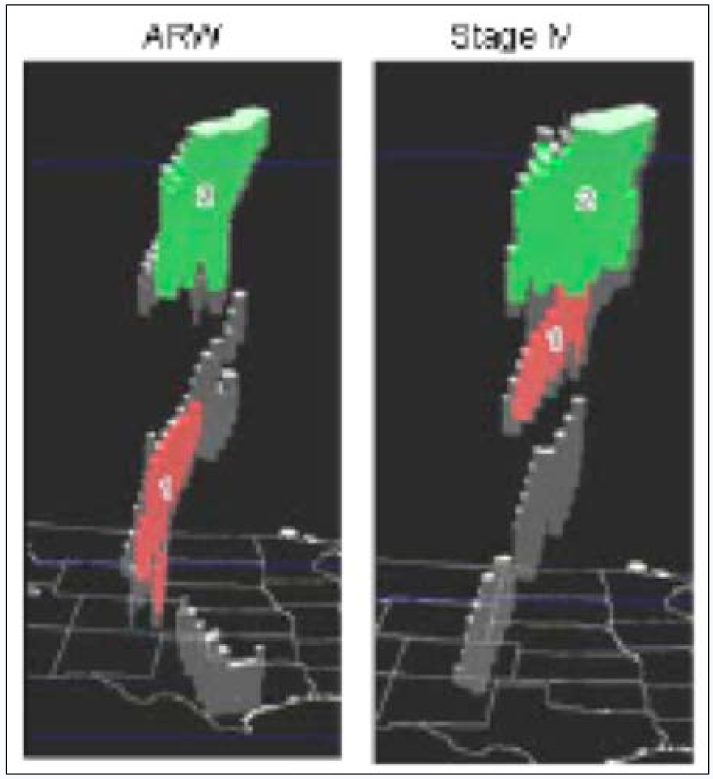

Fig. 4 Example of MODE–TD applied to IHOP case (15 June 2002). Time is the vertical axis. Multiple 3–D objects are identified in the forecast and observed grids (colors do not indicated matches).

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 which 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. Results of these analyses were presented at the AMS conferences on weather analysis and forecasting and numerical weather prediction (Davis et al. 2009a), and the 4th International Verification Workshop in June 2009. Fig. 4 shows an example of MODE-TD objects identified for one of the IHOP cases. Finally, Brown and collaborators have begun an investigation of MODE results for the nowcasts produced as part of the 2008 Beijing Olympics Forecast Demonstration Project (B08). Results of these analyses will be included in a co–authored paper on the application of spatial methods to evaluate the Beijing nowcasts.

FY2010 Plans:

The main scientific focus will be on the understanding and forecasting of orographical convection and elevated convection. For orographical convection, some STEP scientists will examine data collected during TiMREX to further study the life cycle and characteristics of terrain–induced convection. The Rocky Mountain Front–Range will be another focus region for the study. Three WRF–ARW data assimilation systems including 3DVar, RTFDDA Real–Time Four–Dimensional Data Assimilation and Forecasting), and WRF/DART (Data Assimilation Research Testbed) will be demonstrated using data collected in the region. The TiMREX data will also be used for the further development of NCAR's Auto–Nowcasting system. For the study of elevated convection, the importance of land–atmosphere coupling on factors that potentially influence elevated nocturnal convection will be examined using 0–24 h WRF simulations of 3–6 July 2003 BAMEX (Bow Echo and MCV Experiment). Resulting QPF sensitivities will be compared with those found in existing simulations from the differing meteorological regime of 10–16 June 2002 (IHOP). For the microphysics study, the emphasis will be on the implementation of new observation–based parameterization schemes within WRF–ARW. Model simulated microphysics will be compared with observations to develop relations of particle size distribution.

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HYDROMETEOROLOGICAL APPLICATIONS

Coupled Surface Hydrometeorological Processes and Regional Climate

Background

RAL scientists are involved with a variety of projects related to hydrometeorological processes at the land–atmosphere interface such as runoff (flash floods and river discharge), infiltration, snowmelt and soil moisture. A major goal is to improve our understanding of land–atmospheric interactions spanning a variety of time and space scales (weather to climate). This includes development of the community Noah land–surface and coupled WRF/Noah regional climate models to help water managers to more effectively plan for both flash flood events and future climate change.

Current projects include a Front Range flash flood project, the development of a distributed hydrological model for Romania, research studies on the North American Monsoon, collaborative projects with government agencies and university communities to improve the Noah land surface model, investigating land–atmospheric feedback in semi–arid regions in the US and China, ten–year reanalysis of land–surface component for arctic region, medium range and climate forecasting applications in Bangladesh and California, enhancement of land surface models (Noah and CLM) for disturbed (fire and beetle infestation) land surfaces, and a new tool to allow water managers to assess the impact of future climate predicted precipitation on the operation of their watershed or other operation (WEAP). Key tools for these process studies include radars, satellites, surface observational networks, the WRF mesoscale model with the Noah land surface model for both weather and regional climate, an ensemble forecast analysis system, a new distributed version of the Noah land surface model that allows for overland, channel and subsurface flows, and the WEAP water evaluation and planning tool. The community models that include the Noah distributed and WRF/Noah regional climate models will serve as a framework from which further interaction with the hydrological community will occur.

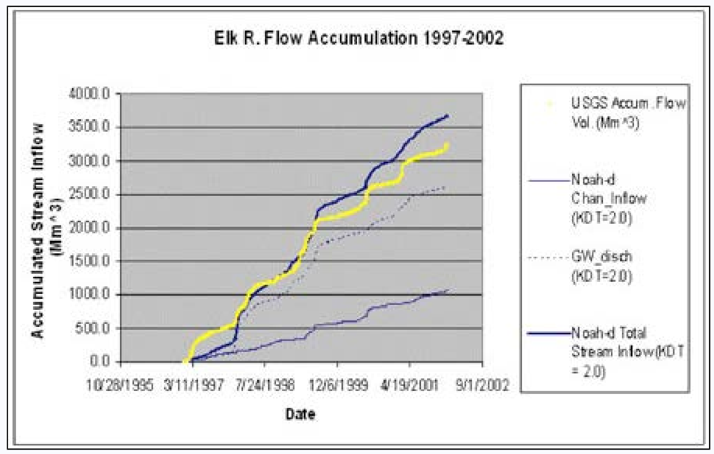

Fig. 1 Final benchmarking of the distributed hydrology version of the Noah land surface model. Accumulated streamflow for the U.S. benchmarking catchment (Elk River, MO) shows excellent correlation and a 10% difference in accumulated model streamflow (thick blue line) compared with observed streamflow (thick yellow line) over the 5–year period. Dotted line shows the portion of model streamflow derived from surface runoff and thin line shows portion derived from baseflow

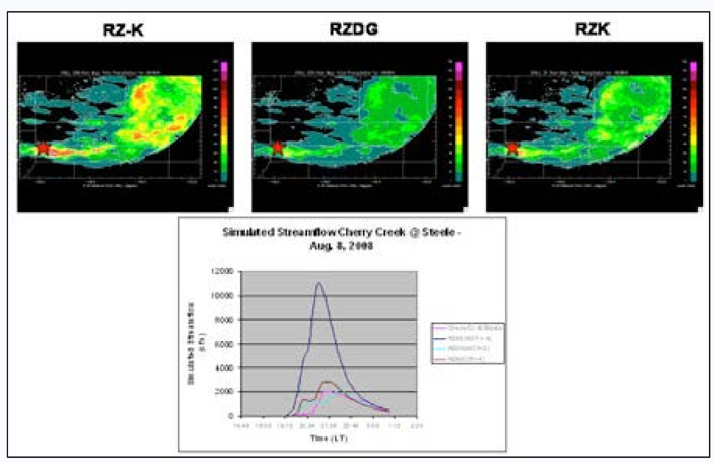

Fig. 2 Simulated flash flood streamflow from the NCAR RAL Front Range Flash Flood Prediction System when driven by NWS/NEXRAD (RZ00), NEXRAD-Adjusted (RZDG) and CSU-CHILL Polarimetric (RZK) rainfall estimates. Inset maps show spatial patterns of rainfall from the three rainfall products and location of flood event (red star)

Accomplishments:

- Added the following modules into Noah
  - groundwater module
  - multi–layer snowpack
  - dynamic vegetation
  - multi–layer canopy vegetation
  - improved snow albedo treatment
  - irrigation treatment
  - spatially varying soil layer thickness
  - new frozen soil scheme
  - a multi–layer urban module
  - adjustment of solar radiation over sloping terrain
- Conducted climate change impacts studies for the Colorado Front Range, State of California, electric power industry, and the Bureau of Reclamation with WEAP
- Completed the technology transfer of the distributed–hydrology version of the Noah model to the sponsor. This effort wraps up a 4–year project aimed at

developing a physically–based hydrological modeling system for the country of Romania. (see Fig. 1)

- Initiated climate change impact studies in various regions of latin America in support of projects funded by the Intra–Americas development bank
- Expanded radar and ground–based field research efforts aimed at improving the quantitative precipitation estimates and forecasts used in hydrological prediction. (Fig. 2 shows the difference in performance of a simulated flash flood event when using the operational NEXRAD rainfall estimate or those derived from locally–tuned NEXRAD or CSU–CHILL polarimetric rainfall estimates.)
- Produced operational flood forecasts for Bangladesh during the 2009 monsoon flood season (see Fig. 3).
- Implemented an enhanced flash flood prediction system for the northeast highland/headwater regions of Bangladesh
- Develop a training course for local forecasters through support from the World Bank

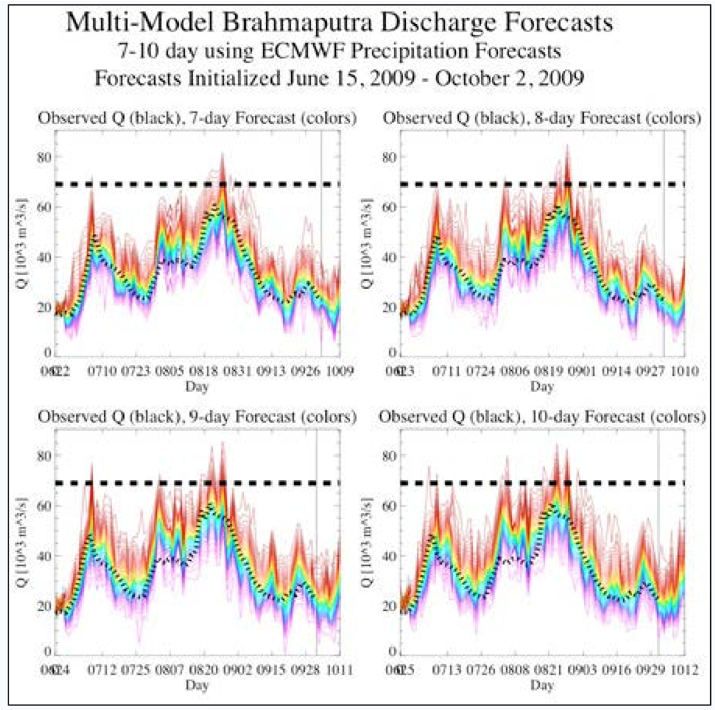

Fig. 3 Operational 2009 Brahmaputra 7–to 10–day lead–time flood forecasts

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HYDROMETEOROLOGICAL APPLICATIONS

Aerosols and Precipitation

Background

Many countries around the world practice cloud seeding to enhance precipitation if there was evidence of its effectiveness. In trying to understand this issue RAL research has focused on various aspects of advertent and inadvertent modification of clouds and precipitation by aerosols. Current efforts have emphasized cloud and aerosol measurements at a variety of locations around the world (Saudi Arabia, Turkey, Australia, and Wyoming). A program of "best practices" has been followed that emphasizes airborne and radar measurements and cloud climatology studies as a prelude to conducting any randomized seeding trials. Education and other kinds of capacity building are a major part of the effort. The following paragraphs provide some highlights of the different programs.

Queensland Cloud Seeding Research Program

RAL has been involved in a cloud seeding research program in southeast Queensland, Australia for the past two years. During this time, two seasons of field measurements have been collected, utilizing dual–polarization and dual–Doppler radar and in situ microphysical (aircraft–borne) observational platforms. A randomized hygroscopic cloud seeding experiment was also conducted. In 2009, the second season's field effort took place during the southeast Queensland wet season. Initial data analyses were completed and submitted to the program sponsor in the form of an interim and final report. The results indicated that clouds seeded with hygroscopic flares typically were longer in duration, having a lower hazard rate (chance of dying in a given time step; Fig. 1), although the sample size of the randomized experiment is still too small to make robust claims. Furthermore, a general tendency for initial drop size distributions in seeded clouds to have larger mean diameters and higher large (>20 µm) drop concentrations compared to non–seeded clouds was also observed. These observations suggest that the first step in the hygroscopic seeding conceptual model is occurring in seeded clouds. Other analyses characterized the regional rainfall and synoptic climatology, as well as the natural aerosol conditions and precipitation microphysics in the region. Such results indicated that the so–called northwest regime (yellow in Fig. 2) produced a large portion of the annual rainfall despite being the least frequent, and regimes like the east (red in Fig. 2) and west (blue in Fig. 2) are more common in the wet season (Oct–Mar) and likewise produce large portions of rainfall in those months. These synoptic regimes (and months) are the most ideal for cloud seeding in the region. Other regimes, like the southeast regime (black) which is observed year–round or the southwest (purple) and southeast 'dry' (cyan) regimes (primarily dry season regimes), produced very little rainfall and were most likely responsible for the clear, dry days where seeding would not be possible due to the lack of suitable clouds.

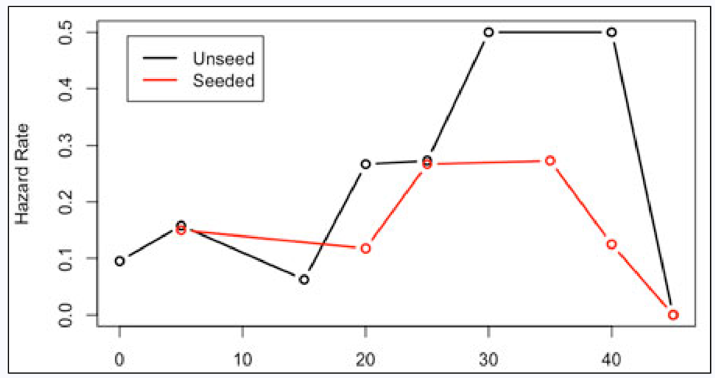

Fig. 1 Hazard rate for unseeded and seeded targets from the southeast Queensland randomized seeding experiment. The hazard rate indicates the likelihood a target will disappear in a given time interval

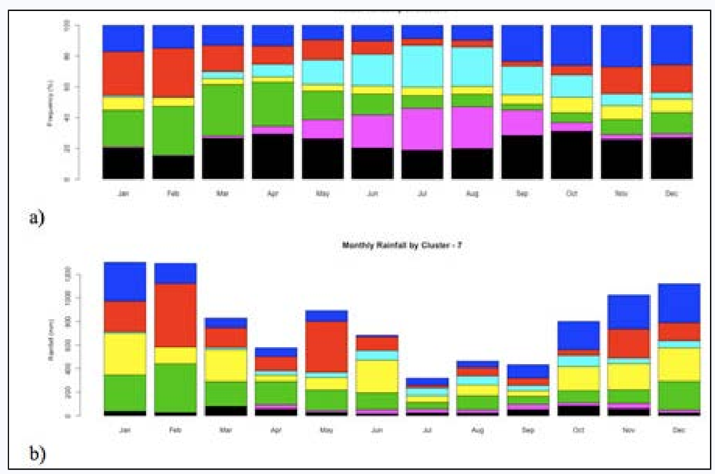

Fig. 2 Frequency and contribution of the 7 synoptic clusters to annual rainfall by month: a) Frequency of occurrence clusters for each month, and b) the contribution of each cluster to the total rainfall per month. Each regime is represented by color: southeast regime (black); southwest regime (purple); southeast 'moist' regime (green); northwest regime (yellow); southeast 'dry' regime (cyan); east regime (red); west regime (blue). The total is for all years in the period 1995–2008 inclusive.

The next steps for the Queensland project are to publish the analysis results that have been produced from the two seasons of data collection, and to continue to develop innovative methods for utilizing the dual–polarization and dual–Doppler radar data for cloud seeding research and also incorporate numerical modeling efforts into the analysis.

Istanbul cloud seeding feasibility study

Turkey and southeast Europe have experienced severe drought and heat waves over the past several years. Istanbul, which is the largest and most populated urban area in that region, has been under extreme water shortage due to these regional climatic effects, extreme population growth, increased air pollution and increased demand for water. In the winter and spring of 2008, RAL conducted a precipitation enhancement feasibility study in Istanbul. Two 6–week intensive observation periods were planned between February 2008 and June 2008. Aerosol and cloud physics measurements were done with a research aircraft to characterize the properties of the aerosols and clouds in the region of Istanbul. The aircraft was equipped with instrumentation for the characterization of atmospheric constituents (gas and aerosols) and cloud particles in addition to measuring atmospheric dynamic and thermodynamic properties. A total of 92 flights with 350 flight hours were carried out during the project. The data analysis effort was completed in May 2009.

The results of this study provide a broad perspective on the cloud and precipitation formation processes in Istanbul. High aerosol loading resulting from air pollution in the region of Istanbul was measured, which may modify the physical properties of the cloud particles, increase the number concentration of cloud droplets, and inhibit the formation of large droplets by the collision–coalescence process. Aircraft measurements documented the high levels of pollution aerosols around the Istanbul area and the effect that these may have on the cloud droplet concentrations and size distributions. In some cases a cloud modification effect was measured that may be attributed to higher concentrations of aerosols when compared to an area with lower concentration of aerosols. Although this effect is not well understood, cloud modeling studies can be useful in understanding such complex cloud modification effects.

Kingdom of Saudi Arabia Assessment of Rainfall Augmentation

During the past year, a field program was conducted in the southwest region of Saudi Arabia in efforts to determine if clouds are amenable to rainfall enhancement through cloud seeding. In particular, the objective of the 2009 Field Program was to sample the thermodynamic properties of the environment and to examine the variability of aerosol, clouds, and precipitation through airborne, radar, and surface instrumentation measurements during the period of peak summertime rainfall in the southwest region. This study builds upon the knowledge gained during the 2008 Field Program in the same region. The field program was conducted from 15 July 2009 – 31 August 2009, with the intense measurement phase occurring during 5–31 August. The expected outcome of this study will be a determination of the suitability of clouds in the southwest region to cloud seeding and based on these observations, determine the optimal method(s) to target the clouds.

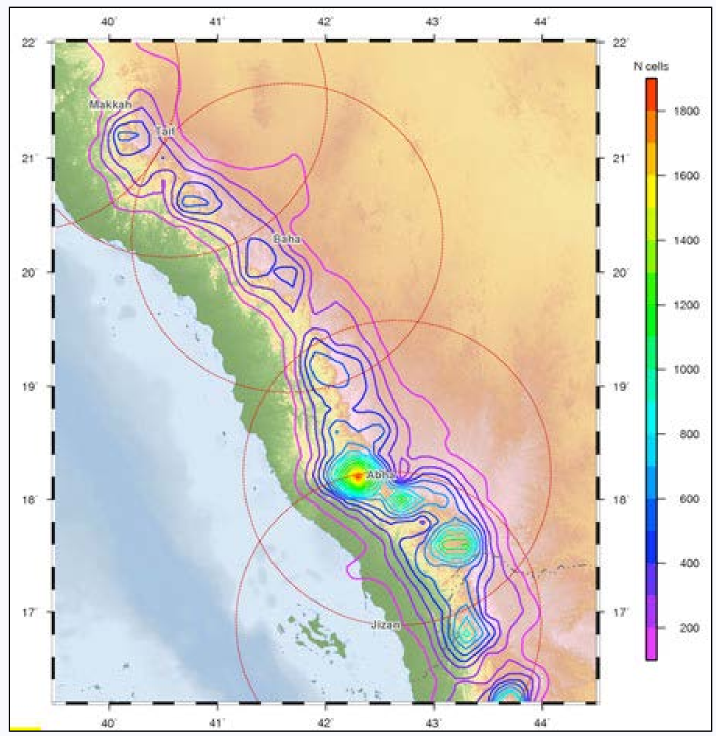

Fig. 3 Spatial distribution of cell frequency estimated by radar in the southwest region of Saudi Arabia

An essential part of the radar analysis is to determine the number of storms occurring over the southwest region of Saudi Arabia. This is important in order to understand and characterize the storms that are observed in the study area. A highlight of the radar analysis is shown in Fig. 3. The plot shows the spatial distribution of the cells identified by TITAN in the southwest region centered on the Abha and Al Baha radar. The cells observed by radar are clearly associated with the escarpment that is orientated northwest to southeast (parallel to the Red Sea). The peaks along the escarpment are associated with specific terrain features. For example, the highest frequency of cells (1800) in this region (and Saudi Arabia) occurs over the highest point (˜9200 ft) in Saudi Arabia, which is Souda Mountain. A secondary maximum is located to the southwest of Abha near the Yemen boarder, which is also centered on a high peak along the escarpment. Based on the observations, one can observe that convection was clearly driven by the orographic processes associated with the sea breeze from the Red Sea interacting with the steep mountains along the escarpment. Rainfall and hence targeting of clouds for the assessment of cloud seeding will have to be focused along the narrow region of cells observed in Fig. 3 as the frequency of potential cells for targeting rapidly decreases to zero on both sides of the escarpment.

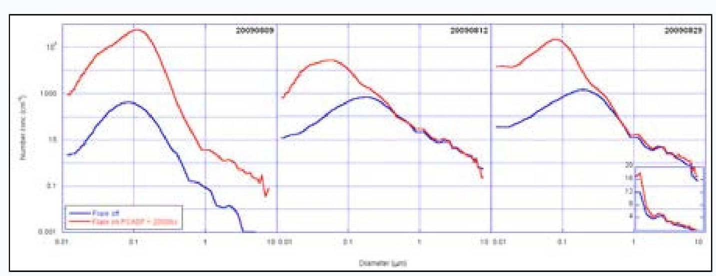
Fig. 4 Size distribution of flare smoke (red trace) compared to the size distribution of background aerosol (blue) at various altitudes relative to cloud formation level. The size distribution was obtained by combining data from the DMA, PCASP and the FSSP

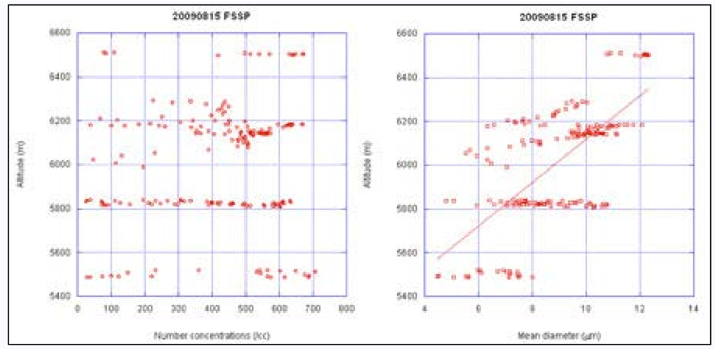

Fig. 5 Plots of particle concentration as a function of height (left) and mean diameter as function of height (right) for the research flight conducted on 15 August 2009

The airborne research effort was very successful during the 2009 Field Program. Research flights were conducted between 5 and 31 August. A total of 35 research flights were flown during August, which comprised 58 hours of flight time. There were 21 boundary layer flights, 9 cloud flights, 3 flare characterization flights, and 2 seeding flights.

Several measurements have been done of the size distribution of the hygroscopic seeding flare smoke using the DMA, PCASP and FSSP (see Fig. 4). What is unique about these measurements is that the DMA measured the size distribution of particles down to 0.01 µm. Previous measurements of flare smoke were only down to 0.1 µm. The additional range in the fine particle mode is important because at high supersaturations flare particles < 0.1 micron in size can become CCN. Future work will focus on determining the minimum dry diameter of activation at various supersaturations and to run simulations of aerosol warm phase cloud microphysics.

Figure 5 shows the distribution of particles (left panel) and distribution of the size (right panel) as function of altitude for the 15 August flight. The observations show a large range in particle concentration and sizes as function of height for the observation day. The concentration in particles ranged from about 25 cm–3 to 700 cm–3 for all altitudes. As for particle sizes, there is a slight dependency with altitude. The particles on average were on the order of 6 µm at the lowest altitude (5500 m) to about an average of 12 µm at the highest sampled altitude (6500 m). These initial observations indicate a tremendous variability in particle concentration and sizes observed during the field program.

Study of the effects of regenerated aerosols on orographic clouds and precipitation

Using a detailed bin microphysics scheme coupled into WRF model, RAL scientists investigated how the size distributions of cloud–processed (regenerated) aerosols affect orographic clouds and precipitation. It is found that the ground rainfall is sensitive to the size distributions of regenerated aerosols which influence the collision–coalescence process through changing the cloud drop size distribution (Figure 6). The rainfall amount from mixed–phase clouds is higher and less sensitive to regenerated aerosols than the warm–phase due to the extra source of large rain drops from the melted ice–phase particles which invigorate the collision–coalescence process resulting in more rainfall on the ground. In the mixed–phase polluted clouds, the concentration of freezing drizzle is similar to that in clean clouds when regenerated aerosols are large, which indicates that under certain conditions, the freezing drizzle will form in polluted clouds as efficiently as in clean ones (Figure 7). Consideration of regenerated aerosols results in less spatial–temporal variability of the background aerosol concentration, which is more realistic than when it is not considered (Figure 8).

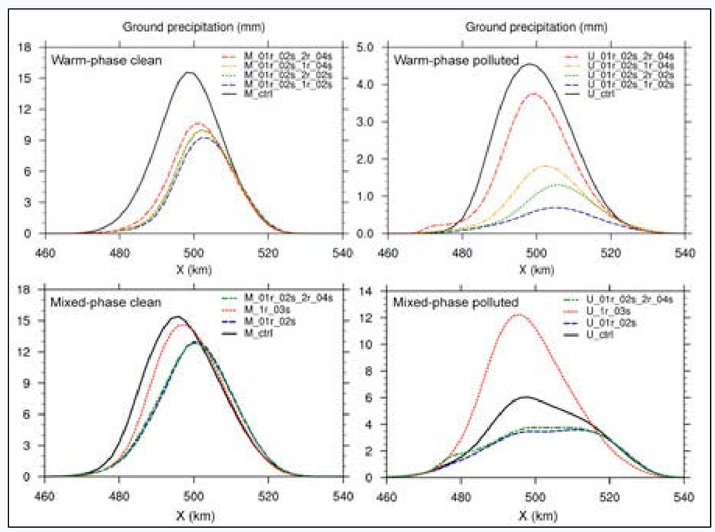

Fig. 6 Ground rainfall distribution in mm. Top panels indicate warm-phase cases and bottom panels for mixed–phase cases. Left columns indicate clean condition and right columns for polluted. For warm–phase clouds, the black line is control run in which the regeneration is not considered, color lines for different size distributions of regenerated aerosols. The legends describe the distribution, ex: M_01r_02s_1r_04s represents Maritime (clean) cloud with 0.1 um small mode mean radius, 0.2 spread and with 1 um large mode mean radius, 0.4 spread

The theoretical study on regenerated aerosol effects on orographic clouds and precipitation in 2009 showed that it is important to incorporate aerosol regeneration process into the numerical model to represent cloud and precipitation processes in a more realistic way. Sensitivity studies of regenerated aerosol size distribution effects and aerosol hygroscopic effects on other cloud types are planned for this coming year.

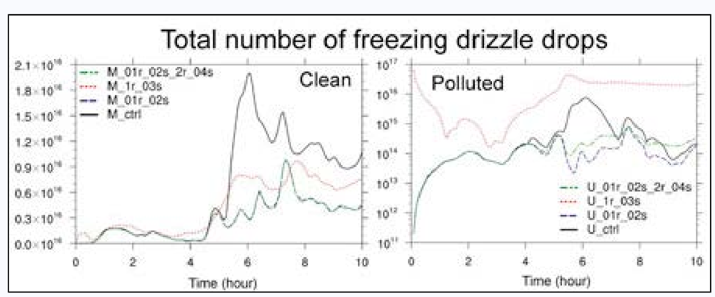

Fig. 7 Time series of domain total number of freezing drizzle drops in clean and polluted clouds

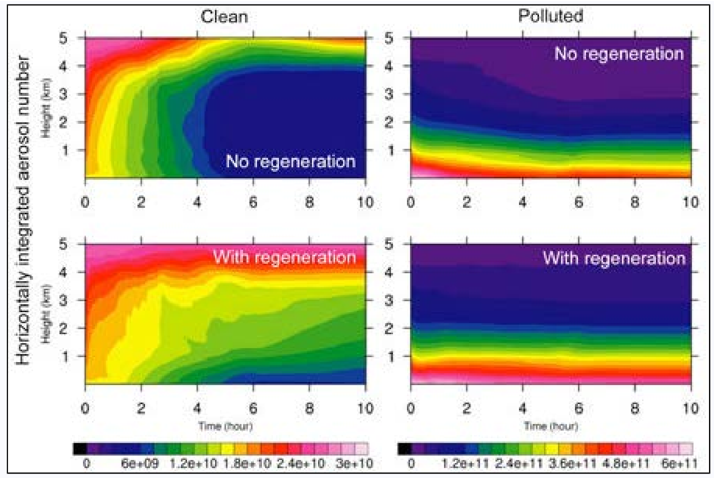

Fig. 8 Time–height contours of horizontally integrated aerosol number for clean and polluted clouds

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HYDROMETEOROLOGICAL APPLICATIONS

Winter Weather

Background

Winter weather efforts include the development of new systems to measure winter precipitation rate and type in support of ground deicing (FAA funded), the development of radar based algorithms to detect winter precipitation type, winter microphysics studies using a video disdrometer and other data at the Marshall Field Test site, participation in winter field programs such as ICE–L, analysis of data from field programs to improve understanding of winter precipitation processes, participation in a winter nowcasting effort supporting the 2010 Vancouver Olympics and weather modification efforts related to winter snowpack enhancement in Wyoming. A recent development is the decision by the NOAA Climate Reference Network program to move their Sterling, VA test facility to the Marshall Test site. We were also recently awarded a contract by the National Weather Service to conduct winter testing of future ASOS sensors such as the All Weather Precipitation Accumulation Gauge at the Marshall Test site. In the following we highlight the Wyoming Weather Modification Pilot program. A link to the FAA winter weather program is given below.

See section 1.3 for winter weather R&D focused on aviation

Wyoming Weather Modification Project

The Wyoming Weather Modification Five–Year Pilot Project (WWMPP) is funded by the State of Wyoming through the Wyoming Water Development Commission (WWDC). Evaluation activities of the project fall under a contract with the Research Applications Laboratory (RAL) of the National Center for Atmospheric Research (NCAR) while most of the logistics, infrastructure, and operations of the project are covered under a separate contract to Weather Modification Inc. (WMI). The primary goals of the WWMPP are to establish an orographic cloud seeding program in three areas of Wyoming and determine its efficacy. The three ranges of interest include the Medicine Bow, Sierra Madre, and Wind River ranges, from which snowmelt eventually affects the Green/Colorado River Basin, the Wind River Basin, and the North Platte River Basin (Fig. 1). Two general approaches are guiding the evaluation: a randomized experiment that builds distributions of seeded and control (unseeded) cases, and exploratory studies to investigate a wide variety of ideas on detecting seeding effects, including physical studies to document the precipitation formation events hypothesized to be important to snowfall production in orographic storms.

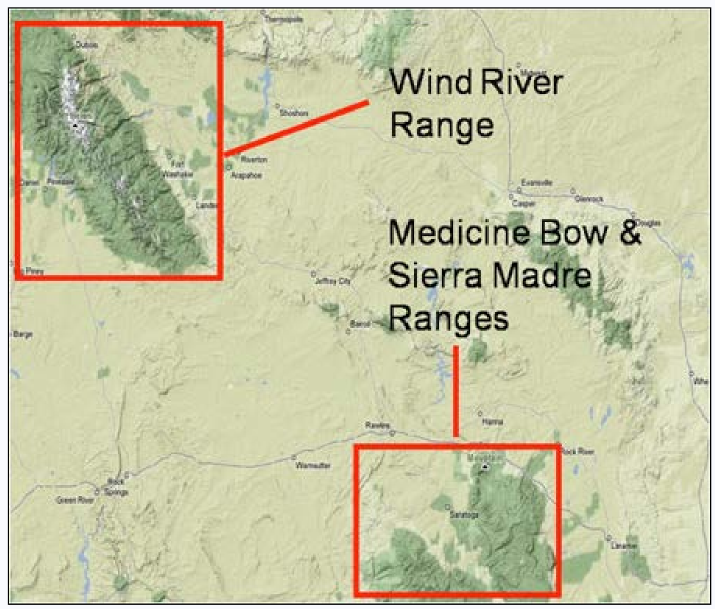

Fig. 1 Partial map of Wyoming showing locations of the three mountain ranges of interest: Wind River, Sierra Madre and Medicine Bow. The latter two make up the "southern" ranges, which encompass the area of the randomized seeding experiment

Design of the Randomized Seeding Experiment

One of the more important results over the last two years has been the development and execution of the Design of the Randomized Seeding Experiment. This design encompasses the two southern ranges (Medicine Bow and Sierra Madre), and instrument sites deployed in support of the design, (illustrated in Fig. 2.) An overview of the elements described in the Design follows:

1. Target areas have been identified near the crests of the Medicine Bows and the Sierra Madres, encompassing the existing National Resource Conservation Service (NRCS) SNOTEL* sites at Brooklyn Lake and Old Battle. The SNOTEL

data indicated that these target areas receive significant snowpack during a season. These sites were also chosen to take advantage of the existing instrumentation and historical precipitation and climate data

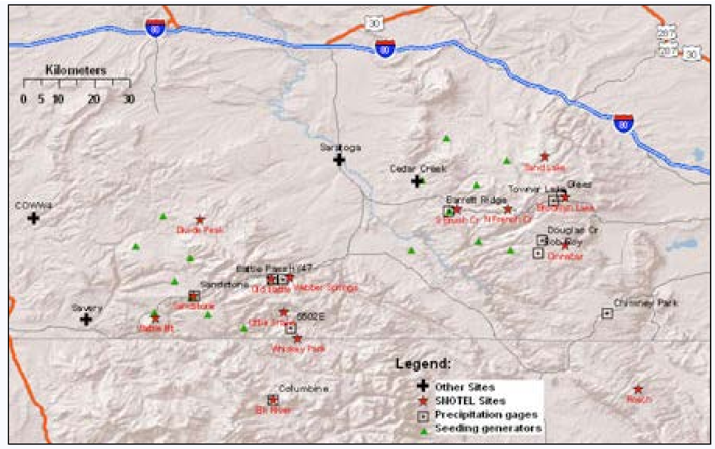

Fig. 2 Layout of the measurement and operational networks in the southern mountains of Wyoming. The precipitation gauge sites are indicated by a square; SNOTEL sites are indicated by red stars; AgI generator sites are indicated by green triangles; and other sites are indicated with bold crosses. The Savery and Cedar Creek are radiometer sites, the Saratoga site is where soundings are released, and COWW4 is the interagency Remote Automated Weather Station (RAWS) site, Cow Creek

2. Seeding generator sites have been chosen to affect target areas under predominant wind directions (roughly from the southwest, west, and northwest directions). Their location on Forest Service lands required long permitting lead time and acceptable forest clearings. The spacing of generators was roughly determined from results of past studies, taking into account practical siting considerations, and was further characterized with plume modeling
3. A majority of the storms in this region affect both ranges. This is evident from the relatively high correlations of 0.41 to 0.47 for daily snowfall between the ranges using SNOTEL data from sites in or near the target areas within each range
4. A cross–over design is planned, in which one range is randomly determined to be seeded while the other becomes the control. This results in paired cases
5. The seeding treatment period will be kept short (4–hr) to strive for homogeneous conditions as well as to obtain a greater number of cases
6. A buffer time period of 4–hr will be used between consecutive treatment periods to clear the area of seeding material
7. High–resolution precipitation measurements (resolution 0.25 mm, recorded in 1–min periods) will be made using redundant gauges at both target and control areas in each range
8. Two closely–spaced (˜2 km apart) gauge sites will be used in each target area in the respective ranges and averaged to decrease the variance in the precipitation measurement for each target area
9. Two control gauge sites, one upwind and one crosswind, will also be used with each target area within each range. The control gauges will be used to help describe the natural variability in precipitation between targets and between events
10. Case selection requires: temperatures cold enough for efficient AgI IN activation; wind speed and direction appropriate for the AgI generators to impact the target; and the presence of SLW. These criteria should be satisfied in both targets simultaneously
11. The primary statistical test will be based on ratios – summation of 4–hr accumulated precipitation at target gauges for seeded versus unseeded events, scaled by the ratio of the 4–hr accumulated precipitation during seed/no–seed events at control gages
12. A secondary statistical test (Wilcoxon–Mann Whitney) will be performed on residuals – difference between 4–hr accumulated precipitation at target gauges and an accumulation based on predicted response at the target area using control gauges. Other tests may also be performed
13. The ratio test will be used to evaluate the null hypothesis that the ratio of the total measured precipitation for seeded versus unseeded conditions is equal to 1. A ratio significantly greater than one would suggest evidence for the effectiveness of the seeding method
14. A rough estimate of the number of paired cases to be expected in an average season is about 50
15. The number of samples needed for statistical significance is estimated to be 140 to 360 to detect a 10–15% precipitation increase
16. Aside from the primary uncertainty of whether seeded clouds will produce additional precipitation, the other uncertainties in this design relate to the dispersal of the seeding material and the subsequent dispersal of seeded snow crystals. Are the generators sited appropriately to affect the small target areas with gages? Will seeded snowfall contaminate the control gages? Will AgI released from the upwind range, the Sierra Madres, affect the Medicine Bows? The issues of targeting uncertainty and contamination potential will be at least partially assessed through collection of a large number of silver–in–snow samples, covering a large majority of cases in both targets for at least two seasons

Instrumentation

Sounding data, collected from the release of rawinsondes ("weather balloons"), play a key role in weather modification activities. These measurements allow a forecaster to determine if temperature and wind conditions are sufficient for effective seeding operations. Soundings are launched from Saratoga, under the guidance of WMI personnel, whenever seeding conditions are forecast to be close to meeting the experimental requirements. Therefore, sounding data are available for each case.

Microwave radiometers are instruments that derive vertical profiles of water vapor, liquid water path, and temperature (if equipped with an infrared sensor). Hence, radiometers are able to provide important data

on the moisture quantities in the atmosphere that allow a forecaster to determine whether enough liquid water exists to make seeding operations effective. Two microwave radiometers have been used in the southern ranges. A two–channel radiometer, owned and operated by WMI, was located outside of Saratoga near Cedar Creek, west of the Medicine Bows. The other was a five–channel profiling radiometer on loan from the South Dakota School of Mines and Technology and operated by NCAR, and was located near Savery, west of the Sierra Madres. Fig. 3 shows the installation of the Savery radiometer.

Fig. 3 The Savery radiometer, looking east over the Sierra Madres

NCAR owns a ceilometer (Vaisala Model CT12K) that can determine cloud base heights up to 12,000 feet above ground level by measuring the scattered/reflected return of an emitted laser beam (also known as reflectivity). Cloud base height measurements can be useful for numerical model verification of orographic cloud formation. With the cooperation of the U.S. Forest Service Saratoga Office, the ceilometer was deployed at the Brush Creek Workstation on the western (upwind) flank of the Medicine Bows. Fig. 4 is an example of the daily plots of the reflectivity that were generated for analysis. The first image (on the left) shows a typical reflectivity pattern associated with non–precipitating clouds. The elevated 'reflectivity' signature shows the cloud base height (˜4000 ft above ground at 1500 UTC). The second image shows a reflectivity pattern common for snowfall occurrences. The reflectivity signature descending to the ground indicates precipitation at the site (˜0130 to 2100 UTC).

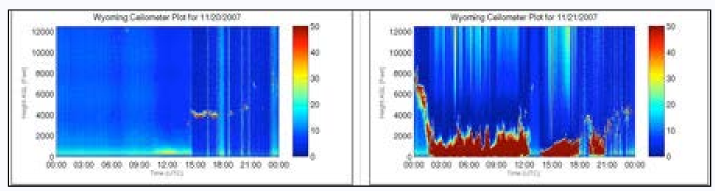

Fig. 4 Ceilometer time–height plots of reflectivity during a non–precipitation event (left image) and a snow event (right image)

Eight sites (four in the Medicine Bows and four in the Sierra Madres) were chosen for the installation of precipitation gauges designed for high–resolution measurements of liquid–equivalent snowfall amounts. Vaisala VRG101 all–weather precipitation gauges were initially purchased to make the snowfall measurements. Once the gauges were deployed and data were collected, it was quickly determined that several problems were occurring with the VRG101 gauges. To address some of the problems, a different style of precipitation gauge (ETI NOAH II) was purchased and installed at the sites to run alongside the VRG gauges, complementing the data collected from the VRG's and helping fill in gaps during time periods when the VRG's had problems. All the sites now have ETI gauges, which are the primary gauges, with several sites also operating VRG's as the complementary gauge.

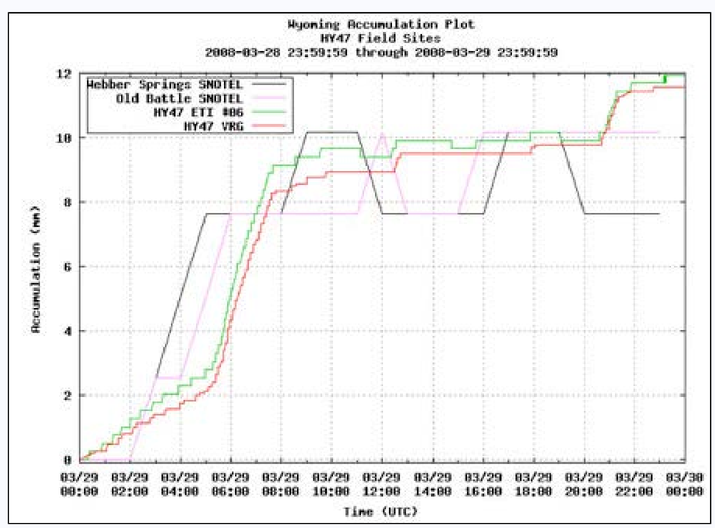

Fig. 5 Example time–series plot of precipitation accumulation from the HY47 gauges compared to the nearest SNOTEL sites

In the southern ranges of Wyoming, there are numerous SNOTEL locations, and each of precipitation gauge sites also has a relatively close SNOTEL location. The SNOTEL observations are too coarse to be used in the randomized experiment, but they are useful in assisting with data quality control of the VRG and ETI gauges by helping determine when false accumulations and periods of noise occur in those data. Fig. 5 shows an example of the SNOTEL liquid–water equivalent data from two nearby

locations with the VRG and ETI precipitation gauge data from one of the Sierra Madre sites (HY47).

Methodology and Results

Based on precipitation data collected in the last two seasons, estimates of the number of cases needed to detect a statistically significant increase of 10% (for example) in snowfall were re–calculated. A decrease to about 150 cases (range of ˜100–250, given the uncertainties) over the original estimate for a 10% change supports the experimental design concept and improves the potential for successfully detecting a change over the course of the project. To date, operations have occurred for 55 cases. However, not all of those cases have adequate precipitation data available. Over the next three seasons, 120 or more cases are expected. Continued analysis of the precipitation data for variance, correlation, and other properties affecting estimates of the number of cases will be needed to ensure that the project is on track for a valid evaluation effort.

Fig. 6 Snow pit profile samples for trace chemistry analysis collected in the Sierra Madres

Baseline levels of silver in the target ranges were investigated prior to any seeding in 2005–2006. These data were collected in order to evaluate potential environmental effects and to establish background levels in snow for future studies using trace chemistry analysis to detect seeding effects. Additional profile sampling (from digging snow pits – see Fig. 6) was performed in 2006–2007. Final results of the 2006–2007 samples are still being compiled, but preliminary results indicated that no significant silver concentrations were detected in the few profiles collected. Although the profiles were not timed well with seeding events (causing compaction of snow to further mask any silver 'seeding' signal), some elevated concentrations were expected to be found due to seeding cases based on past experience. These preliminary findings led to two approaches to sampling for the 2007–2008 season: detailed snow profiles on a few occasions (as before), and more frequent but coarser sampling after a significant snowfall. The frequent snow sampling was carried out by NCAR. Preliminary results from the January 2008 silver–in–snow samples suggest that much of the variability in silver deposited to the sites before 9 January was due to natural processes, with little evidence of seeding or pollution. A possible exception was snow deposited from the 5th to 6th at HY47 and Old Battle, which both show elevated silver levels not associated with dust or thallium. [Note: seeding in the Sierra Madres occurred late on the 5th.]

In 2008–2009, the snow sampling was limited to a few profile samples and several timed (2–6 hour) samples, collected in conjunction with AgI ice nuclei sampling in the Medicine Bow target area. The profile sampling and all the sample processing and analysis were performed under the DRI subcontract.

The Weather Research and Forecasting (WRF) model and the Real Time Four Dimensional Data Assimilation (RT–FDDA) system is used in operations to guide forecasters on expected conditions specific to seeding criteria, particularly when super–cooled liquid water might be expected and for estimating plume trajectories from individual seeding generators into the target regions. Several display features (maps, cross–sections, etc.) have been customized to the WWMPP, and a separate website is dedicated to providing the model output. Two changes to the setup of the WRF RT–FDDA have occurred prior to the last field season. The planetary boundary layer (PBL) parameterization (i.e., how the lowest level of the atmosphere is impacted by surface features and conditions) was changed to one that was thought to be more representative of winter–time conditions. In general, this change did not affect the model output much, but occasionally there were cases when the conditions seemed to be more faithfully represented with the new boundary layer scheme. A more extensive evaluation is currently in progress. Increasing the cycle times was a more significant change to the setup. To take full advantage of the RT–FDDA system, the cycle times were changed to occur every 3–hr (rather than 6–hr) but at the expense of allowing only 24–hr forecasts (instead of 36–hr forecasts). The more frequent input of data usually improved the analysis and short–term forecasts, and were designed to better represent airflow and hence trajectories from the seeding generators.

Two ice nuclei (IN) counters were deployed in 2007–2008, one as an airborne unit and one as a ground unit. While not adequate for measuring the low concentrations of IN that occur naturally, the IN counters are effective in detecting the copious IN in AgI plumes. The detection and mapping of AgI plumes are valuable adjuncts to the detection of silver–in–snow samples, and provide more detailed information for evaluating targeting issues. The utility of the ground–based unit in particular was demonstrated in the 2007–2008 deployment and further measurements were taken in 2008–2009.

Collaborations with researchers at the University of Wyoming have been extensive, particularly since several studies that complement or directly address WWMPP evaluation activities have been funded through the Wyoming Water Research Program. For example, a hydrology study, headed by Glenn Tootle of the Department of Civil and Architectural Engineering (as an adjunct professor), aims to develop relationships between snowpack and streamflow in the southern ranges of Wyoming and eventually to quantify streamflow changes due to cloud seeding operations. Also, Bart Geerts has expanded the focus of his airborne measurement studies to use the Wyoming Cloud Radar and flight–level particle probes to describe the signature of glaciogenic cloud seeding in orographic snowstorms in Wyoming. These types of studies are valuable additions to the WWMPP and the WRP grant process has provided an excellent opportunity to enhance the program.

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2009 Lab Annual Report

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HYDROMETEOROLOGICAL APPLICATIONS

Colorado Headwaters Project

Background

The Colorado Headwaters effort is a project under the RAL/ISP Water System program. It was initiated in the spring of 2008, and is focused on assessing the impact of climate change on winter precipitation, snowpack and runoff processes from Colorado's headwater basins using a very high resolution fully coupled atmospheric–hydrologic model (WRF coupled with the NOAH land surface model). Scientists involved in the project are: Roy Rasmussen, Changhai Liu, Kyoko Ikeda, David Gochis, David Yates,Kathy Miller, Fei Chen, Mike Barlage, Mukul Tewari, Ethan Guttman (ASP Postdoc), Greg Thompson, Jimy Dudhia, Rit Carbone, Mitch Moncrieff from NCAR and Vanda Grubisic from the University of Vienna Professor Yang Liang from the University of Texas and Kristi Arsenault and Paul Houser from George Mason University

Methodology

The project competed for and was awarded 500,000 computer GAUs offered from CISL as part of an Accelerated Science Discovery competition in the spring of 2008. The GAUs were available for a three–month period starting fall of 2008, and all the awarded GAUs were used to complete most of the planned numerical experiments. The Advanced Research WRF (ARW) model was applied to conduct high–resolution regional climate simulations of cold–season snowfall, snowpack, evapotranspiration and runoff in the Colorado Headwaters region. The domain of the high resolution model is shown in figure 1a, and the SNOTEL observation sites used to evaluation the simulations in figure 1b as the black dots. The specific simulations performed were as follows: i) five 6–month, 2–km–resolution simulations of present–day climate using the North American Regional Reanalysis (NARR) data, covering two cold seasons (i.e., year 2004–2005, and year 2005–2006) of normal (i.e., approximately multi–year mean) precipitation and snowpack, one cold season (i.e., year 2007–2008) of anomalously high snowfall and snowpack, one cold season (i.e., year 2002–2003) of anomalously low snowfall and snowpack, and the 2008 warm season; ii) a few coarse-resolution simulations of the 2007–2008 cold season with grid spacings of 6km, 18km and 36 km; iii) one 6–month, 2–km–resolution simulation of snowfall and snowpack in response to a pseudo climate warming, in which the initial and boundary conditions were derived from the combination of the 3–hourly NARR data with the climate perturbations representing the differences between the present (i.e., 10–year averages from 1995–2005) climate and the future (i.e., 10–year averages from 2045–2055) climate projected by CCSM; and iv) two future climate simulations at grid spacings of 6km and 18 km for the 2052–2053 cold season using the 6–hourly CCSM output for the IPCC SRES A1B scenario.

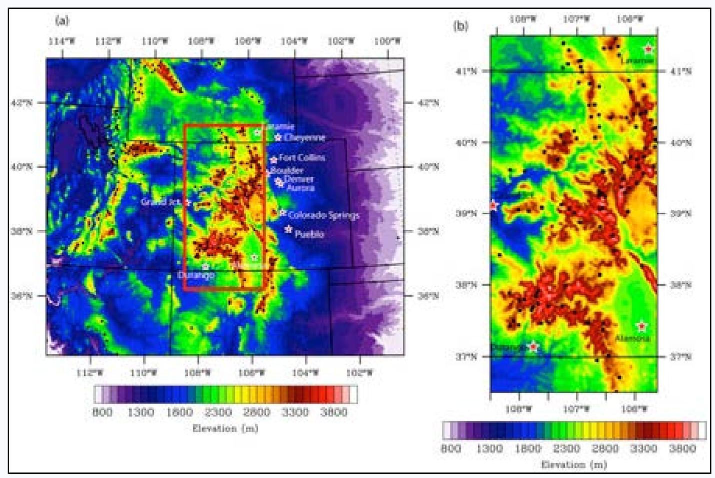

Fig. 1 Retrospective model domain and location of SNOTEL sites (black dots). (a) represents the full domain, while (b) is a sub–domain focused on the SNOTEL sites in the Colorado Headwaters region

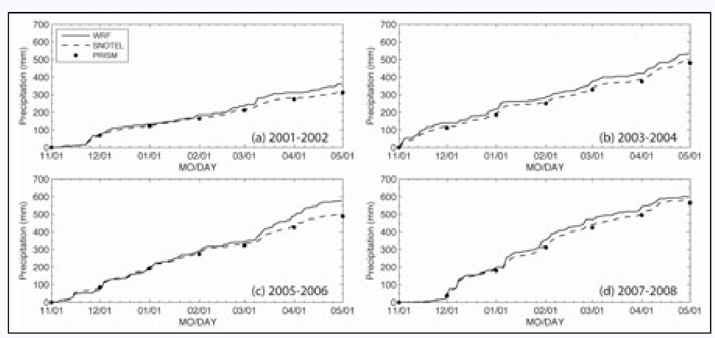

Fig. 2 Comparison of 2 km WRF to SNOTEL site average accumulative precipitation (mm) for a 6–month simulation period during (a) 2001/2002 (dry year), (b) 2003/2004 (average year), (c) 2005/2006 (average year), and (d) 2007/2008 (wet year) water years. Also overlaid is precipitation from monthly PRISM data corresponding to the individual SNOTEL sites

Preliminary Results

The diagnostic analysis of the simulations are in progress, but thus far results have shown that the model is able to reproduce observed SNOTEL precipitation amounts within 10% of observations from 111 SNOTEL sites for all four simulated years (figure 2).

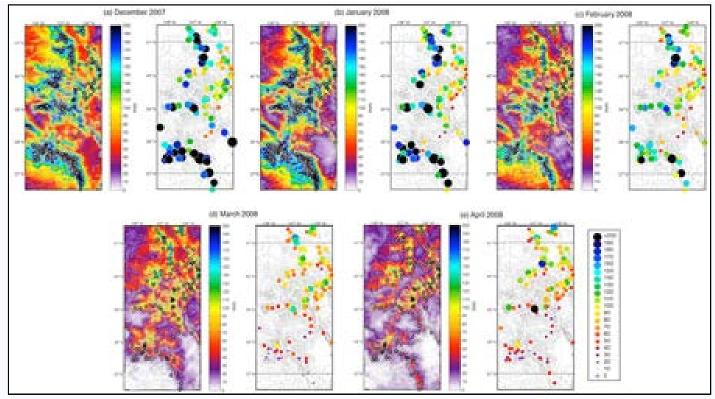

Fig. 3 Spatial pattern comparison of monthly total precipitation between the 2–km WRF simulation (left panels) and SNOTEL observations (right panels) for (a) December 2007, (b) January 2008, and (c) February 2008. Precipitation amount at SNOTEL sites is shown with filled circles (references to the filled circles are shown in bottom right)

High resolution model simulation spatial patterns of precipitation also showed excellent agreement with the SNOTEL observations as shown in figure 3. Responses of snowfall and snowpack to an idealized warming climate showed increases in snowfall on the order of 10%, consistent with the simulated increase in water vapor. The increase was not confined to the highest peaks as might be expected, but exhibited complex structures associated with changes in the mesoscale structure of the weather patterns. The simulated strong dependence of snowfall and snowpack on grid resolutions illustrates the importance and usefulness of high–resolution models in improving the future climate projections by global climate models. Future work will focus on analysis of the future climate runs and conducting nested regional climate runs. A number of papers are close to submission.

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CLIMATE, WEATHER & 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.

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CLIMATE, WEATHER & SOCIETY

Strategies for Regional Adaptation to Climate Change

Background

The FY2009 ISSE program addressed strategies for regional adaptation to climate change to improve the scientific foundation for regional–scale adaptation to climate change by conducting integrated regional–scale analyses of climate change, its impacts, vulnerabilities and adaptation by generating regional–scale scenarios of projected climate change, developing tools and methods for analyzing vulnerability and evaluating adaptation options. The following initiatives fell into this category.

The North American Regional Climate Change Assessment Program (NARCCAP)

The North American Regional Climate Change Assessment Program (NARCCAP) is systematically investigating the uncertainties in regional scale projections of future climate and produce high resolution climate change scenarios using multiple regional climate models (RCMs) nested within multiple atmosphere ocean general circulation models (AOGCMs) forced with the A2 SRES emission scenario, over a domain covering the conterminous US, northern Mexico, and most of Canada. The project also includes an evaluation phase through nesting the participating RCMs within re–analyses of observations. This international program includes RCMs developed or maintained by European groups (PRECIS and RegCM3), the Canadian regional climate model (CRCM), and U.S. models including the ECPC regional spectral model (RSM), MM5, and the Weather Research and Forecasting Model (WRF). AOGCMs include the NCAR CCSM3, the Canadian Climate Centre CGCM3, the GFDL CM2.1, and the Hadley Centre HadCM3. High resolution (50 km) global time slice experiments based on the GFDL atmospheric model (AM2.1) and the NCAR atmospheric model (CAM3) are also being produced and compared with runs of the regional models, also run at 50 km resolution. 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 US and Canada. In 2009, the data for the first phase of the project was released to the public.

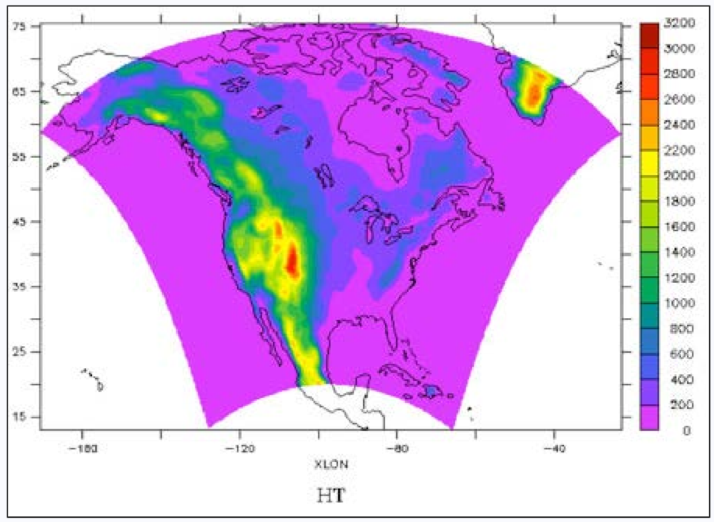

Fig. 1 The NARCCAP regional model grid over North America

Water Resources

ISSE/RAL researchers worked with urban water providers to develop and apply a structured approach for evaluating the implications of climate change for water resource planning. This recently–completed project sets a new standard for climate change adaptation planning by explicitly accounting for uncertainty. Specifically the project encourages the participating utilities to assess the performance of their planning options under a range of possible realizations of future climate, where that range is based on downscaled climate model simulations. The utilities can then evaluate their options on the basis of their robustness to uncertainty, resilience to extremes and adaptability to new information. In addition, the team also has been active in disseminating climate change information to the user community, through numerous presentations.

ISSE also collaborated with Rob Wilby (University of Loughborough, UK) to write a series of technical briefing papers on various climate change/water resource impacts topics. These have been broadly distributed to the urban water supply and waste–water management communities through industry channels. See: http://www.theclimatechangeclearinghouse.org/Resources/TechBrief/default.aspx.

Urban Vulnerability

Societal resilience and urban vulnerability are the focus of the RESUCCITIES project that is examining how changes in the magnitude of societal drivers relate to variations in urban atmospheric emissions across 84 cities. In addition, a model–centered meta–analysis of existing case studies on cities' vulnerability to climate change, using a set of frameworks (impacts assessments, political ecology, and urban resilience) is being developed to illustrate the key theoretical determinants and outcomes of cities' vulnerability to climate change.

ADAPTE (Adaptation to the health impacts of multiple stresses in Latin American cities), an IAI–funded project, seeks to investigate the independent and combined effects of exposure to heat stress and air pollution and human vulnerability to urban health in four Latin American cities (Buenos Aires, Bogota, Mexico City, and Santiago Chile). The project explores how patterns in human mortality/morbidity and vulnerability vary spatially, and what are human and environmental factors accounting for this differential distribution. Scientists are working on defining social vulnerabilities in the context of urban heat and air pollution in Latin American cities, and on the spatial analysis of environmental and social variables.

Weather, Climate and Health

Scientists are researching the complex interactions among climate processes, ecosystems, and human health in order to improve projections of climate impacts on human health and the health of the planet. This research will also help to:

1. Determine appropriate adaptations to potential threats to human health
2. Sort out the complex relationships between climate and ecosystems
3. Help educate the next generation of researchers in these complex interwoven areas

Work has focused in four areas thus far:

Health Risks from Extreme Heat in Phoenix, AZ

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. Central to understanding societal vulnerability, is adaptive capacity, the potential of a system or population to modify its features/behaviors so as to better cope with existing and anticipated stresses and fluctuations. Understanding societal risks, vulnerabilities and adaptive capacity to extreme heat events and climate change requires an interdisciplinary approach that includes information about weather and climate, the natural and built environment, social processes and characteristics, interactions with stakeholders, and an assessment of community vulnerability. Toward this end, residents of 360 households in the Phoenix area were interviewed in a door–to–door survey conducted in August 2009. Analysis and write–up are currently underway.

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. This transmission is especially important in geographic areas where dengue has more recently emerged. Research in these areas seeks to develop interventions to slow or halt the further expansion of dengue, and to efficiently focus preventive efforts. An outbreak investigation within the Lower Rio Grande was conducted in Brownsville, Texas and Matamoros, Mexico in 2005. This research revealed the highest prevalence of human anti–dengue antibodies in the continental United States in the last 50 years and the first case of classic dengue hemorrhagic fever acquired in the continental United States. The data indicate many more infections in Matamoros than in Brownsville and highlight the need to delineate the various influences, including climate, on dengue transmission dynamics.

Because dengue fever is transmitted by an urban, peridomestic mosquito, examination of waste tires and other water–holding containers in close proximity to households is critical to a clear understanding of the potential role that tires play in mosquito breeding sites. To better inform educational campaigns directed toward tire clean–up, it is necessary to ensure that household members understand the risk and are willing to engage in activities leading to tire removal/mosquito breeding site mitigation. Local government efforts to control tires must also be informed by careful evaluation to ensure efficient and effective quality control efforts.

Analysis and write–up of the 2008 field work is under way, and a poster has been presented at the annual meeting of the American Society of Tropical Medicine and Hygiene to further document the ecology of Aedes aegypti and Aedes albopictus in this border region.

Workshops on Climate and Health

The effects of climate on human health are a very sensitive and complex area of impacts research. It is also one that society is most concerned about when facing climate change. Careful training is necessary to perform high quality research in this area. Three successful interdisciplinary workshops on Climate and Health were conducted by ISSE (FY04, FY06 and FY09), in which graduate students and early career faculty learned from a wide range of experts how to develop complex interdisciplinary health projects. These workshops form part of the Weather and Climate Impacts Assessment Science Program (WCIASP). The most recent workshop in FY09 and focused on the individual and combined effects of heat stress and air pollution. This topic reflects the growing concern regarding these combined stresses on human health. The workshop also linked with on–going research efforts regarding heat stress, vulnerability and adaptive capacity in Phoenix, Arizona.

A prototype Earth–gauging System Integrating Weather and Health Data to Manage Meningitis

This project 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 2009 we established local partnerships in Ghana, undertook a site visit and developed a survey on knowledge, attitudes and practices (KAP) and cost of illness (COI) regarding meningitis in the Navrongo region of Ghana which will be conducted in early 2010. Work is ongoing to demonstrate weather–meningitis links, and develop and verify ensemble–derived forecasts for meningitis management.

GIS Program

Health Risks from Extreme Heat in Phoenix, AZ

The study is focused on developing a framework for an interdisciplinary approach and a case study that explore linkages between quantitative and qualitative data for a more comprehensive understanding of local level vulnerability and adaptive capacity to extreme heat events in Phoenix, Arizona (see project description above). GIS technology is being used as a component of this study.

Global assessment of urban heat island effect and future heat waves: GIS applications in urban climate modeling

CCSM outputs from global coupled simulations of present–day climate and future climate are being analyzed in a GIS with respect to the urban heat island effect, future heat waves and their impacts on urban population. This project involves development of geoprocessing techniques for working with the netCDF model outputs in a GIS; spatial analysis of projected heat waves intensity and spatial extent (future work includes analysis of frequency and duration); and analysis of potential impacts of combined effect of urban heat island and future heat waves on urban population through spatial integration of urban climate model and population projections.

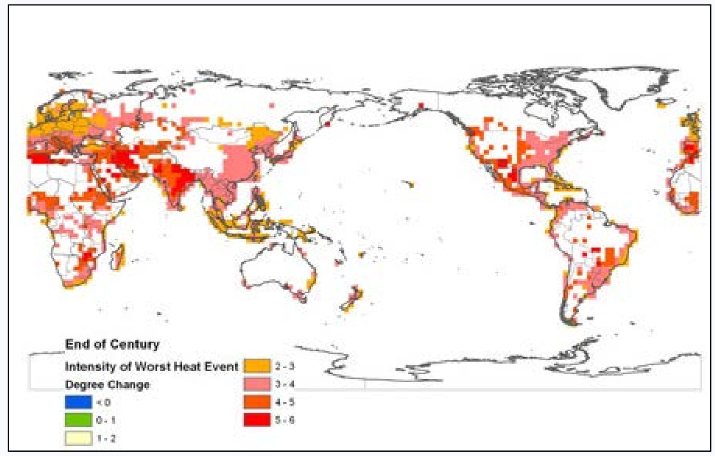

Fig. 2: Increased severity of the worst annual heat events in urban areas by 2099

3rd NCAR Community Workshop on GIS in Weather, Climate and Impacts

The 3rd Community Workshop on GIS in Weather, Climate and Impacts, organized by NCAR GIS program, took place at NCAR on October 27–29, 2008. The workshop brought together 62 leading researchers and practitioners from multiple disciplines to discuss visions, challenges, and research needs in spatial integration of information from social, atmospheric and related sciences. The workshop reviewed progress in AtmoGIS research, applications and data interoperability, and discussed integration of physical and social science data in a GIS. The workshop included presentations, panel and breakout group discussions, poster session, reception and a hands–on GIS training course, developed by the GIS program staff for the workshop participants. In working groups the workshop participants identified:

1. Atmospheric data needs for spatial societal research and applications
2. Social science data needs for integrative assessments and Earth System modeling; and discussed
3. Methodologies for integration of natural and social science data (both quantitative and qualitative) for weather hazards preparedness and climate change adaptation

The workshop summary was presented at the AGU joint assembly meeting in Toronto. Journal article on the key findings and research direction is now in preparation. The workshop proceedings can be found at http://www.gis.ucar.edu/08workshop/index.jsp.

Marine Ecosystem Vulnerabilities

The vulnerability of marine ecosystems to climate change was an important topic addressed by ISSE/RAL in FY2009. Coral reefs, in particular, are considered one of the most vulnerable ecosystem to climate change. ISSE's work continues to examine the effects of rising temperature and increasing ocean acidification on this ecosystem. In collaboration with colleagues from the University of Miami, the University of Colorado, and NOAA, work in the Galapagos Islands, which experiences naturally acidified conditions, indicates that lack of cementation in this region is a likely contributor to the rapid erosion of coral reefs following a coral die–off in the 1982–83 ENSO event. Because ocean acidification affects cementation rates (See Fig. 3), this indicates that reef vulnerability to erosion is likely to increase in the future. ISSE's Joanie Kleypas has lead several national imperatives related to ocean acidification, in particular the development of a National Research Program on Ocean Acidification, and is part of a National Academy of Science panel to recommend the research strategy for such a Program.

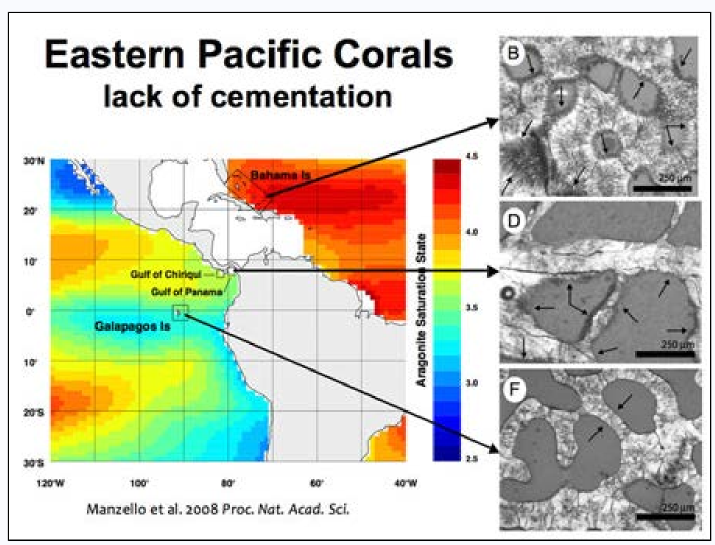

Fig. 3

The vulnerability of coral reef bleaching to rising temperature remained an ongoing topic of research in ISSE in FY09. Recent work through the Weather and Climate Assessment Program highlighted the importance of local sea surface temperature variability as a factor in determining temperature thresholds to bleaching. ISSE was also a co–organizer of the Advanced Study Program's Summer Colloquium on Marine Ecosystems and Climate. As part of a project to examine coral reef vulnerability to future sea surface temperature increases, students used CCSM sea surface temperature projections to test the effect of different rates of coral adaptation on coral bleaching frequency. The analysis highlighted the importance of the time scales of variability associated with natural climate mode variability.

ISSE research also focused on the governance of fisheries and marine ecosystems in the context of rapid socioeconomic change and a variable and changing climate. ISSE organized a workshop on the role of integrative science in marine resource governance in conjunction with the 3rd GLOBEC Open Science Meeting (Victoria B.C.) in June 2009, and led a multi–author team in preparing a paper that has been submitted to Progress in Oceanography. The other institutions involved in that effort were: Saint Mary's University, Plymouth Marine Laboratory, Technical University of Denmark, University of Maryland, University of Washington, University of São Paulo, Memorial University of Newfoundland, University of British Columbia, University of Victoria, and Fisheries and Oceans Canada.

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CLIMATE, WEATHER & SOCIETY

Use and Value of Weather Information

Background

The overall goal of this body of work is to improve the effectiveness of weather forecasting by integrating social sciences and meteorology to study the communication, interpretation, use, and value of weather forecast information, including uncertainty.

Weather and climate affect all economic sectors, regions, individuals and communities. Improved weather forecasts – and better use of current forecasts – could provide any number of societal enhancements, including improved personal safety, reduced property damage, and increased economic efficiency, as well as saving multiple lives and millions of dollars annually. To realize the potential benefits associated with improved weather forecasts, researchers, industry, and policy makers must better understand how individuals and socioeconomic sectors currently – and potentially could – use different types of weather information.

Few assessments of the benefits of weather information have been performed, and much of the knowledge available on the use and value of weather information is difficult to locate and utilize. To address this need, NCAR, with funding from NSF and the U.S. Weather Research Program, established the Collaborative Program on the Societal Impacts and Economic Benefits of Weather Information (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 following efforts were collaborative with researchers from the Institute for the Study of Society and the Environment (ISSE), which was integrated into RAL in FY08 and FY09, and has transitioned into the Integrated Science Program (ISP) in FY10.

Milestones

WAS*IS

In August 2009, SIP conducted the 7th Weather and Society * Integrated Studies (WAS*IS) Workshop in Boulder, Colorado. The vision of WAS*IS is to change the weather enterprise by comprehensively and sustainably integrating social science into meteorological research and practice. A total of 198 individuals have participated in WAS*IS workshops to date.

Fig. 1 The 27 invited participants of the 2009 WAS*IS Workshop and the WAS*IS organizers and external advisory committee members. Photo taken in Fort Collins on 11 August 2009

Household Survey on Use and Value of Hurricane Forecasts

Data collected from a survey with households in Miami, Florida evaluated their use and values for hurricane forecasts – including assessing their use of forecasts in evacuation decision making. Using stated–choice valuation methods to analyze choices between potential forecast–improvement programs and the accuracy of existing forecasts, we found that the total average willingness–to–pay for a significantly improved hurricane forecasts was $14.34 per household per year.

National Household Survey on Use of Weather Forecast Information

Data collected from a national survey designed to assess how the public interprets weather forecasts and probability information is being analyzed to understand how the public obtains, understands, and uses weather forecast information, including uncertainty information, in decision making.

Survey of Broadcast Meteorologists Use of Weather Information

SIP researchers conducted a study with broadcast meteorologists to assess broadcast meteorologists' (a) use of and preferences for current and future forecast uncertainty information, and (b) perceptions of the public's understanding of, use of, and preferences for forecast uncertainty information.

Assessment of Hurricane and Flash Flood Warnings

Work is underway on an 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. This project represents the first effort by a balanced research team representing the fields of meteorology, sociology, economics, public policy analysis, and decision sciences to look at warning processes and systems holistically.

FY2010 Plans:

Work will continue on three related projects on communication, understanding and use of warning information particularly with respect to flash flood warnings and hurricane warnings. These NSF and NOAA funded projects will continue over the next one to three years.

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:

1. Addressing the role of uncertainty throughout the warning process, including information dissemination and decision making
2. Identifying more completely the suite of factors influencing organizational and public decision making and action during extreme weather events
3. Characterizing public preferences for different attributes of forecast and warning information

In a closely related effort, a second project advances the communication of hurricane forecast advisories and warnings by examining:

1. The process through which advisories and warnings are developed, and the resulting content
2. The communication channels used by various actors in this process
3. How at–risk coastal residents, including more vulnerable populations, comprehend and react to specific components of advisories and warnings

A third project is designed to meet the socio–economic research needs of the Hurricane Forecast Improvement Project through an assessment of emergency managers information needs and a survey of households' value for HFIP improvements.

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NCAR is sponsored by the National Science Foundation.

CLIMATE, WEATHER & SOCIETY

New Quantitative Models that Integrate Socioeconomic and Biophysical Components of Climate Change

Background

Through the development and application of new quantitative models that integrate socioeconomic and biophysical components of climate change, we are enhancing our ability to identify and evaluate climate change response options, including mitigation and adaptation.

Development of iPETS (integrated Population–Economy–Technology–Science) Model

A new integrated assessment model, iPETS (integrated Population–Economy–Technology–Science model), was brought to NCAR in 2008 and development focused on two areas during FY09, land use and demographic change. iPETS is a regionally–disaggregated model of the global economy and energy system. A land use model is being added to facilitate links between economic activity and impacts on land, including greenhouse gas emissions from the conversion of land to agriculture or forestry. When complete, the module will provide a direct means of coupling iPETS to land cover models such as NCAR's Community Land Model. In addition, an analysis of the effect of future demographic change on emissions from energy use was completed. The study examined how urbanization, aging, changes in household size, and population growth rates could affect carbon dioxide emissions globally and in various regions around the world. This analysis required the development of global projections of future population and households for major world regions. In addition, work was also initiated on developing spatially explicit scenarios for future population, for use in impact assessment and for use in developing spatial scenarios of other outcomes such as energy use and pollutant emissions.

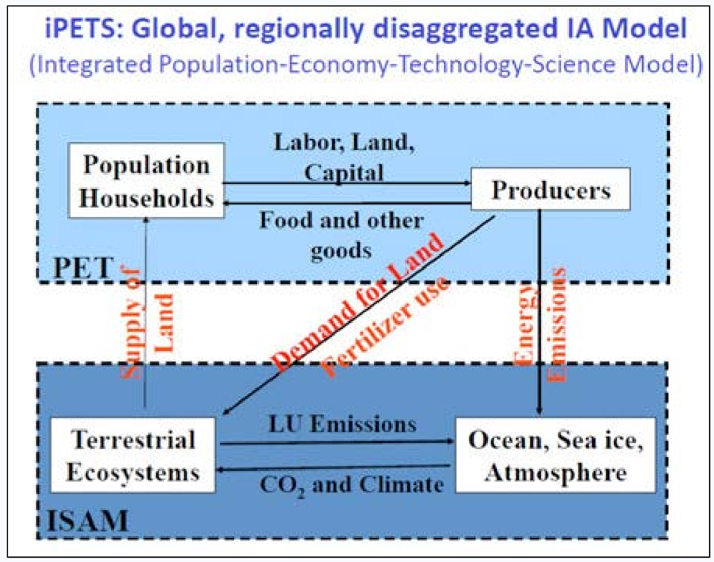

Fig. 1

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