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A Message from the NCAR Director

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A MESSAGE FROM THE NCAR DIRECTOR

The National Center for Atmospheric Research (NCAR) is one of the world’s premier scientific institutions, with an internationally recognized staff and research program dedicated to advancing knowledge, providing community-based resources, and building human capacity in the atmospheric and related sciences. In this Annual Report, as well as the accompanying Laboratory Reports, I invite you to learn more about how our staff are collaborating with the broader research community, nationally and internationally, to produce impressive advances in our understanding of fundamental atmospheric processes and how the atmosphere interacts with and is influenced by other components of the Earth and Sun system. This progress is being driven, in part, by new technologies and their effective utilization at NCAR, including advanced observing facilities for field studies, powerful supercomputing capabilities, valuable research data sets that describe the Earth and the Sun, and widely used state-of-the-science community models that are providing improved capabilities for predictions of weather (including catastrophic events), air quality, hydrology, climate variability and change, and space weather. Moreover, educational and technology transfer activities at NCAR continue to encourage outstanding young scientists into the field and bring new research and technical achievements into the public and private sectors. Although only a small sampling of the many notable accomplishments of the past year, these aspects are illustrated through the accompanying set of highlights of our work. I also wish to call out that 2015 was extremely special in that we celebrated the 75<sup>th</sup> anniversary of the High Altitude Observatory (<http://www2.hao.ucar.edu/HAO-75th-anniversary>), a milestone in an ongoing quest to learn about the Sun’s behavior and its impact on Earth.

In 2015 NCAR continued to work under its new strategic plan, which is easily accessible from our main web page (<http://ncar.ucar.edu/>). For example, we launched a new initiative to develop a user-focused, integrated system for the discovery and access of our digital scientific assets (<https://ncar.ucar.edu/data-stewardship-engineering-team-dset>), and we began a new cross-center effort to enhance community facilities in data assimilation. The recently introduced Atmospheric Chemistry Center for Observational Research and Data (<https://www2.acom.ucar.edu/accord>) hosted a community workshop in 2015 to identify *in situ* atmospheric chemistry measurement priorities. All of these initiatives will remain priorities in 2016, a year in which we also look forward to the public release of version 2.0 of the Community Earth System Model (<https://www2.cesm.ucar.edu>), as well as the continued development, support and application of other major community modeling efforts, including the Weather Research and Forecasting model (<http://wrf-model.org/index.php>) and the Model for Prediction Across Scales (<http://mpas-dev.github.io/>). NCAR will continue its commitment to world-class airborne, ground-based and space-based observational facilities and services, including the pursuit of new instrumentation, such as the Airborne Phased Array Radar (<http://president.ucar.edu/development/capability/airborne-phased-array-radar-apar>) and the Coronal Solar Magnetism Observatory (<http://www2.hao.ucar.edu/cosmo>). NCAR will also install a new powerful supercomputer, named *Cheyenne*, at the NCAR-Wyoming Supercomputing Center (<https://nwsc.ucar.edu/>) in 2016, which will continue our commitment to provide supercomputing systems and services specifically tailored for the atmospheric, geospace and related sciences community. *Cheyenne* will be capable of more than 2.5 times the amount of scientific computing performed by



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*Yellowstone*, the current NCAR supercomputer.

In pursuing these and other objectives laid out in the strategic plan, NCAR will continue to work synergistically with and in support of the broader academic community, not least the 109 member universities of its management entity, the University Corporation for Atmospheric Research (UCAR). This includes relations with university researchers coming to NCAR as both short- and long-term visitors, serving on NCAR advisory committees and working groups, and working as principal investigators on field campaigns. In so doing, NCAR will embrace a leadership role in delivering objective information in support of national and international decisions on mitigation, adaptation, resiliency and sustainability, and it will continue to actively engage with the stakeholders and the consumers of its science.

For now, please enjoy this Annual Report as but a snapshot of recent NCAR competencies, facilities, and scientific accomplishments. In addition, please accept my sincere thanks for your ongoing support and your hard work.

With best wishes for 2016,

Jim Hurrell

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EXTREME HEAT EXPOSURE COULD QUADRUPLE BY MID-CENTURY

BOULDER – U.S. residents' exposure to extreme heat could increase four- to six-fold by mid-century, due to both a warming climate and a population that's growing especially fast in the hottest regions of the country, according to new research.

The study, by researchers at the National Center for Atmospheric Research (NCAR) and the City University of New York (CUNY), highlights the importance of considering societal changes when trying to determine future climate impacts.

"Both population change and climate change matter," said NCAR scientist Brian O'Neill, one of the study's co-authors. "If you want to know how heat waves will affect health in the future, you have to consider both."

Extreme heat kills more people in the United States than any other weather-related event, and scientists generally expect the number of deadly heat waves to increase as the climate warms. The new study, published May 18 in the journal *Nature Climate Change*, finds that the overall exposure of Americans to these future heat waves would be vastly underestimated if the role of population changes were ignored.

The total number of people exposed to extreme heat is expected to increase the most in cities across the country's southern reaches, including Atlanta, Charlotte, Dallas, Houston, Oklahoma City, Phoenix, Tampa, and San Antonio.

The research was funded by the National Science Foundation, which is NCAR's sponsor, and the U.S. Department of Energy.

CLIMATE, POPULATION, AND HOW THEY INTERACT

For the study, the research team used 11 different high-resolution simulations of future temperatures across the United States between 2041 and 2070, assuming no major reductions in greenhouse gas emissions. The simulations were produced with a suite of global and regional climate models as part of the [North American Regional Climate Change Assessment Program](#).

Using a newly developed demographic model, the scientists also studied how the U.S. population is expected to grow and shift regionally during the same time period, assuming current migration trends within the country continue.

Total exposure to extreme heat was calculated in "person-days" by multiplying the number of days when the temperature is expected to hit at least 95 degrees by the number of people who are projected to live in the areas where extreme heat is occurring.

The results are that the average annual exposure to extreme heat in the United States during the study period is expected to be between 10 and 14 billion person-days, compared to an annual average of 2.3 billion person-days between 1971 and 2000.

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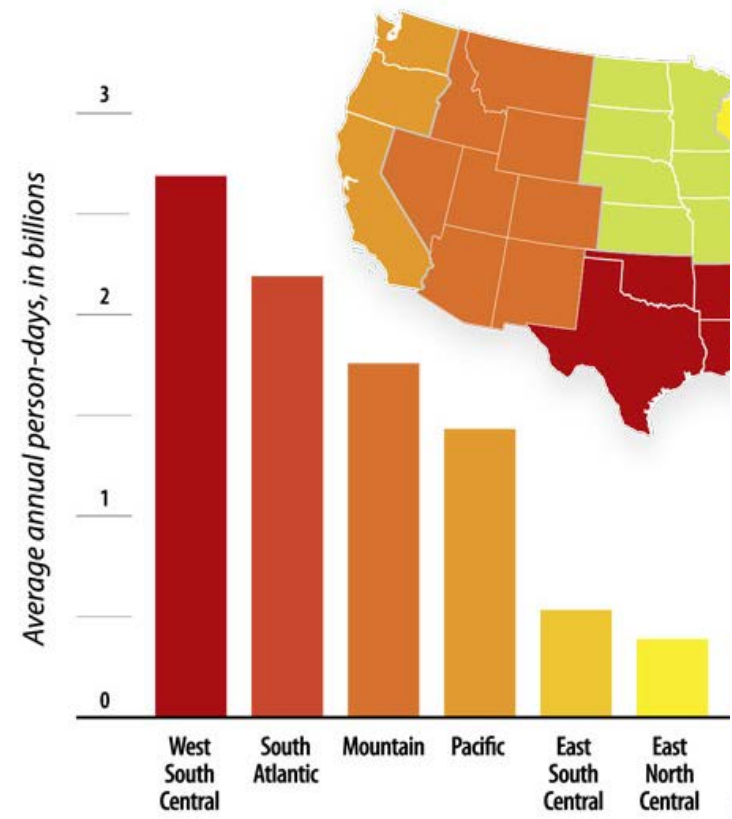
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# Exposure to Extreme Heat on 1971–2000 vs. 2041–2070



This graphic illustrates the expected increase in average annual person-days of exposure to extreme heat for each U.S. Census Division when comparing the period 1971–2000 to the period 2041–2070. Person-days are calculated by multiplying the number of days when the temperature is expected to hit at least 95 degrees by the number of people who are projected to live in the areas where extreme heat is occurring. The scale is in billions. (©UCAR. This image is freely available for [media & nonprofit use](#).)

Of that increase, roughly a third is due solely to the warming climate (the increase in exposure to extreme heat that would be expected even if the population remained unchanged). Another third is due solely to population change (the increase in exposure that would be expected if climate remained unchanged but the population continued to grow and people continued to moved to warmer places). The final third is due to the interaction between the two (the increase in exposure expected because the population is growing fastest in places that are also getting hotter).

"We asked, 'Where are the people moving? Where are the climate hot spots? How do those two things interact?'" said NCAR scientist Linda Mearns, also a study co-author. "When we looked at the country as a whole, we found that each factor had relatively equal effect."

At a regional scale, the picture is different. In some areas of the country, climate change packs a bigger punch than population growth and vice versa.

For example, in the U.S. Mountain region—defined by the Census Bureau as the area stretching from Montana and Idaho south to Arizona and New Mexico—the impact of a growing population significantly

outstrips the impact of a warming climate. But the opposite is true in the South Atlantic region, which encompasses the area from West Virginia and Maryland south through Florida.

EXPOSURE VS. VULNERABILITY

Regardless of the relative role that population or climate plays, some increase in total exposure to extreme heat is expected in every region of the continental United States. Even so, the study authors caution that exposure is not necessarily the same thing as vulnerability.

"Our study does not say how vulnerable or not people might be in the future," O'Neill said. "We show that heat exposure will go up, but we don't know how many of the people exposed will or won't have air conditioners or easy access to public health centers, for example."

The authors also hope the study will inspire other researchers to more frequently incorporate social factors, such as population change, into studies of climate change impacts.

"There has been so much written regarding the potential impacts of climate change, particularly as they relate to physical climate extremes," said Bryan Jones, a postdoctoral researcher at the CUNY Institute for Demographic Research and lead author of the study. "However, it is how people experience these extremes that will ultimately shape the broader public perception of climate change."

ABOUT THE ARTICLE

Title: "Future population exposure to U.S. heat extremes"  
Authors: Bryan Jones, Brian C. O'Neill, Larry McDaniel, Seth McGinnis, Linda O. Mearns, and Claudia Tebaldi  
Publication: *Nature Climate Change*

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CHEMICAL CHANGES IN CORAL TO SHOW THAT WEAK TROPICAL PACIFIC TRADE WINDS COINCIDED WITH GLOBALLY WARMING TEMPERATURES EARLY IN THE TWENTIETH CENTURY

BOULDER — New research indicates that shifts in Pacific trade winds played a key role in twentieth century climate variation, a sign that they may again be influencing global temperatures.

The study, led by scientists at the National Center for Atmospheric Research (NCAR) and the University of Arizona (UA), uses a novel method of analyzing chemical changes in coral to show that weak tropical Pacific trade winds coincided with globally warming temperatures early in the twentieth century. When the natural pattern shifted and winds began to strengthen after 1940, the warming slowed.

The finding gives support to the theory that strong Pacific trade winds are currently helping to prevent global temperatures from climbing, even as society continues to emit carbon dioxide and other greenhouse gases. When the winds weaken as part of a natural cycle, warming will likely resume once again, the authors say.

“Strong winds in the tropical Pacific are playing a role in the slowdown of warming over the past 15 years,” said lead author Diane Thompson, a postdoctoral scientist at NCAR. “When the winds inevitably change to a weaker state, warming will start to accelerate again.”

“Mother Nature is always going to inject little ups and downs along our path to a warmer world,” said University of Arizona professor Julia Cole, a co-author. “We’re trying to understand how those natural variations work so that scientists can do a better job of predicting the actual course of climate change into the future. ”

The study is being published this week in *Nature Geoscience*. It was funded by the National Science Foundation, NCAR’s sponsor, as well as by the National Oceanic and Atmospheric Administration, University of Arizona, Philanthropic Education Organization, U.K. Natural Environment Research Council, and U.S. Department of Energy.

WHERE IS THE HEAT GOING?

Despite increases in greenhouse gases, global surface temperatures have not risen significantly since 2001. This pause in global warming, often called the hiatus, has become the focus of research by climate scientists who are trying to track the missing heat.



A coral core drawn from these equatorial atolls of western Kiribati has

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By using climate models and observations, scientists are finding evidence that the heat is going into the subsurface ocean, perhaps as a result of changes in atmospheric circulation. A study earlier this year in *Nature Climate Change*, by an international team of climate scientists, pointed to unusually strong trade winds along the equator in the Pacific Ocean that are driving heat into the ocean while bringing cooler water to the surface. This is leaving less heat in the air, thereby temporarily offsetting warming from increasing greenhouse gases.

revealed the influence of Pacific winds on global temperatures. New research shows that weak trade winds from about 1910 to 1940 contributed to warmer temperatures worldwide, while stronger winds from about 1940 to 1970 helped lead to more stable temperatures. (Photo by J. Warren Beck, University of Arizona.)

The study by Thompson and her colleagues indicates that this process has happened before, and in the opposite direction: weaker winds allowed warming to accelerate.

The research team focused on the early twentieth century – a time when a third of the century’s global warming took place, even though major accumulations of greenhouse gases were not yet occurring. Some previous research suggested that rising sea-surface temperatures in the Atlantic Ocean were to blame. That warming did not begin until the mid-1920s, however, when the global atmospheric warming was already well underway.

As it turned out, the researchers had access to an important piece of evidence. Sitting in a UA lab was an old core drawn from a coral skeleton near a western tropical Pacific island. It had been chemically analyzed in the 1990s and then largely forgotten.

Thompson, while working on her doctoral dissertation, realized that the core could reveal tropical Pacific wind patterns during the period from 1894 to 1982 when it had grown just outside of the island’s lagoon.

The reason has to do with the effects of wind on water chemistry. When strong bursts of wind came in from the west, they stirred up manganese in the sediment at the bottom of the lagoon. The local corals took up the manganese in their skeletons as they grew. Such wind bursts from the west occur more commonly when the trade winds, which normally blow from the east, are weak.

Chemical analysis of the yearly banded coral skeleton showed a comparatively high occurrence of spikes in the manganese-to-calcium ratio from about 1910 to 1940—the same period when Earth experienced significant warming. However, the number of these events dropped between the 1940s and 1970s, when temperatures leveled off.

Thompson and her co-authors compared the ratio to wind observations since 1960, when observations became more reliable, and verified that the high manganese-to-calcium ratio correlated with weaker trade winds. They also combed through more scattered records before 1960 and again found a correlation of the chemical ratio to wind strength.

Thompson stressed that the winds are just one contributor to changes in global climate. Another reason that temperatures leveled off in mid-century likely has to do with increased industrialization and emissions of particles that block sunlight and exert a cooling influence. Later in the century, increased emissions of greenhouse gases played a dominant role.

“This research shows that the influence of winds on climate is not anything new. These mechanisms have been at work earlier,” Thompson said. “We believe this is a significant contribution to understanding the role of natural processes in modulating global temperature change.”

ABOUT THE ARTICLE

**Title:** Early 20th century global warming linked to tropical Pacific wind strength

**Authors:** Diane M. Thompson, Julia E. Cole, Glen T. Shen, Alexander W. Tudhope, Gerald A. Meethl

**Journal:** *Nature Geoscience*, doi:10.1038/ngeo2321

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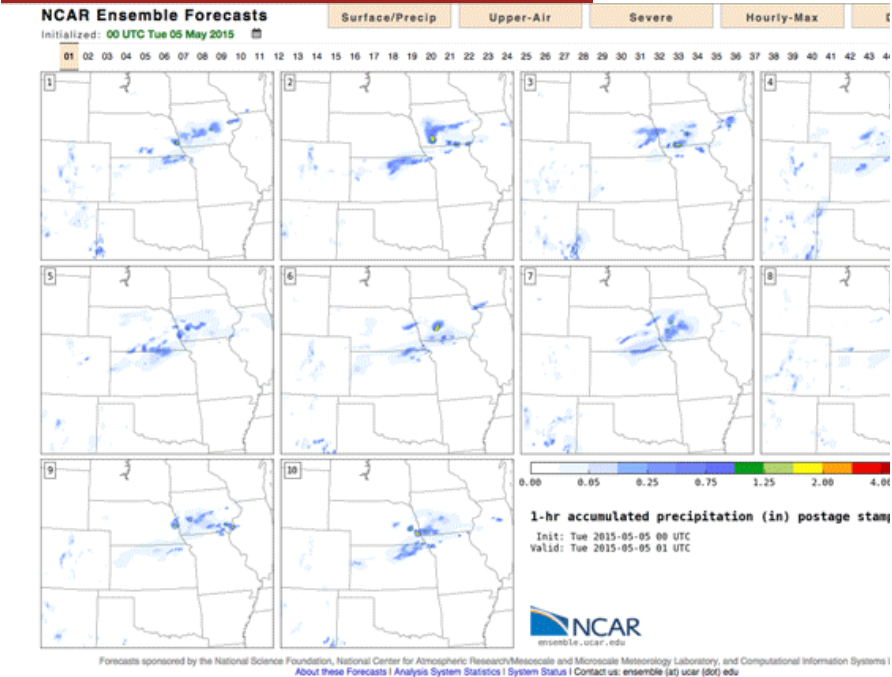
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NEXT-GENERATION FORECASTING SYSTEM AVAILABLE ONLINE FOR THE WIDER WEATHER COMMUNITY TO TEST

Storm-studying scientists have made their next-generation forecasting system available online so the wider weather community can put it to the test. After using the real-time system during short-lived field research campaigns, developers at the National Center for Atmospheric Research (NCAR) are now ready to see how it performs year-round, and they're eager for user feedback.

In April, NCAR scientists began running daily forecasts using the sophisticated system, which has proven its mettle by skillfully predicting the path of early summer storms as they roll across the country's midsection. The new project, which is funded to run through at least mid-June 2016, will allow scientists to see if the forecasts are as adept at predicting weather phenomena that more frequently occur at other times of the year.

"This type of system has never been run year round," said NCAR scientist Craig Schwartz, who co-leads the project. "We want to examine a wide range of weather phenomena, like winter storms, that are not typically studied with high-resolution models and see how the system performs."



NCAR's high-resolution ensemble forecasts show 10 possible scenarios for how much precipitation was expected to fall across the central Great Plains over a two-day period in early May. Check out current forecasts at [ensemble.ucar.edu](http://ensemble.ucar.edu). (©UCAR. This animation is freely available for [media](#) & [nonprofit](#) use.)

The high-resolution forecasting system was first developed to aid field scientists trying to get up-close views of severe weather events. Detailed information about where an individual storm is likely headed



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helps ensure that ground- and air-based observing equipment gets deployed to the best locations.

"We found that the forecasts did a really good job of showing us where the greatest hazards were going to be and allowed us to put field crews in the right places," said NCAR scientist Glen Romine, who has been involved in running the forecasts for past field campaigns.

Now Romine and Schwartz, along with NCAR's Kate Fossell and Ryan Sobash, are extending the forecasts beyond the field, across the country and onto the Internet. By making their forecasts for the continental United States easily available at [ensemble.ucar.edu](http://ensemble.ucar.edu), they hope to get feedback from the meteorological community and hear from scientists who may want to use the data in their own research.

The NCAR team is also supplying the forecasts to the National Severe Storms Laboratory and the Storm Prediction Center, both part of the National Oceanic and Atmospheric Administration. Scientists there are interested in seeing if the data can help them better track individual storms and issue more precise severe weather forecasts.

TO ADD PROBABILITY, MOVE BEYOND A SINGLE FORECAST

To predict the path of an individual storm—instead of the general area where conditions are ripe for storm formation—scientists need a weather model that can run at a higher resolution than is commonly used.

Because these detail-oriented models burn through so much computing power, they're typically used to create just a single, deterministic forecast. Deterministic forecasts describe just one possible future weather scenario—a single path that a storm might follow, for example. Because of this, the forecast is either right or wrong; there's no gray area in between.

Several years ago, NCAR scientists and their colleagues, working on storm-focused field campaigns, began using a different technique, known as ensemble forecasting, that allowed them to move away from black-or-white deterministic forecasts and instead create forecasts that incorporated the probability that a certain weather scenario would actually come to pass.

Armed with the vast power of the new Yellowstone supercomputer, they were able to start producing high-resolution ensemble forecasts by running the same model—the advanced research version of NCAR's Weather Research and Forecasting Model (WRF-ARW)—multiple times for the same forecast period using different initial estimates of atmospheric conditions to kick off each run.

"When most groups run a high-resolution forecast, they grab a single estimate of the state of the atmosphere, plop it down on their high-resolution forecast grid, and just run it," said Romine, who is co-leading the project with Schwartz. "When you initialize an ensemble forecast, you want a range of estimates of the state of the atmosphere that are all equally likely. What you end up with is a variety of different forecast solutions, despite the fact that the forecasts were started with just small initial differences."

Using an array of initial estimates is important because scientists can't measure exactly what conditions exist in every part of the atmosphere at any given moment. In the expanses between weather stations and other observational equipment, scientists must use models to help them make best guesses of the true conditions. Small variations in those estimates can result in big differences in the forecast outcome.

The multiple forecasts that are generated using a range of initial estimates, known as the ensemble members, show a breadth of possible outcomes. This range of results gives scientists and forecasters the ability to determine how probable any particular weather event occurring in any particular location might be. Where the member forecasts tend to agree, the probability is higher. Where they don't agree, the probability drops.

The real-time daily ensemble forecasts now available at [ensemble.ucar.edu](http://ensemble.ucar.edu) have 10 member forecasts, each of which is initialized using estimates of the atmosphere generated by [NCAR's Data Assimilation Research Testbed \(DART\)](#) toolkit.

"Because these forecast methods are so new, a lot of research and testing is needed to understand how

to put surface, radar and satellite data properly into the models to start them off correctly so we get better forecasts," said Louis Wicker, a research meteorologist at the National Severe Storms Laboratory, where they are testing a number of different ensemble systems. "NCAR's ensemble forecast system is one of the best storm-scale ensemble systems currently being tested."

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DIVE DEEPER

Learn more about [NCAR's ensemble forecast details](#). Anyone interested in more information, providing feedback, or collaborating on the project can email [ensemble@ucar.edu](mailto:ensemble@ucar.edu).

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Writer/contact

[Laura Snider](#)

Collaborating institutions

- National Center for Atmospheric Research
- NCAR Mesoscale & Microscale Meteorology Laboratory
- NCAR Computational & Information Systems Laboratory
- NOAA National Severe Storms Laboratory
- NOAA/NWS Storm Prediction Center

Funders

- National Science Foundation

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## WACCM-X AND GRAVITY WAVES

Just as waves ripple across a pond when a tossed stone disturbs the water's surface, gravity waves ripple toward space from disturbances in the lower atmosphere.

Gravity waves are born when air masses are pushed up or down—by a thunderstorm, perhaps, or when wind is forced up and over a mountain range—but in the lower atmosphere, their impacts usually remain regional. By the time they reach the upper atmosphere, however, the waves have built in amplitude and extent. There, they can dominate atmospheric processes on a much larger scale, sometimes threatening the reliability of Earth-based communication systems.

For the first time, scientists have found a way to "watch" the propagation of gravity waves toward space—and the view is captivating ([watch video](#)). The trick, according to a team of researchers led by NCAR Senior Scientist Hanli Liu, was to push the NCAR-based Whole Atmosphere Community Climate Model to a resolution that is fine enough to pick up gravity waves at their source, when they're still relatively small.

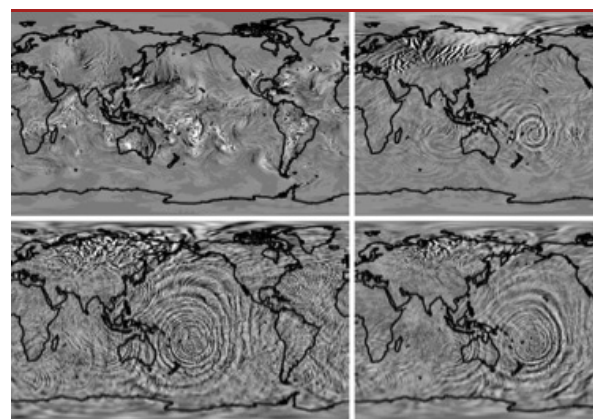
"We've never seen a global picture of gravity waves in the upper atmosphere before, either from observations or simulations, even though we have suspected their importance up there," said Liu, who studies the upper atmosphere at NCAR's High Altitude Observatory. "This is the first time we have been able to capture these waves with a computer model of the whole atmosphere."

The standard version of the model gets only a blurry look at phenomena that take place on scales less than 2,000 km (about 1,243 miles) across—and it's blind to anything smaller than 200 km. The higher-resolution model has much sharper vision all the way down to 200 km. The intense computing power of the NCAR-Wyoming Supercomputing Center's Yellowstone system made the higher-resolution runs possible.

In a study published in the journal *Geophysical Research Letters*, Liu and his colleagues demonstrated the finer-scaled model's abilities by showing how gravity waves such as those created by a tropical cyclone east of Australia grew as they traveled upwards. The model shows that what starts out as a localized phenomenon extends across the entire Pacific Region at 100 km above Earth's surface.

"For the middle and lower atmosphere, if you miss the gravity wave, you're not missing too much," Liu said. "But it's a different story in the upper atmosphere."

Disturbances in the upper atmosphere—which can endanger satellites, skew GPS readings, and shut down radio transmissions—are often thought about as originating from the Sun, where solar storms can



A model simulation illustrates how gravity waves kicked off by a cyclone east of Australia build as they travel toward space. The simulation was created using a high-resolution version of the Whole Atmosphere Community Climate Model (WACCM). Clockwise from upper left corner: Vertical winds at 11, 30, 87, and 100 km above Earth's surface. (Image courtesy Hanli Liu, NCAR. This image is freely available for [media & nonprofit use](#).)

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kick off geomagnetic storms around Earth. But the ionosphere, the upper reaches of the atmosphere affected by this kind of space weather, is also influenced by disturbances originating on Earth.

For the first time, scientists have simulated what gravity waves look like as they ripple upward through the atmosphere. This visualization, created on a supercomputer using a high-resolution version of the Whole Atmosphere Community Climate Model (WACCM), shows meridional (north-south) winds at two heights. The first segment shows winds at Earth's surface, where gravity waves usually have only regional impacts. The second segment shows winds at an elevation of 100 km (about 60 miles), where their influence can become dominant. The video simulations cover a three-day period when a hypothetical tropical cyclone was present off the east coast of Australia. (©UCAR. Simulations courtesy Hanli Liu, NCAR. This image video is freely available for [media & nonprofit use](#).)

These Earth-born disturbances can be difficult for scientists to disentangle when solar storm activity is strong, but the relative tranquility of the Sun during the last solar cycle has given scientists an opportunity to home in on the disturbances reaching the ionosphere from below, creating a fuller picture of processes in the ionosphere.

"When gravity waves propagate to the bottom side of the ionosphere, they can kick off instabilities," Liu said. "If you want to have a better understanding of space weather—the ionosphere—you need this kind of modeling capability."

**H.-L. Liu, J.M. McInerney, S. Santos, P. H. Lauritzen, M. A. Taylor, and N. M. Pedatella, [Gravity waves simulated by high-resolution Whole Atmosphere Community Climate Model](#), *Geophysical Research Letters*, doi: 10.1002/2014GL062468**

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[Laura Snider](#)

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LARGE STORMS MOVE SIGNIFICANT AMOUNTS OF OZONE FROM THE STRATOSPHERE DOWN TO THE TROPOSPHERE

A new study in *Geophysical Research Letters* offers for the first time unequivocal evidence that large storms move significant amounts of ozone from the stratosphere down to the troposphere, the lowest part of the atmosphere. The finding has implications for global climate because tropospheric ozone is a powerful greenhouse gas as well as a pollutant that affects human health and the environment.

The research, led by NCAR scientist Laura Pan, means that scientists may have to re-evaluate climate models with regard to the transport of ozone. Those models generally do not include the role of thunderstorms, as they deal with larger and longer-range phenomena.

It was already well established that tropospheric ozone originates in significant measure in the stratosphere. But the transport was primarily attributed to jet streams and other sources of circulation.

The new study has its roots in a 2012 field project, known as the **Deep Convective Clouds and Chemistry Experiment (DC3)**, that was based in the Great Plains and focused on the impact of storms on chemical composition of the atmosphere. On the night of May 30, the research aircraft flew through a line of large thunderstorms over Kansas. One of the research aircraft, the NASA DC-8, flew just above the storms in the lower stratosphere, carrying an instrument known as a Differential Absorption Lidar, or DIAL, to measure ozone levels.

Pan subsequently discovered that, during that flight, the DIAL instrument recorded a phenomenon that was only hinted before but never observed in an unambiguous fashion. Above the leading edge of the eastward moving storm, DIAL registered a curtain of ozone dipping below the stratosphere, where it was relatively abundant, into the troposphere. On a graph, this ozone-rich air resembled a ram’s horn whose wide end was pushed eastward ahead of the storm and whose narrow end curved westward into the storm.

By examining the DIAL data and those from other instruments, the scientists determined that the “ram’s horn,” containing 150 parts per billion by volume (ppbv) of ozone, extended down to an altitude of about 8 km—or about 4 km (~2.5 miles) into the troposphere. At the same altitudes, but away from the storm system, ozone accounted for only 60 to 100 ppbv. In addition, thin filaments of the enhanced ozone extended about 100 km from the cloud’s edge.

The researchers then set out to study the ozone transport process by numerically simulating the May 30 storm. Their simulation reproduced the ram’s horn and other observations made during the flight, demonstrating that deep convective storms like the one studied are capable of perturbing the tropopause, normally a stable barrier between stratosphere and troposphere.

The authors say that the phenomenon challenges global chemistry climate models, since hundreds of



A rotating supercell thunderstorm moves across northeast Colorado. Thunderstorms such as this move ozone down from the stratosphere into the lower atmosphere. (©UCAR. Photo by Carlye Calvin.)

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storms like the one observed occur over the United States every summer, adding an as yet undermined quantity of ozone into the troposphere. Further, they say, as storm behavior may change in an evolving climate, it is important to understand and incorporate this process into global chemistry-climate models.

**Laura L. Pan, Cameron R. Homeyer, Shawn Honomichl, Brian A. Ridley, Morris Weisman, Mary C. Barth, Johnathan W. Hair, Marta A. Fenn, Carolyn Butler, Glenn S. Diskin, James H. Crawford, Thomas B. Ryerson, Ilana Pollack, Jeff Peischl, and Heidi Huntrieser (2014), Thunderstorms Enhance Tropospheric Ozone by Wrapping and Shedding Stratospheric Air, *Geophysical Research Letters*, 41, 7785-7790, doi: 10.1002/2014GL061921**

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**Collaborating institutions**  
NASA Langley Research Center  
National Oceanic and Atmospheric Administration Earth System Research Laboratory  
Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA  
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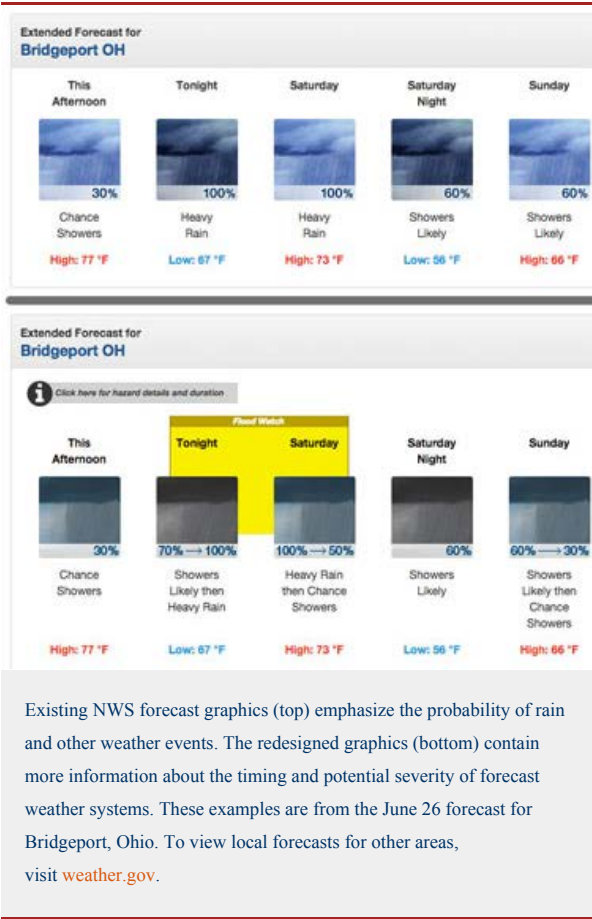
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NWS USES GRAPHICS DEVELOPED BASED ON RISK COMMUNICATIONS RESEARCH AT NCAR

BOULDER – New online graphics being rolled out this summer by the National Weather Service (NWS) are based on research by a team of risk communication experts at the National Center for Atmospheric Research (NCAR) who focused on how to better convey forecast information visually.

Beginning July 7 the NWS will use the redesigned icons for all weather.gov local forecasts. These point-and-click forecasts influence weather-related decisions by people across the country, drawing 2 to 4 million unique web views daily.

The new icons will feature split images and color-coded boxes to better communicate the existence, timing, and potential severity of upcoming weather threats. For example, instead of portraying a night as entirely rainy, a split image could show a 30 percent chance of rain in the early part of the evening, followed by partial clearing after midnight. Colored rectangles drawn around the images will also be used to call attention to weather threats, with yellow denoting a watch, orange denoting an advisory, and red denoting a warning.



The changes are based on several years of work by a multidisciplinary team at NCAR that worked closely with the NWS, an agency within the

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National Oceanic and Atmospheric Administration. The team developed prototype graphics and surveyed tens of thousands of weather.gov local forecast users, finding that specific improvements to the graphics could greatly improve public understanding of the forecasts.

"We want to help people better understand when there's a major weather threat and when it's likely to occur," said NCAR's Julie Demuth, a researcher who specializes in communicating weather risks to the public. "The main goal is to better convey information that's critical for protecting lives and protecting property."

Eli Jacks, acting chief of the NWS's Forecast Services Division, said the changes are an important step toward helping people make better use of NWS forecasts.

"Just putting out the forecast is no longer enough," he said. "This helps users interpret the forecast more easily and use it to make informed decisions."

NWS director Louis Uccellini said the new project demonstrates the importance of research in communicating forecasts to the public.

"Research provides the essential backbone to any effective operational product used by the National Weather Service to protect lives and property," Uccellini said. "Not only must we have advancements in atmospheric science to improve forecasts and services, we must also infuse social science to ensure we are communicating forecast information in a way that is clear and understandable so people can take appropriate action."

The work was primarily funded by the NWS, with additional support from NOAA and the National Science Foundation, which sponsors NCAR.

## FORECASTS AT A GLANCE

Demuth and her colleagues began looking into the issue several years ago when the NWS wanted to determine if the icons could communicate weather information more clearly. An icon depicting rain, for example, might prompt people to cancel outdoor plans even if there was just a 10 percent chance of showers for a few hours.

The research team, working with the NWS, focused on better transmitting two aspects of a forecast that are crucial for helping people understand their risk: the existence of a hazardous weather threat and the timing of that threat. They developed experimental graphics and text with the goal of conveying sometimes complex information in a way that is easy to interpret.

"This is supposed to be a forecast at a glance, so we adapted the approach using NCAR's work as a basis," Jacks said. "Ideally a user will look at it and get a pretty good idea of what is expected."

Demuth and her colleagues conducted two rounds of surveys with more than 13,000 users of NWS forecasts, asking them to evaluate designs to see which one was best at communicating a severe thunderstorm warning and a flood watch.

The surveys showed that users were significantly better at identifying the timing and nature of the weather threat when the information was presented with new graphics and reinforced with wording that stated the start and stop times of the threat. For example, more than 97 percent of survey respondents correctly identified the start and end time of the flood watch with the revamped graphics and text, compared to less than 4 percent in a control group using the existing NWS presentation.

The research team summarized its findings in a [2013 paper in \*Weather and Forecasting\*](#), an American Meteorological Society journal.

Building on this work, the NWS further refined the icons and began to test them last year, asking for input from thousands of users. The agency is now previewing the new graphical approach on its website as it prepares to launch the new version across the nation next month.

"This work illustrates the importance of evaluating how people interpret information about risks,

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particularly when it’s a matter of public safety,” Demuth said. “Making improvements in how we communicate hazardous weather information—even seemingly small improvements—can translate into very large benefits for society.”

“It’s gratifying to be part of a collaboration where NCAR research is being used to help the National Weather Service alert people across the U.S. about potentially dangerous weather,” said Thomas Bogdan, president of the University Corporation for Atmospheric Research, which manages NCAR. “This is a great example of how investments in science lead to substantial benefits for society.”

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## PLAINS ELEVATED CONVECTION AT NIGHT (PECAN) FIELD CAMPAIGN

BOULDER – Thunderstorms that form at night, without a prod from the Sun's heat, are a mysterious phenomenon. This summer scientists will be staying up late in search of some answers.

From June 1 through July 15, researchers from across North America will fan out each evening across the Great Plains, where storms are more common at night than during the day. The research effort, co-organized by the National Center for Atmospheric Research (NCAR) and several collaborating institutions, will use lab-equipped aircraft, ground-based instruments, and weather balloons to better understand the atmospheric conditions that lead to storm formation and evolution after sunset.

Their results may ultimately help improve forecasts of these sometimes damaging storms.

The Plains Elevated Convection at Night (PECAN) field campaign will involve scientists, students, and support staff from eight research laboratories and 14 universities. The \$13.5 million project is largely funded by the National Science Foundation (NSF), NCAR's sponsor, which contributed \$10.6 million. Additional support is provided by NASA, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Energy.

### ALOFT IN THE NIGHT

Thunderstorms that form during the day are less puzzling than nighttime storms. The Sun heats the Earth's surface, which in turn, warms the air directly above the ground. When that warm air is forced to rise, it causes convection—a circulation of warm updrafts and cool downdrafts—and sometimes creates a storm.

The formation of thunderstorms at night, however, when the Sun is not baking the land, is less well understood.

"At night, the entire storm circulation is elevated higher off the ground," said NCAR scientist Tammy Weckwerth, a PECAN principal investigator. "This makes observations of the conditions leading to nighttime thunderstorms much more challenging because that part of the atmosphere is not well covered by the network of instruments we normally rely on."

The vast array of instruments available to PECAN researchers will allow them to collect data higher in the atmosphere. This data will help scientists characterize the conditions that lead both to individual storm formation as well as to the clustering and organizing of these storms into large-scale systems, which can drop significant precipitation.

"Nighttime thunderstorms are an essential source of summer rain for crops but are also a potential hazard through excessive rainfall, flash flooding, and dangerous cloud-to-ground lightning," says Ed Bensman, program director in NSF's Division of Atmospheric and Geospace Sciences. "Weather forecast models often struggle to accurately account for this critical element of summer rainfall on the Great Plains. The PECAN field campaign will provide researchers and operational forecasters with valuable insights into thunderstorms at night—and improve our ability to model them more accurately."

### DEPLOYING IN THE DARK

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The campaign, based in Hays, Kansas, will begin each day at 8 a.m., when a crew of forecasters starts developing a nightly forecast. At 3 p.m. the scientists will use the forecast to determine where across northern Oklahoma, central Kansas, or south-central Nebraska to deploy their mobile resources. Moving dozens of people around the Great Plains each night will be a challenge for PECAN, but it's also what distinguishes it from past field projects.

"Previous severe weather campaigns have focused mostly on daytime storms, for largely practical reasons, as it is more difficult to set up instruments in the dark," said Bart Geerts, a professor of atmospheric science at the University of Wyoming and a PECAN principal investigator. "But the large thunderstorm complexes travelling across the Great Plains at night really are a different beast."

Scientists believe that several interacting factors may contribute to nocturnal storm formation and maintenance: a stable layer of air at the surface; a strong wind current above that layer, known as a low-level jet; and atmospheric waves, some of which are called "bores," that ripple out from the storms themselves.

"But we just don't really know how they interact," Geerts said. "That's what PECAN is about."

A better understanding of these storms will have relevance for areas beyond the Great Plains. Clustered nighttime thunderstorms are common in various regions scattered across the globe.

### A FLEET OF INSTRUMENTS

PECAN will use three research aircraft, two of which—a University of Wyoming King Air and a NASA DC-8—will fly in the clear air away from the storms. Only the third, a NOAA P-3, which is widely used in hurricane research and reconnaissance, will be able to fly into the trailing region of storms.

The researchers will also rely on a number of ground-based instrument suites, known as PECAN Integrated Sounding Arrays, or PISAs. Six of the PISAs will operate from fixed locations around the study area, and four will be mobile, allowing them to be repositioned each night depending on where storms are expected to form.

The instruments within each PISA vary, but collectively they will give each array the ability to measure temperature, moisture, and wind profiles, as well as launch weather balloons. Among the instruments are several newly developed at NCAR's Earth Observing Laboratory (EOL), including one that uses an innovative laser-based technique to remotely measure water vapor and an advanced wind profiler.

Finally, the scientists will have a fleet of mobile and fixed radars, including the NCAR S-Pol. In all, PECAN researchers will have access to more than 100 instruments brought to the effort by partner institutions from across North America.

"The sheer number of instruments being coordinated is unprecedented," said Weckwerth, who has participated in more than 15 other field expeditions.

The planning necessary to manage this large collection of instruments—from finding property suitable for a fixed radar to making sure the mobile instruments are out of harm's way while tracking a storm—is being taken on by EOL's Project Management Office. That team is also responsible for housing, food and other logistics for the scientists and students who are participating in the campaign.



NCAR's portable S-Pol radar is one of the many instruments that will be deployed during the PECAN field campaign to help scientists better understand nighttime thunderstorms. (©UCAR. This image is freely available for [media & nonprofit use](#).)

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## NCAR AND UCSD COLLABORATING ON VISUALIZATION CAPABILITIES

BOULDER - The National Center for Atmospheric Research (NCAR) is partnering with the University of California, San Diego (UC San Diego) to expand and enhance visualization capabilities in the bio- and geosciences through a grant from the National Science Foundation.

The collaboration builds on existing software capabilities developed at NCAR and UC San Diego, and it will combine them to produce new open-source tools for scientists to explore large data sets.

The project is known as WASP (Wavelet-enabled Progressive Data Access and Storage Protocol).

Current advances in digital imaging and numerical modeling technologies have enabled the creation of vast amounts of data. A challenge for many researchers is making sense out of these digital outputs. One way of dealing with extremely large data sets is known as progressive data access (PDA), which is the enabling technology behind consumer applications like Google Maps. In mapping applications, PDA reduces data volumes by only loading areas of interest, not the entirety of the map database, and allows the user to view these images in greater or lesser detail.

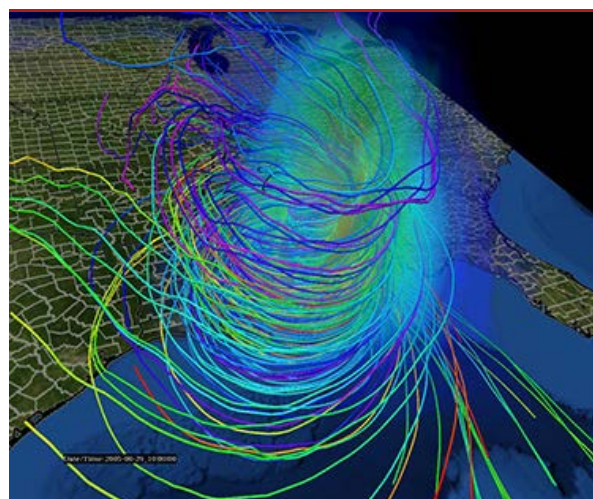
The problem is that similar tools are scarce in the biosciences, despite a need for analyzing data gathered from advanced imaging technologies such as MRI and CT scans. Also, as the size and complexity of the data increase, the computing resources commonly available for data analysis are over-subscribed. The geosciences encounter similar issues, with models for weather, climate, oceans and other Earth systems generating very large and complex data.

Given the similar nature of the challenge across various disciplines, researchers at NCAR and UC San Diego put their heads together to work on a solution, capitalizing on complementary work that was already ongoing at both institutions. Though the bio- and geosciences are very different scientific disciplines, with different data, the underlying forms and structure of the data are very similar, allowing for shared methods of dealing with the information.

### TWO SOFTWARE APPROACHES

An NCAR team has developed a software solution known as VAPOR (Visualization and Analysis Platform for Ocean, Atmosphere and Solar Researchers). VAPOR provides an interactive 3D-visualization environment that runs on most UNIX and Windows systems. At the heart of VAPOR is a progressive data access scheme based on mathematical linear transforms using wavelets. An NSF grant launched the development of the technology in 2003, and VAPOR is currently on its third major release, with over 6,000 users worldwide.

"VAPOR is an application specifically designed to facilitate researchers' interaction with very large data sets, but while using only relatively modest





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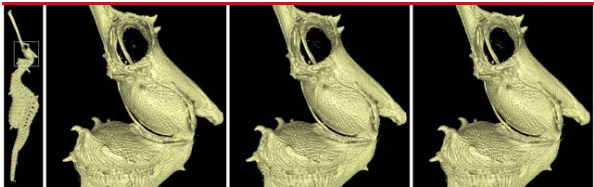
computing resources,” said John Clyne, a software engineer and computer scientist who is the principal investigator for VAPOR in NCAR’s Computational and Information Systems Laboratory (CISL). “VAPOR is already widely used in the geosciences community, and with this award we will not only be able to expand and improve it for its current users, but also make it usable for the biosciences and bioimaging communities.”

At UC San Diego, the Center for Scientific Computation in Imaging has been developing a general analysis and visualization software toolkit for the bioimaging community, known as the Shape Analysis for Phenomics from 3D Imaging Data (SAPID) ToolKit (STK).

The goal of the SAPID project is to develop advanced computational methods for researchers in evolutionary biology to characterize subtle morphological variations from high-resolution 3D voxel-based digital imaging modalities. (A voxel is analogous to a pixel, but in three-dimensional space.)

A critical issue that arose during this project was the necessity of being able to handle very large datasets. This new NSF award will address this important issue and thus provide innovative capabilities to the bioimaging community.

“This award is exciting because it allows us to take our existing software, combine and reuse it in new ways, and expand its capabilities to serve more broadly across scientific disciplines,” said Lawrence Frank, the principal investigator for the WASP award and the SAPID Project and a researcher at UC San Diego’s Institute of Engineering in Medicine at the Jacobs School.



This image demonstrates progressive data access applied to a high-resolution CT scan of a seadragon. The leftmost view of the seadragon head was constructed using a fraction of the data (1/100th), yet is morphologically identical to the rightmost image constructed using all of the available CT data. (Image courtesy UC San Diego.)

This high-resolution simulation of 2005's Hurricane Katrina as it makes landfall on the Gulf Coast was visualized with VAPOR. (Image courtesy John Clyne, NCAR.)

Both Frank and Clyne point out that the most important aspect of this collaboration is it will reuse existing NSF-funded software to provide a common framework benefitting both biological digital imaging and geosciences numerical modeling communities. It will have a profound impact for scientists working with large data sets.

“We’ll be able to provide better tools to the climate and weather science communities, while providing the first such tools for the biosciences community,” said Clyne. “It’s especially gratifying that NSF’s initial investments in both VAPOR and STK can be augmented with this award to produce

an impactful and inter-disciplinary tool.”

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## RAL WIND FORECASTING TECHNOLOGY WINS CO-LABS AWARD

**BOULDER** – A cutting-edge wind and solar energy forecasting system that has saved electricity consumers \$40 million has won a prestigious 2014 Colorado Governor's Award for High-Impact Research in the Sustainability category as well as an honorable mention in Public-Private Partnerships.

The advanced system, developed by the National Center for Atmospheric Research and implemented for Xcel Energy, has dramatically increased the amount of renewable energy provided to the grid. It was funded by Xcel Energy, which is a national leader on wind energy.



Workers install panels being used by the U.S. Department of Energy to leverage a Power Purchase Agreement with Sun Edison and Xcel Energy. A prediction system developed at NCAR is helping Xcel Energy increase the amount of power going from renewable energy systems into the grid. (Wikimedia Commons photo by Dennis Schroeder.)

"It is very gratifying to take our scientific and technological expertise and apply it in a way that has a meaningful impact on society," said William Mahoney, deputy director of NCAR's Research Applications Lab. "We're developing systems that offer the dual benefit of saving costs and reducing emissions of pollutants that are harmful to the environment."

The Governor's Award is given each year by CO-LABS, a nonprofit that works to inform the public about the breakthroughs and impacts from Colorado's 30 federally funded labs and research facilities. The CO-LABS consortium includes Colorado federal research laboratories, research universities, state and local governments, economic development organizations, private businesses, and nonprofit organizations.

Ken Lund, executive director of Colorado's Office of Economic Development and International Trade, will present the awards at this year's reception on November 12 to teams from NCAR and three other Colorado-based research centers for extraordinary research in the areas of Atmospheric Science, Foundational Technology, Public Health, and Sustainability.

The awards presentation will take place at the Denver Museum of Science & Nature. The sponsor, the Alliance for Sustainable Energy, manages the National Renewable Energy Laboratory (NREL) on behalf of the Department of Energy (DOE). NREL is the DOE's primary national laboratory for renewable energy and energy efficiency research and development.

The annual reception is the major CO-LABS event to showcase Colorado's research facilities and the work of the CO-LABS organization.

NCAR's energy forecasting system relies on a suite of tools, including highly detailed observations of atmospheric conditions, energy generation, an ensemble of cutting-edge computer models, and advanced statistical techniques, to issue high-resolution forecasts of wind energy generation that are updated with new information every 15 minutes.

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Advanced Study Program
Climate & Global Dynamics
Computational & Information Systems Laboratory
Earth Observing Laboratory
High Altitude Observatory
Mesoscale & Microscale Meterology Laboratory
National Center for Atmospheric Research
Research Applications Laboratory

"The wind and solar forecasting system developed with NCAR has given Xcel Energy increased confidence each day in determining the amount of renewable energy we can expect, as we strive to provide reliable power at a competitive price for our Colorado customers," said David Eves, president and CEO of Public Service Co. of Colorado, an Xcel Energy company. "We believe this modeling will provide equal certainty for other U.S. utilities as they also increase the amount of renewable generation in their portfolios."

"We're very pleased that this investment in an energy forecasting system has paid such significant dividends," said UCAR president Thomas Bogdan. "This work illustrates how an increasingly detailed understanding of the atmosphere leads to important advances for society."

NCAR also received honorable mention in the Sustainability category this year for the Global Energy and Water Exchanges (GEWEX) Project, which focuses on developing better ways to understand global and regional climate, especially water resources. NCAR senior scientist Kevin Trenberth and the international GEWEX research team collectively studies the water cycle and how to translate research results into practical applications. Trenberth chaired the GEWEX scientific steering committee from 2010 to 2013.

Other winners of this year's Governor's Award include:

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**Atmospheric Science**

"Into the Air"  
Cooperative Institute for Research in Environmental Sciences and the National Oceanic and Atmospheric Administration

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**Foundational Technology**

"Commercialization of Cold-Atom Technology"  
JILA, University of Colorado Boulder

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**Public Health**

"An Oral Vaccine Produced in Rice Grain to Reduce the Risk of Lyme Disease"  
Centers for Disease Control and Prevention (CDC)

"Researchers in Colorado's federal laboratories continue to lead the nation with valuable study that addresses some of today's most pressing problems," said Scott Sternberg, chair of CO-LABS. "Our annual ceremony does more than just recognize new discoveries, it also celebrates the impact research and science have on our state."

The University Corporation for Atmospheric Research (UCAR) manages NCAR under sponsorship by the National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this release do not necessarily reflect the views of the National Science Foundation.

< NCAR and UCSD collaborating on visualization capabilities	up	Futureproofing High School Science Students through Data Analytics >
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- Extreme heat exposure could quadruple by mid-century
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- WACCM-X and gravity waves
- Large storms move significant amounts of ozone from the stratosphere down to the troposphere
- NWS uses graphics developed based on risk communications research at NCAR
- Plains Elevated Convection at Night (PECAN) field campaign
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- Futureproofing High School Science Students through Data Analytics
- 2015 Metrics

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FUTUREPROOFING HIGH SCHOOL SCIENCE STUDENTS THROUGH DATA ANALYTICS

One of NCAR’s Strategic Imperatives is the training and preparation of the next generation of scientists to continue NCAR’s work. We believe that this training needs to start early, and one of the key elements is preparing students still in high school for the challenges of working with the huge amounts of data required to make progress in our field. Science of all flavors is destined to be based on ever-larger datasets as our technologies and methods improve, so programming skills, the ability to proficiently manipulate these data sets, and a strong understanding of statistics (collectively known as “data analytics”) are all vital skills for tomorrow’s scientists.

This past summer, NCAR’s Computing and Information Systems Laboratory (CISL) ran the “Data Analytics Bootcamp for High School Students” – an opportunity for 10 Boulder Valley School District high school sophomores and juniors to gain a hands-on introduction to being a Data Scientist. This five-day workshop was held 22–26 June 2015 at NCAR’s Mesa Lab facility in Boulder.



Demand for data scientists continues to increase as the Big Data era produces data in varieties and volumes far exceeding anything scientists and engineers have ever had to manage before. Effective data analysis – using data to answer practical questions – underpins decision making in many fields and is the power behind many of the most successful web enterprises including Google, Facebook, Amazon, and Orbitz. For NCAR research, effective data analysis also promises to unlock more scientific information from observations and numerical simulations in the geosciences. This bootcamp introduced data analysis concepts by presenting exercises using real data applied to real-life situations. Some of the examples covered concepts in climate, but others were just fun, for example analyzing the performances of basketball players and pricing used cars.

The workshop was sponsored by CISL’s Institute for Mathematics Applied to the Geosciences (IMAGe) and was provided at no cost to the students. Organizer Dorit Hammerling (IMAGe Project Scientist II) and sponsor/co-organizer Doug Nychka (IMAGe Director) designed the curriculum to be a hands-on and engaging experience for the students. Supported by a team of instructors and programming coaches from NCAR, UCAR, CU Boulder, Colorado School of Mines, and Columbia University, the students were

Dorit Hammerling (standing), lead organizer and developer of the workshop stated, “Data analytics might sound scary at first to young people, but by approaching the field using data sets and problems that are both interesting and practical, this effort is designed to attract new talent to the discipline by providing hands-on experience for young people interested in pursuing careers involving scientific data analysis.”  
—Photo by Brian Bevirt, CISL



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presented with a sequence of 15-minute lessons: 5 minutes of teaching followed by 10 minutes of hands-on exercises for students to apply their new knowledge. Students used a research-level software package called R to carry out the data analysis, while covering six fundamental concepts in data analytics:

- Fundamentals of statistics and data types.
- Exploratory data analysis and visualization.
- Multivariate linear regression.
- Categorical data analysis.
- Data collection and survey analysis.
- High performance computing and its role in data analysis.



By connecting with self-motivated young people as early in their lives as possible, Hammerling and Nychka aim to stimulate their interest and build their skills in using data analysis to solve real problems and prepare them for future careers in science. Hammerling summarized this new workshop's outcome: "All the students learned about data analysis and developed skills using the R statistical programming environment to solve problems. They left the workshop with R skills that they can readily apply in internships or other employment opportunities. And IMAGE hopes to hire some of these freshly trained people as student assistants to help advance our current research projects."

Each pair of students received guidance from one expert during the workshop exercises. The support staff shown in this photo includes, from left to right, Colette Smirniotis, Dorit Hammerling, Lee Richardson, and Nathan Lenssen. The 10-minute exercise being conducted here followed five minutes of instruction in a new concept. This format was designed to sustain student interest during the intensive training and ensure that each participant had immediate, supported practice applying their new skills. —*Photo by Brian Bevirt, CISL*

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2015 Metrics

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2015 METRICS

The metrics featured below offer qualitative and quantitative measurements and assessments of the productivity, quality, and impacts that NCAR staff, programs and activities have on our research community, sponsors, and society in general for data reported in the Metrics Database, iVantage HRIS system and OpenSky Database as of November 10, 2015 for fiscal year 2015 (October 1, 2014-September 30, 2015). Staff continue to update their entries and expand their contributions throughout the year so visit the Metrics Database for the most current data. (2015 METRICS AS OF NOVEMBER 10, 2015)

LAB/OBSERVATORY/PROGRAM-LEVEL METRICS

NCAR-Hosted Community Events

Each year, events are hosted by labs, divisions, and programs. These include colloquia, conferences, symposia, tutorials, and workshops.

In FY15, a total of 85 events were hosted: 49 workshops, 11 tutorials, two symposia, five conferences, and 17 colloquia with an average audience of 44 colleagues per event and estimated total audience of over 3,700. Event co-sponsors groups included the National Business Aviation Association and the The Climate Corporation, the Department of Energy and the Climate and Cryosphere group and universities including the University of Washington STATMOS Group and the University of Ljubljana (Slovenia).

Field Campaigns

NCAR’s geosciences research facilities, instrumentation and field support services support field campaigns around the globe.


In FY15, NCAR participated in 11 field campaigns ranging in duration from 5 to 2,283 operational field days. A total of 174 institutions, including 66 UCAR member institutions participated in these campaigns. The projects involved 155 investigators, 86 undergraduate students, and 157 graduate students.

Campaign Acronym	Campaign Full Name
ARISTO	Airborne Research Instrumentation Testing Opportunity
HAIC-HWIC	High Altitude Ice Crystals - High Water Ice Content Project
TCI	Tropical Cyclone Intensity Experiment
SHOUT	Sensing Hazards with Operational Unmanned Technology
IceBridge 2015	IceBridge 2015
WINTER	Wintertime Investigation of Transport, Emissions, and Reactivity
PECAN	Plains Elevated Convection at Night

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CSET	Cloud System Evolution in the Trades
Nor'easter	Nor'easter

For example, the Plains Elevated Convection at Night (PECAN) was a multi-agency project (NSF, NOAA, NASA, DOE) designed to advance the understanding of continental, nocturnal, warm-season precipitation. PECAN focused on nocturnal convection in conditions over the Southern Great Plains with a stable boundary layer (SBL), a nocturnal low-level jet (NLLJ) and the largest CAPE (Convectively Available Potential Energy) located above the SBL. Thunderstorms are most common after sunset across this region in summer and much of the resulting precipitation falls from mesoscale convective systems (MCSs). Nocturnal MCSs may produce heavy rainfall; their intensity is correlated with the NLLJ. To date, an accurate prediction and an in-depth understanding of elevated convection in this environment remains an elusive goal.

Facility Tours

Each year, NCAR facilities host a number of participants for tours organized for a specific organization or group. This year, NCAR hosted a total of 79 tours.

The NCAR-Wyoming Supercomputer Center hosted 59 tours in FY15, for groups ranging in size from 1 to 57 people. Fourteen tours were by K-12 groups, including the Boy Scouts of Douglas, Wyoming and various local high school visits. Fourteen groups took science- or technical-related tours, including a group from the NSF and the US Senate. There were twelve college or university groups, ranging from the Front Range Community College in Fort Collins to the Western Wyoming Community College in Rock Springs, WY. Green building and engineering tours were provided to groups such as Phelps Construction and the Black Hills Corporation. There were twelve tours by political/sponsor groups, including the South Korean Consulate and WYDOT. There were also five tours by peer centers to include the San Diego Supercomputing Center and USGS Powell Center.

The Rocky Mountain Metropolitan Airport hosted a total of 19 tours in FY15. Thirteen tours were by college and university groups, including Front Range Community College and Colorado State University. Two tours were by science and technical groups, including the US Air Force and NOAA. Four tours were made by political/sponsor groups, including Senator Thom Till's Office and James Change, Congressional Staffer for Brian Schatz of Hawaii.

NWSC Walk-In Public Tours

The NCAR-Wyoming Supercomputing Center (NWSC) is based in Cheyenne, Wyoming. The Center provides advanced computing services to scientists studying a broad range of disciplines, including weather, climate, oceanography, air pollution, space weather, computational science, energy production, and carbon sequestration. The Center is open to the public for self-guided tours, field trips for school groups, and non-school group special tours.

In FY15, the Center received 811 walk-in public visitors, and averaged 68 visitors per month.

INDIVIDUAL STAFF METRICS

Contributions to Individual Graduate Student Education

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

Of the 239 graduate students that have NCAR staff serving as graduate advisors or committee members, 73% hail from U.S. universities; 27% study at schools in 23 countries around the world, including a student from Addis Ababa University in Ethiopia who was advised by Kyle Augustson.

Editorships

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

78 NCAR staff served in 108 different editorial roles on 75 different publications or journals. Publications included top-tier journals such as AMS Journal of Hydrometeorology and Geoscience Data Journal.



External Awards

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

Twenty-nine staff received special recognition for their work. Mary Barth (Principal Investigator), Jim Bresch, Louisa Emmons (Principal Investigator), Laura Pan and Christine Wiedinmyer received the NASA Group Achievement Award to SEAC4RS for outstanding accomplishments, Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC4RD). This award is one of the most prestigious awards a group can receive and is presented to selected groups who have distinguished themselves by making outstanding contributions to the NASA mission.

Matthias Steiner (RAL) was named as a American Meteorology Society Fellow. The AMS Fellow honor celebrates outstanding contributions to the atmospheric or related oceanic or hydrologic sciences or their applications during a substantial period of years.

George Bryan (MMM) received the Atmospheric Science Letters Editor’s Award from the Royal Meteorological Society (UK). Dr George Bryan has made a significant contribution to the increasing impact of Atmospheric Science Letters on the atmospheric science community. His expertise in the area of severe storms, tropical cyclones and their numerical modelling has proved invaluable.

Fellowships

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

Eleven NCAR staff received fellowships in 2015. Among the highlights: Tanya Peevey (ACOM) was awarded a place in the International Research Fellowship Program (IRFP) offered by the National Science Foundation (NSF).

K-12 Outreach

Staff across NCAR work directly with classes and groups of K-12 students to develop or deliver lectures, conduct tours, and lead or participate in field trips and other educational activities.

Forty-nine NCAR Staff worked with K-12 students from 57 schools. Activities included a career fair, helping teachers, mentoring, and field trips reaching 21 different communities. Examples range from a career fair at Lake County High School and Peak to Peak Charter School to advising K-12 students at the Monash Lab Rats facility in Melbourne Australia to advising as a consultant and contributor to the Solar Superstorms Planetarium show in New York.

Among the highlights: David Schneider (CGD) a Science Speed Dating event for K-12 teachers hosted at NCAR; Tara Jensen (RAL) built an automated weather station for Mead Elementary School in Mead, Colorado; and Thomas Cram (CISL) taught Bubbles on Bottle classroom kit to a second-grade class at Laurel Elementary School in Fort Collins, Colorado.

Talks and Posters

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

Many thousands of people were in the audience when 242 NCAR staff gave more than 1,100 talks across the country and around world, from Biddeford Maine to Amsterdam, Netherlands. Examples range from Matthias Rempel’s (HAO) talk on “Magnetocovection - the Global and the Local Dynamo” at the Conference on Coupling and Dynamics of the Solar Atmosphere in Pune, India to Wojciech Grabowski’s (MMM) talk “Untangling microphysical impacts on deep convection applying a novel modeling methodology” in La Jolla, California.

One hundred and two NCAR staff made more than 170 poster presentations across the country and around world, from Madison, Wisconsin to Montpellier, France. Examples include Peisang Tsai’s (EOL) poster “Real-time, Active Platform Stabilized HIAPER Cloud Radar and its engineering challenges” in Norman, Oklahoma at the 37th Conference on Radar Meteorology and Sarah Gison’s (HAO) poster

“Coronal Magnetism and FORWARD IDL SolarSoft Package” in Punta Leona, Costa Rica at the IAU Symposium 305.

External Committee Service

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

This year, 163 NCAR staff served in a multitude of roles on 526 external committees for national and international scientific, education, and governmental organizations, including entities such as the Department of Energy, Environmental Canada and the World Meteorological Organization. More than 63% served on more than one committee.

Staff Collaboration Visits to Universities

NCAR staff take leaves to visit other institutions for two weeks or more for intellectual growth, professional development, collaboration with research community peers, community support, teaching, or sabbatical. Examples of work include teaching courses or workshops, lecturing, giving tutorials, working with graduate students on dissertation-focused research, student mentoring, collaborative research, and participating in the host institution's outreach to community colleges, minority-serving institutions, and high schools.

This year, 15 NCAR staff members took leaves at 17 different institutions, ranging from the University of Leeds to the Korean Institute of Atmospheric Prediction Systems (KIAPS). Among the highlights: Paul Kucera (RAL), a Project Scientist II, visited the University of Hamburg to engage in collaborative research.

Teaching in University/College Classrooms

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

Teaching appointments at institutions of higher education currently number 31. Twenty-one percent of these appointments occur in 9 countries around the world; 79% took place in 15 U.S. states, including Puerto Rico. The longest term is 30 years, by Grant Branstator (CGD) who is an Adjunct Professor at Iowa State University. The class sizes range from 5 to 150 students.

Teaching or Training at Workshops/Tutorials/Colloquia

NCAR staff teach classes and offer training in workshops, tutorials, and colloquia to colleagues and students ranging from model users, to scholars, to fellow researchers.

During this year, 65 staff members taught at a total of 119 workshops, tutorials, and colloquia. In all, 497 individual classes were taught, with class sizes ranging from one to 45 people. Fourteen percent of these events occurred in 13 countries around the world including Seychelles and Croatia; 86% took place in five U.S. states, including Michigan and Kansas. Examples range from Mary Barth's (ACOM) contributions at the “Atmospheric Composition and the Asian Monsoon Training School” in Bangkok, Thailand to Mary Haley’s (CISL) teaching at the Visualization with NCL - Hands on Workshop Fall 2014 in Hamburg, Germany.

Mentoring

NCAR staff participate in mentoring colleagues and students.

During this year, 71 staff members mentored mentees both inside and outside of NCAR. John Ortega (ACOM) mentored a student from the National Space Research and Development Agency (NASRDA) from the Kogi State University in Nigeria on various ways of sampling common pollutants from urban emissions and photochemistry. These included ozone, NO/NOx, volatile organic compounds using gas chromatography and CO. The mentoring also included instrument calibration, instrument control using Labview software, data logging, and instrument maintenance.

Special Appointments

**NCAR Affiliate Scientists:** Select university and research-community scientists are invited to carry out long-term, highly interactive, collaborative work with UCAR scientists and are appointed as Affiliate Scientists with three-year terms. This appointment is particularly suitable for parties who desire an extended, close-working relationship on scientific problems of mutual interest. Currently, 34 hold appointments including Dr. Guido Cervone of Pennsylvania State University. Dr. Cervone is collaborating with scientists in the Research Applications Laboratory on forming better methods of optimization that can be applied to numerous problems including wind energy optimization.

**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 25 with the recent appointment of Dr. Maura Hagan who is continuing her research on upper atmospheric physics and the exploration and investigation of the mesosphere, thermosphere and ionosphere.

**Scientific and Technical Visits to NCAR**

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

This year, colleagues visited NCAR 864 times and hailed from 360 institutions, located in 47 different U.S. states and 43 different countries.

Visit Length - Number of Scientific and Technical Visits in FY15

- 1 day to 1 week: 191
- 8 days to 2 weeks: 94
- >2 weeks to 2 months: 241
- >2 months to 6 months: 163
- > 6 months to 1 year or more: 157
- Total: 846

Scientific and Technical Visit Types - FY15

- Visits by Visitors on Payroll: 58
- NCAR funded Visits: 285
- Externally funded Visits: 503
- Total: 846

**Publications in the UCAR Open Sky Institutional Repository as of March 15, 2016**

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

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

mission of UCAR to foster science, support its community, and facilitate the transfer of knowledge.

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

A publication is an academic or technical work of writing containing original research results, reviews of existing results, or scholarship. "Refereed" publications undergo an editorial "blind" or anonymous process of peer review by one or more referees (who are experts in the same field) in order to check that the content of the paper is suitable for publication in the journal. A paper may undergo a series of reviews, edits and re-submissions before finally being accepted or rejected for publication. "Non-refereed" articles have been reviewed by editors or boards before being accepted for publication but have not gone through a formal blind review. **Attached** are NCAR's refereed lists for the period October 1, 2014 to September 30, 2015. To search for recent NCAR publications by author, date, keyword or status please visit the OpenSky database. For excellent library resources please go the **NCAR Library Web site**.

697 Refereed Total Publications

- No UCAR Authors 0 (0%)
- UCAR and Other 75 (10.76%)
- UCAR and University 209 (29.99%)
- UCAR only 67 (9.61%)
- UCAR, University and Other 345 (49.5%)

**UCAR Outstanding Publication Award:**

Stephen Yeager (NESL/CGD), Alicia Karspeck (NESL/CGD), Gokhan Danabasoglu (NESL/CGD), Joe Tribbia (NESL/CGD), and Haiyan Teng (NESL/CGD) received the Outstanding Publication Award for 2014 for their paper "A decadal prediction case study: Late Twentieth-Century North Atlantic Ocean heat content," published in the Journal of Climate, 25, 5173–5189, doi: **10.1175/JCLI-D-11-00595.1**.

Predicting climate change in the near-term, over time horizons of up to a few decades into the future, is a relatively new and rapidly evolving field of climate science. Such "decadal prediction" research is aimed at bridging the gap between seasonal-to-interannual forecasting carried out by many operational weather services worldwide, and the centennial timescale future climate change projections that are the mainstays of the periodic IPCC assessments. Decadal time scales and regional spatial scales are particularly relevant to policy makers and other climate stakeholders. Skillful decadal predictions have the potential to confer tremendous benefits to society by providing advance warning of climate changes such as prolonged droughts, severe heat waves, and increased hurricane activity. This publication distinguishes itself as an outstanding publication on the topic of decadal prediction in several respects:

- This study has provided impetus for continued and expanded decadal prediction efforts at NCAR, and influenced the latest Strategic Plans of NCAR, NESL and CGD that now highlight decadal climate prediction as a Grand Challenge objective (NCAR Strategic Plan: 2014-2019).
- It demonstrates that significant decadal prediction skill is possible today using community models developed by NCAR.
- It goes beyond simply documenting predictive skill by providing a clear explanation of the physical processes that give rise to that skill through a rigorous and innovative analysis of a relevant case study.

Its immediate and lasting impact on the international research community is evidenced by a high and accelerating citation rate.

<a href="#">&lt; Futureproofing High School Science Students through Data Analytics</a>	<a href="#">up</a>
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- NCAR Imperative 3: Develop, deliver and support a suite of advanced community models.
- NCAR Imperative 4: Develop and sustain advanced computing and data system services
- NCAR Imperative 5: Develop and transfer science to meet societal needs.
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NCAR Imperative 1: Conduct innovative fundamental research to advance the atmospheric and related sciences.

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- B4) Ozone and water vapor measurements from the CONTRAST field campaign – a bi-modal structure of tropospheric ozone over the tropical western Pacific (TWP) warm pool region.

NCAR Imperative 2: Develop, maintain and deploy advanced observational facilities and services.

- C1) The Inaugural “ACCORD” Workshop
- C2) A New Atmospheric Chemistry Simulation Chamber
- C3) Characterization of Atmospheric Radiation Measurement Systems
- C4) Manitou Experimental Forest Observatory (observations of oxygenated VOCs and fire emissions)
- C5) Participation of ACOM scientists in the University-led WINTER (Wintertime Investigation of Transport, Emissions, and Reactivity) campaign

NCAR Imperative 3: Develop, deliver and support a suite of advanced community models.

- D1) Development of a new prognostic capability for stratospheric aerosols and stratospheric aerosol optical depth in CESM
- D2) Ethane emissions inventory
- D3) Expanded Representation of Halogens in CAM-Chem

NCAR Imperative 4: Develop and sustain advanced computing and data system services

- E1) Combining MOPITT and OCO-2 data to estimate combustion efficiency of Southern African fires

NCAR Imperative 5: Develop and transfer science to meet societal needs.

- F1) Understanding the seasonal cycle and impacts of Black Carbon aerosols in India

NCAR Imperative 6: Educate and entrain a talented and diverse group of students and early career professionals.

- G1) Atmospheric Composition and the Asian Monsoon (ACAM) Workshop and



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Meterology Laboratory

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A1) THE FRONT RANGE AIR POLLUTION AND PHOTOCHEMISTRY EXPERIMENT (FRAPPÉ) – COMMUNITY WORKSHOP AND UPDATE

The Front Range Air Pollution and Photochemistry Experiment –FRAPPÉ – was successfully carried out 15 July – 18 August 2014 (<http://www2.acd.ucar.edu/frappe>), concurrent with the 4th deployment of the NASA DISCOVER-AQ field project. FRAPPÉ addresses the following main science question: What are the factors controlling surface ozone in the Front Range and are current emission controls sufficient to reduce ozone levels below the NAAQS?

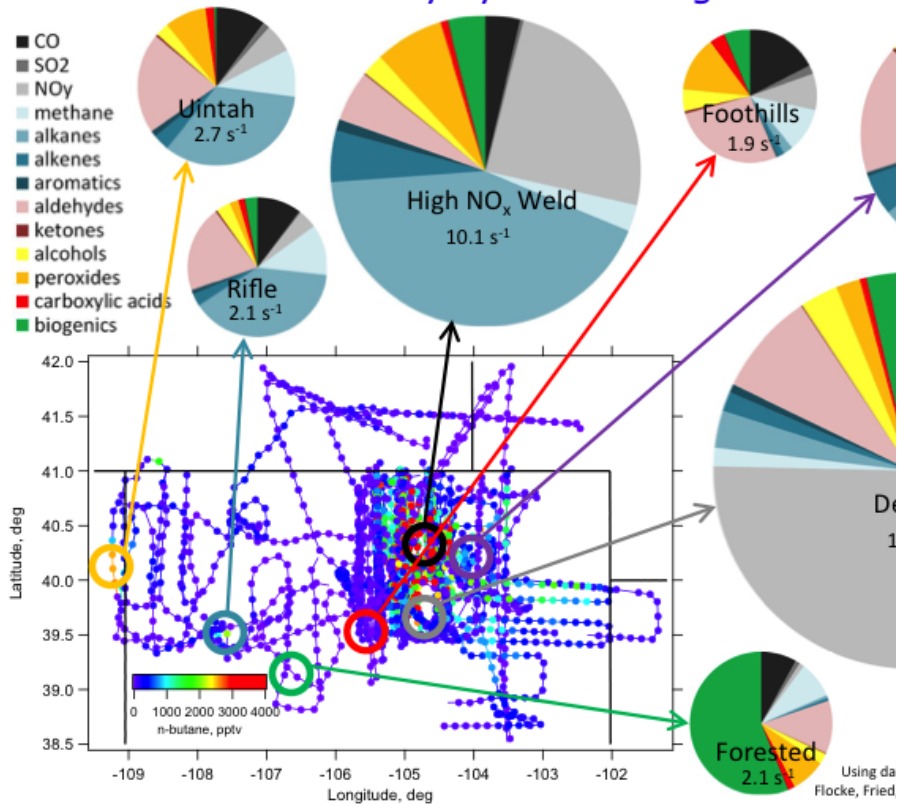
The campaign yielded the most comprehensive dataset to study and characterize local AQ at a level of detail not possible previously and has been (and is) a showcase for the tight collaborations between the research community and air quality agencies [Colorado Department of Public Health and Environment (CDPHE), the Regional Air Quality Council, EPA Region 8, the Western Regional Air Partnership and the National Park Service (NPS)].

The collected data set has been thoroughly evaluated for quality and accuracy and was released to the public in April of 2015. This constitutes an enormous amount of work and a tremendous effort by all involved. The data set consists of more than a million individual data points covering hundreds of chemical tracers and their oxidation products in the atmosphere, which are crucial for understanding ozone pollution. This data set is being used by the university community, national agencies such as the NPS, scientists from NCAR, NOAA and NASA as well as regulatory agencies including CDPHE and EPA. Ultimately the analysis will lead to the development of emission control strategies to reduce summertime ozone pollution in the Front Range and visibility and nitrogen deposition problems in Rocky Mountain National Park.

From 4-8 May 2015 ACOM held a community workshop at NCAR for all groups involved in last summer’s campaign to present and discuss first results. This meeting was attended by over 200 people. The analysis is ongoing and we hold monthly telecons to guide the analysis and strengthen the collaborations. At the upcoming AGU there will be 40+ presentations on FRAPPÉ with most of them presented in a session lead by ACOM Scientists on “Air Quality Research: From Emissions to Impact”.

While it is too early for final results, first results and publications are beginning to show. These focus on emission evaluations and constraints, transport and flow analysis, NOx and VOC sensitivities, model evaluations, and others. As one example we show results using the NCAR/ACOM Trace Organizer Gas Analyzer (TOGA) data collected on the NCAR/NSF C-130 together with several other trace gas measurements. The analysis of the detailed VOC measurements shows that oil and natural gas activities in Weld County contribute significantly to the OH reactivity in this region and much of the reactivity is from C4-C6 alkanes, typically not well represented in the chemical schemes used in global and regional models. Follow-up work is focused on estimating the ozone production efficiency of these species.

## Calculated OH Reactivity by FRAPPÉ region



**Figure 1** (From Rebecca Hornbroke, NCAR/ACOM) Contributions to OH reactivity for different FRAPPÉ regions.

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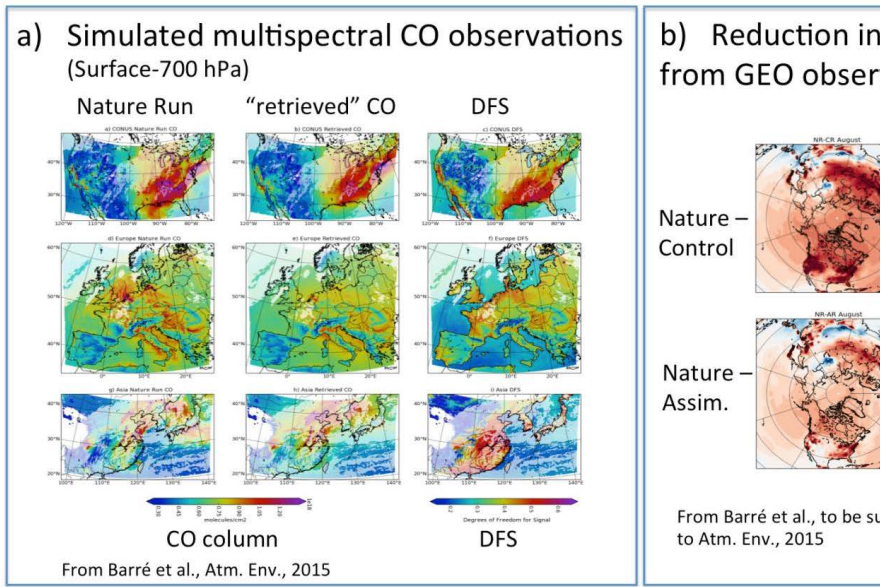
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A2) ASSESSING THE PERFORMANCE OF A GEOSTATIONARY CONSTELLATION IN PREDICTING GLOBAL TRANSPORT OF AIR POLLUTION

We performed observing system simulation experiments (OSSEs) to evaluate potential measurements of carbon monoxide from a constellation of satellites in geostationary orbit (GEO). OSSEs are a powerful method for quantifying how much information new observations will add for air quality prediction on local to global scales, especially when considering possible new satellite measurements. Carbon monoxide (CO) measurements were simulated for these OSSEs because CO is an excellent tracer of combustion, from both human activities and fires, and can be used to assess the impact of GEO observations on quantifying pollution transport and emissions.

OSSEs require a “Nature Run” using a model that represents what is considered to be the “true” atmosphere, a “Control Run” that uses a different model and an “Assimilation Run” that uses the same model as the Control Run, but assimilates simulated observations. Comparisons of these runs give objective criteria for evaluating the performance of the potential measurements. We simulated observations that are based on existing MOPITT multispectral CO measurements with realistic variability in sensitivity to CO (see plots of DFS) and expected loss of coverage due to clouds.



**Figure 1.** Panel (a) shows the “true” (i.e., Nature Run) and simulated observations of CO for the 3 GEO viewing domains in August, with corresponding measurement sensitivities given by the Degrees of Freedom for Signal (DFS). Faded colors indicate persistent cloud

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cover. Panel (b) shows the reduction in error achieved when the simulated CO observations are assimilated (bottom), as compared to the Control Run that only assimilates meteorology observations (top).

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## B1) RATE COEFFICIENTS FOR REACTION OF BR-ATOMS WITH OXYGENATED VOCs

Reactive chemistry involving inorganic bromine-containing species is now recognized as playing a role in the determination of the oxidative capacity of the Earth's troposphere, contributing significantly to ozone loss and exerting a controlling influence on the global distribution and partitioning of mercury. Despite this importance, the database for reaction of Br-atoms with volatile organic compounds (VOCs) is not nearly as well established as for VOC reactions with other atmospheric oxidants, such as OH, Cl, NO<sub>3</sub> or O<sub>3</sub>. In particular, the Br-atom reactivity with key oxygenated species is poorly constrained and data on reactions with multifunctional species are almost completely lacking.

In this work, rate coefficients for reaction of Br-atoms with eight oxygenated VOCs have been obtained, all using the NCAR gas-phase environmental chamber and all using the relative rate method. For five of the compounds studied, this is the first report of their Br-atom rate coefficient. Furthermore, rate coefficients obtained span a range of about a factor of 25, and thus provide a basis upon which a larger and more reliable Br/VOC database can be constructed. Compounds studied include two alcohols, two ethers, and four multi-functional species. Final values for the alcohol and ether species are as follows (in units of 10<sup>-14</sup> cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup>): k(Br+2-propanol) = 3.1; k(Br+2-butanol) = 3.8; k(Br+diethyl ether) = 4.7; k(Br+diisopropyl ether) = 5.7, with uncertainties in all cases ≈ 15%.

The four multi-functional species are all well-known by-products of isoprene oxidation, and included two hydroxycarbonyl species (hydroxyacetone, CH<sub>3</sub>COCH<sub>2</sub>OH, HYAC; and glycolaldehyde, HOCH<sub>2</sub>CHO, GLYALD) and two dicarbonyls (glyoxal, HCOCHO, GLY; and methylglyoxal, CH<sub>3</sub>COCHO, MGLY). Final values for the four species are as follows (in units of 10<sup>-14</sup> cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup>): k(Br+HYAC) = 69; k(Br+GLYALD) = 45; k(Br+MGLY) < 14; k(Br+GLY) = 3.5, with uncertainties again ≈ 15%. To the best of our knowledge, these are the first data reported for HYAC, GLYALD and MGLY. Of particular interest is the higher than expected reactivity of Br-atoms with HYAC. The fact that Br-atoms react more rapidly with HYAC than with the simple alcohols implies that the carbonyl group serves to activate the adjacent alcohol functionality in HYAC. Similarly, the rather high reactivity of GLYALD towards Br is surprising. Product studies of the Br/GLYALD reaction reveal a significant yield of glyoxal, implying that about 30% of the reaction occurs at the CH<sub>2</sub> group, and thus a site-specific rate coefficient at the CH<sub>2</sub> group of ≈ 16 × 10<sup>-14</sup> cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup>. This again implies an activation of the reactivity of the CH<sub>2</sub>- group in GLYALD by the adjacent carbonyl functionality.

Current work is extending this study, focusing on reactions of Br-atoms with unsaturated VOCs, including simple alkenes, isoprene, and unsaturated oxygenated species, such as methacrolein and methylvinyl ketone. These reactions are interesting in that they occur via reversible addition of Br to the carbon-carbon double bonds.



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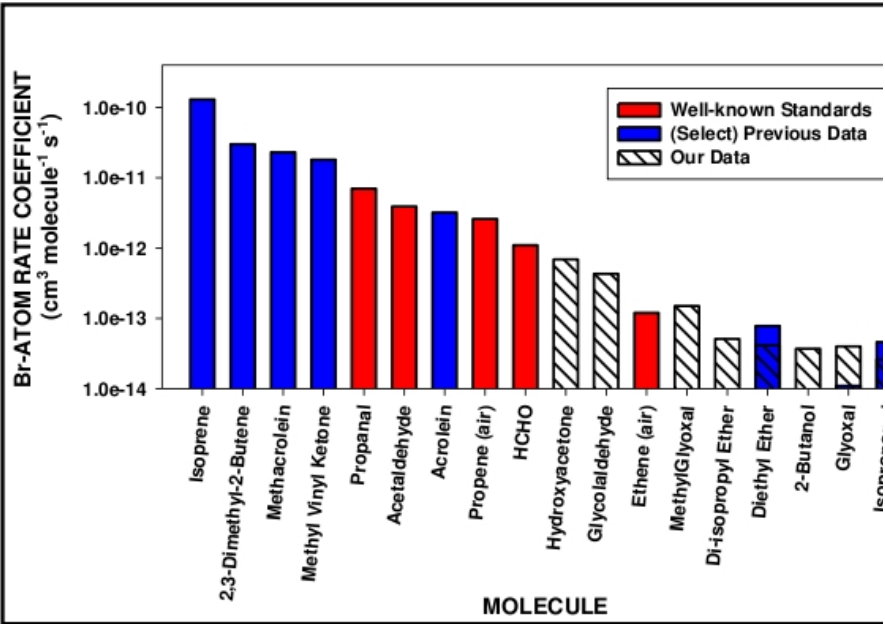
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**Figure 1:** Measured rate coefficients (y-axis, units of  $\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ ) for reactions of Br-atoms with various VOC species of atmospheric interest. Data from this study are indicated by the black-and-white hatched columns. Current work is focusing on more reactive species, such as isoprene, methacrolein and methyl vinyl ketone, for which only 1-2 previous measurements exist.

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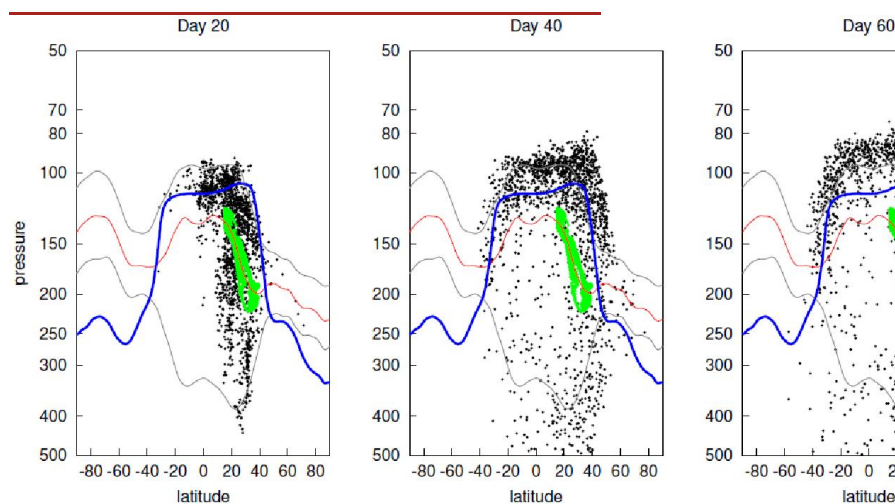
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## B2) TRAJECTORY CALCULATIONS OF TRANSPORT TO THE STRATOSPHERE IN THE ASIAN MONSOON

Satellite observations show that the outflow of deep convection within the Asian monsoon persistently transports low-level air pollution to the upper troposphere ( $\sim 10$  km), and this pollution can subsequently transit to the lower stratosphere with a time scale of one-to-two months. The detailed transport pathways of air that originate from the outflow of deep convection in the monsoon anticyclone have been investigated using trajectories driven by ERA-interim reanalysis meteorological data. Calculations include isentropic estimates, plus fully three-dimensional results based on kinematic and diabatic transport calculations. Isentropic calculations show that air parcels are typically confined within the anticyclone for 10–20 days, and spread over the tropical belt within a month of their initialization. Calculations with fully 3-dimensional winds show that approximately half of the trajectories reach the stratosphere within 60 days. Most parcels that reach the stratosphere are transported upward within the anticyclone and enter the stratosphere in the tropics, typically 10–20 days after their initialization at 360 K. This suggests that trace gases, including pollutants, that are transported through the Asian monsoon system can enter the upward stratospheric Brewer-Dobson circulation and thus be transported into the deep stratosphere. Sensitivity calculations with respect to the initial altitude of the trajectories showed that air needs to be transported to levels of 360K or above by deep convection to likely reach the stratosphere through transport by the large-scale circulation.



**Figure 1.** Dispersion of 3 dimensional particle trajectories initialized in the Asian monsoon anticyclone after 20, 40 and 60 days (left to right). The initial position of the particles (shown as green points) is within the monsoon anticyclone at the 360 K potential temperature level, consistent with the outflow of observed deep convection. The evolution shows the net upward transport of material across the tropopause (heavy blue line) into the lower stratosphere with a time scale of 1-2 months. The light lines show the 340, 360 and 380 K potential temperature levels

REFERENCE:

Garney, H., and W.J. Randel, 2015: Transport pathways from the Asian monsoon anticyclone to the stratosphere. Atmos. Chem. Phys. Discuss., 15, 25981–26023, 2015 doi:10.5194/acpd-15-25981-2015.

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B3) LOSS OF SECONDARY ORGANIC AEROSOL VIA PHOTOLYSIS

The atmospheric burden and lifetime of organic aerosols (OA) are highly uncertain due to the limited understanding and inadequate representation in chemistry-climate models of processes controlling their formation, aging and removal in the atmosphere. Organic molecules in both gaseous and aerosol phase contain chromophores (eg carbonyl, peroxide, and/or nitrate groups) that are highly sensitive to photolysis. Although recent laboratory experiments clearly show that photolysis can fragment relevant molecules into smaller and more volatile compounds and significantly modify OA composition and properties during atmospheric aging, photolysis of semi-volatile organic molecules are not considered in 3D models due to the lack of mechanistic understanding of species and reactions involved, or whether these reactions are happening in the gas or particle phase. We used the unique capabilities of the chemical mechanism generator GECKO-A to perform the first modeling estimates of the potential effect of gas- and particle-phase organic photolysis reactions on the formation and lifetime of secondary OA. Our results show that after a typical week of atmospheric ageing in the summer mid-latitudes, gas-phase photolysis leads to a moderate decrease in SOA formation i.e 15-25% for typical anthropogenic and biogenic precursors, and that many molecules containing chromophores are preferentially partitioned into the particle phase before they can be photolyzed in the gas-phase. Our estimates also suggest that particle phase SOA is sensitive to photolysis and that a photolytic loss rate of  $J_{SOA}=4\times10^{-4} J_{NO_2}$  (our best estimate) could decrease SOA mass by 40-60% if applied in a chemistry-climate model (see figure 1). These modeling results clearly illustrate how NCAR modeling tools can be used to interpret laboratory data, and help estimate regional impacts of specific processes.

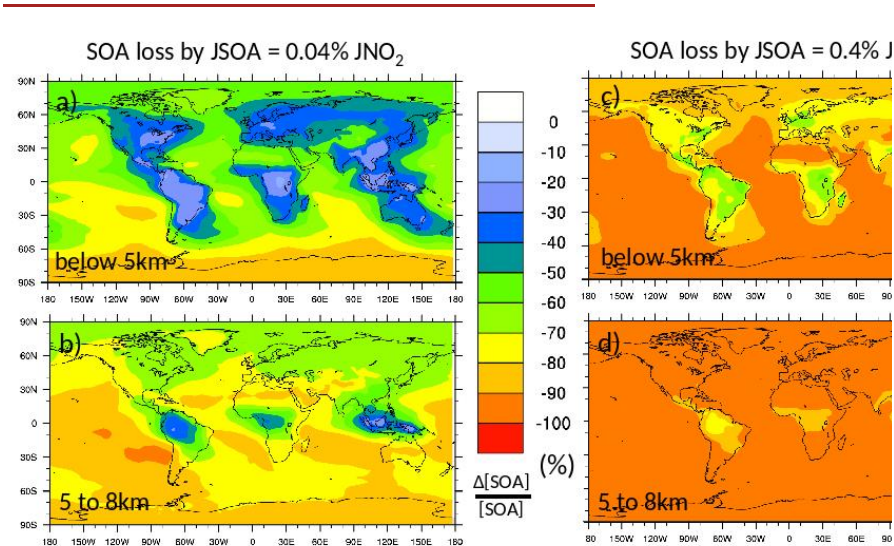


Figure 1: Relative reductions in SOA concentrations due to particle-phase photolysis in the lower (a) and upper (b) troposphere. In-particle photolysis rates of  $J_{SOA}=4\times10^{-4}J_{NO_2}$  is considered.

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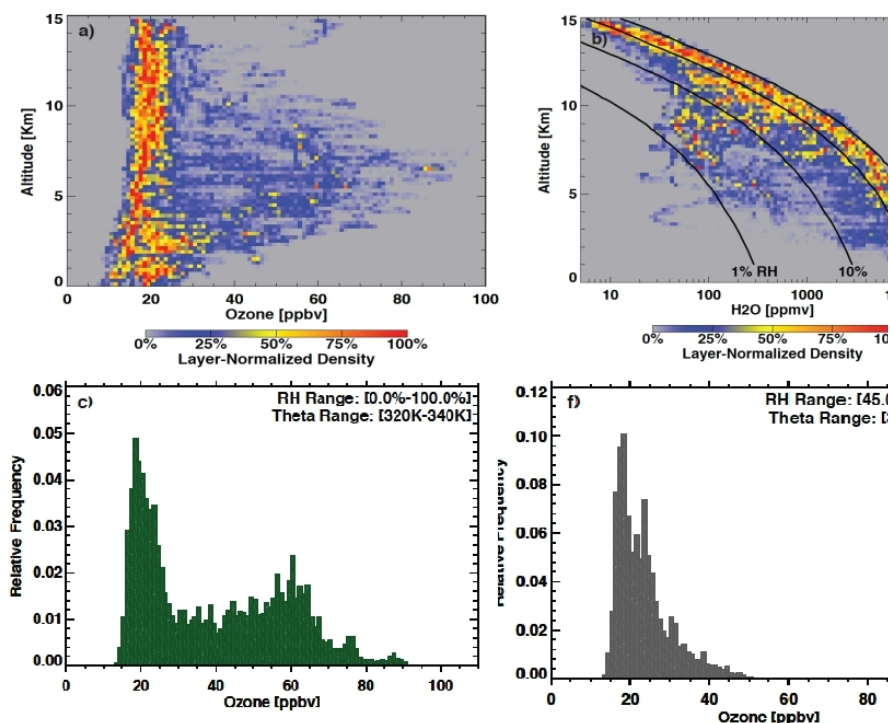
## B4) OZONE AND WATER VAPOR MEASUREMENTS FROM THE CONTRAST FIELD CAMPAIGN – A BI-MODAL STRUCTURE OF TROPOSPHERIC OZONE OVER THE TROPICAL WESTERN PACIFIC (TWP) WARM POOL REGION.

Tropospheric ozone plays an important role in atmospheric chemistry and climate forcing. Ozone controls the atmospheric oxidizing capacity via its photochemical link to OH, and this link is especially important in the moist, high radiation environment of the tropics. Tropospheric ozone is also a significant greenhouse gas, and its contribution to the radiative forcing of climate change continues to have significant uncertainty. Levels of ozone in the remote tropical western Pacific (TWP) region are uncertain, and also highly variable, due to the influence of deep convective outflow. For example, ozonesonde measurements showed cases of extremely low ozone (near zero) between 12-15 km altitudes, but it is unclear to what extent the ozonesonde results are limited by the measurement capabilities of the ozonesondes in this low ozone environment.

The high-resolution, high-accuracy *in situ* ozone instrument aboard the NSF/NCAR Gulfstream V (GV) research aircraft during the CONvective Transport of Active Species in the Tropics (CONTRAST) experiment performed high intensity sampling over the TWP warm pool region in January and February 2014. These new observations reveal a bi-modal distribution of tropospheric ozone in the TWP (figure 1), with a primary mode, narrowly distributed around 20 ppbv, dominating the troposphere from the surface to 15 km. A secondary mode, broadly distributed with a 60 ppbv modal value, is prominent between 3-8 km (320 K to 340 K potential temperature levels). The latter mode occurs as persistent layers of ozone-rich drier air and is characterized by relative humidities under 45%. The primary mode is consistent with convectively mixed near-surface ozone values. The secondary mode occurs primarily in horizontal layered structures over ~320-340 K and is consistent with advection and mixing from outside of the deep tropics. The minimum ozone sampled in the 12-15 km altitude range was 13 ppbv. No near zero ozone case was found.

The recognition of the bi-modal structure is important because the different controlling mechanisms behind each mode may behave differently in model simulations, and they may evolve differently in a changing climate. The CONTRAST data shows that the secondary mode contributes ~ 20% to the tropospheric total ozone (Pan et al., 2015).





**Figure 1.** Relative frequency distribution (with respect to the layer maximum) from all GV TWP a) ozone and b) water vapor profiles in altitude (200 m interval) and selected RH profiles in GPS altitude coordinates, and (c) the relative frequency distribution of ozone from 320-340 K potential temperature layer. The distribution shown in c) highlights the bi-modal distribution. Figure f) shows that same distribution as c) with measurements less than 45% RH excluded, highlighting the dryness of air mass in the secondary mode.

PUBLICATION:

Pan, L.L., S. B. Honomichl, W. J. Randel, E. C. Apel, E. L. Atlas, S. P. Beaton, J. F. Bresch, R. Hornbrook, D. E. Kinnison, J-F Lamarque, A. Saiz-Lopez, R. J. Salawitch, and A. J. Weinheimer, Bimodal distribution of free tropospheric ozone over the tropical western Pacific revealed by airborne observations, *Geophys. Res. Lett.*, 42, 7844–7851, Doi: 10.1002/2015GL065562

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#### C1) The Inaugural “ACCORD” Workshop

#### C2) A New Atmospheric Chemistry Simulation Chamber

#### C3) Characterization of Atmospheric Radiation Measurement Systems

#### C4) Manitou Experimental Forest Observatory (observations of oxygenated VOCs and fire emissions)

#### C5) Participation of ACOM scientists in the University-led WINTER (Wintertime INvestigation of Transport, Emissions, and Reactivity) campaign

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## C1) THE INAUGURAL “ACCORD” WORKSHOP

The inaugural ACCORD workshop was held in Boulder, CO, March 30 - April 1, bringing together more than 100 scientists to discuss the future of U.S. *in situ* observational atmospheric chemistry, with an additional 50 people attending remotely. ACCORD – the Atmospheric Chemistry Center for Observational Research and Data - is a new partnership between NCAR’s Atmospheric Chemistry Observations and Modeling Laboratory (ACOM), NCAR’s Earth Observing Laboratory, NSF Atmospheric Chemistry, and the University community. Its mission is to build a better alliance between ACOM and University partners to address critical, emerging questions in *in situ* observational atmospheric chemistry, and to provide a vehicle for community input into ACOM’s role in answering these questions.

The ACCORD Science Committee (consisting of 6 University and 3 NCAR scientists, and an NSF representative, <https://www2.acom.ucar.edu/accord/science-committee>) was formed in spring 2014, and put forward the idea of this community workshop, designed to obtain a bottom-up consensus on major science questions facing our field and the facilities needed to answer these questions. To help structure the workshop, a survey was first distributed to the community. Survey results were used to generate the workshop discussion themes, and to provide a starting point for discussions.

Seven **workshop discussion themes** were identified, including five science themes: Secondary Organic Aerosol, Aerosol Optical and Physical Properties, Reactive Nitrogen, Biosphere-Atmosphere Interactions, and Regional and Global Oxidants. A major goal was to bring early-career scientists to the workshop to allow them a platform to present their ideas – more than 30 attended - and a separate theme on early-career scientists was included. The final discussion topic was related to general facilities.

The workshop consisted of a series of breakout discussions, and plenary presentations and discussions. Potential activities associated with each of the seven themes were identified and are outlined in the **workshop summary**, <https://www2.acom.ucar.edu/accord/accord-2015-workshop>.

Some **central ideas** brought forward in the discussions are as follows:

1. The need for a community engineering center, in particular to provide support for aircraft instrumentation was strongly articulated.
2. The need for well-characterized ground site(s) for scientific study and instrument testing, and/or a mobile laboratory that can be deployed at a ground site, was expressed.
3. The community expressed a desire for an increased focus on re-analysis of previous field campaign results. Topics for study via ‘virtual campaigns’ included global HO<sub>x</sub> budgets, ozone production in biomass burning plumes, the evolution of Arctic composition, BVOC fluxes, and SOA formation.
4. The need for training (particularly for early-career scientists and newcomers to the field) on all aspects of instrumentation development and field deployment was communicated.
5. The continuing (and expanding) need for standards, calibration, and intercomparison exercises was prevalent.
6. A field campaign in a terpene-dominated landscape was discussed as part of multiple science themes (HO<sub>x</sub> budgets, biosphere-atmosphere exchange, and SOA formation).
7. There was a desire to develop a chamber collaboration network, with a focus on a centralized data repository.

Key ACCORD activities, many associated with developing a better infrastructure for carrying out *in situ* observational atmospheric chemistry research, are currently under discussion and development.

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C2) A New Atmospheric Chemistry Simulation Chamber >

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## C2) A NEW ATMOSPHERIC CHEMISTRY SIMULATION CHAMBER

The Atmospheric Chemistry and Observations and Modeling (ACOM) Laboratory has completed re-building its large (10 m<sup>3</sup>, 353 ft<sup>3</sup>) Teflon atmospheric simulation chamber. The goal of this chamber is to perform atmospheric chemistry and aerosol experiments in conditions that are atmospherically relevant. A large chamber of this type provides a number of important advantages, including minimization of wall effects that can confound quantification of products, and enhancement of the ability to work at concentration levels and conditions that mimic those found in nature.

The ACOM chamber is constantly flushed with clean air from a “zero-air generator” that uses compressed house air, and removes particles, water, NO, NO<sub>x</sub> ozone, volatile organic compounds and methane prior to an experiment. The chamber sweep air is controlled using a high-volume mass flow controller at approximately 40 volumetric liters per minute, which gives an average chamber residence time of 4.2 hours. There are 4 sample ports on each side of the chamber, which enables researchers to add reactants to the chamber in different locations as well as sample reaction products. Each of the 4 sides contains 32 “black lights” (total of 128), to allow studies of photochemical processes.

Each experiment has a standard set of measurements to control and monitor basic chamber behavior. This includes measurements of ozone, temperature, particle size distribution, relative humidity, internal pressure, and light intensity. Other instruments used to monitor reaction products include gas-chromatography (GC) and proton-transfer reaction – mass spectrometry (PTR-MS) for volatile organic compounds, and a number of other chemical ionization mass spectrometers (CIMS) to monitor gas-, cluster-, and particle-phase chemical constituents. Figure 1 below shows one side of the chamber, along with a number of other instruments as described in the figure caption.

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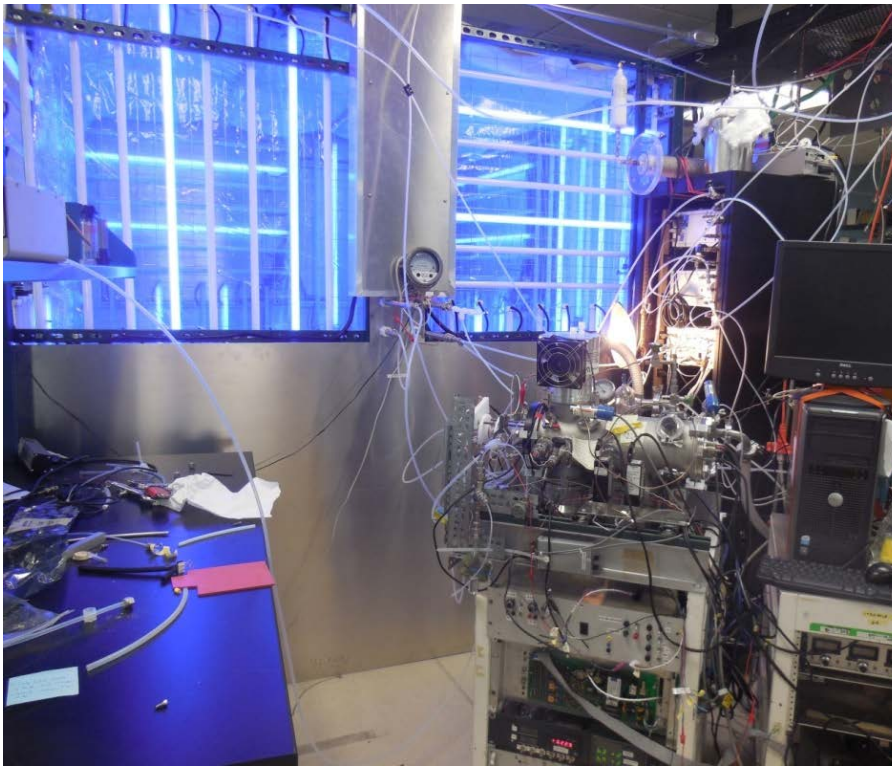
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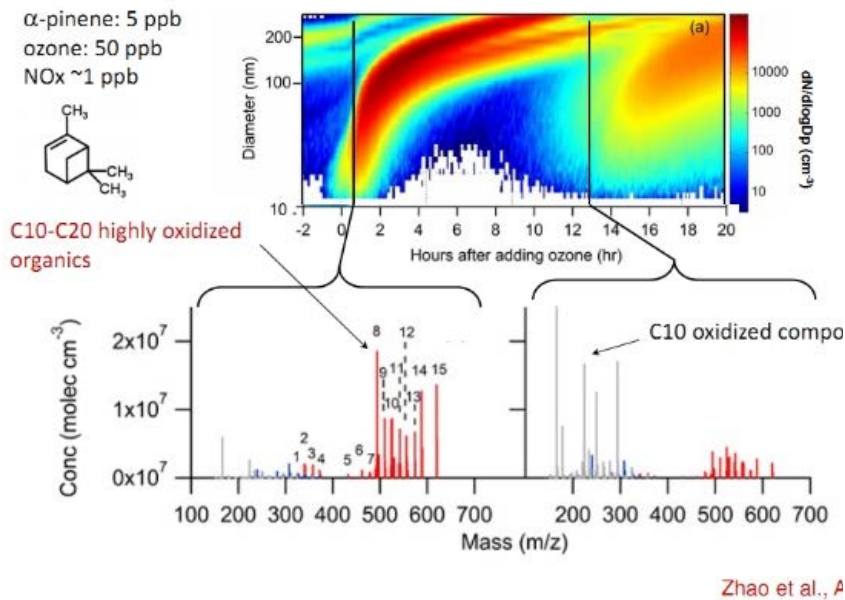


**Figure 1:** ACOM 10 m<sup>3</sup> Teflon-film environmental chamber at the NCAR Foothills laboratory; Boulder, CO. In the foreground is an Ambient Pressure Mass spectrometer (AmP-MS) used to measure gas-phase ammonia and amines using water and water clusters as the reagent ions. Behind is a calibration and dilution system containing 7 organic acids, ammonia, and 3 organic amine compounds under constant pure N<sub>2</sub> flow and temperature controlled for precise delivery rates.

Previous experiments (without lights) using our former facility were primarily focused on monoterpene (C<sub>10</sub>H<sub>16</sub>) oxidation using either NO<sub>3</sub> radicals or ozone and characterizing gas-phase reactions, particle formation and particle growth. One study used the NCAR Cluster CIMS (NCC) which is specifically tuned to for a transmission of large (up to m/z=700) ions, to observe larger clusters of low volatility reaction products and their partitioning between the gas- and particle-phases. Figure 2 below shows qualitative differences between the beginning (particle formation) and end (growth) phases of one of these experiments.



Cluster CIMS: Identifying secondary organic nanoparticle precursor from  $\alpha$ -pinene + ozone chamber experiment



**Figure 2:** Results from  $\alpha$ -pinene+ozone oxidation experiment in the ACOM 10 m<sup>3</sup> environmental chamber. The top color plot shows the evolution of particle size distribution from nucleation (0-0.5 hours) and into growth (2-10 hours). The bottom 2 plots show representative Cluster CIMS mass spectra from the two phases of the process. The cluster composition is dominated by heavier (C<sub>10</sub>-C<sub>20</sub>) oxidized compounds during particle formation, whereas during growth, clusters are more dominated by smaller (C<sub>10</sub>) oxidized compounds as the heavier species partition into the particle phase.

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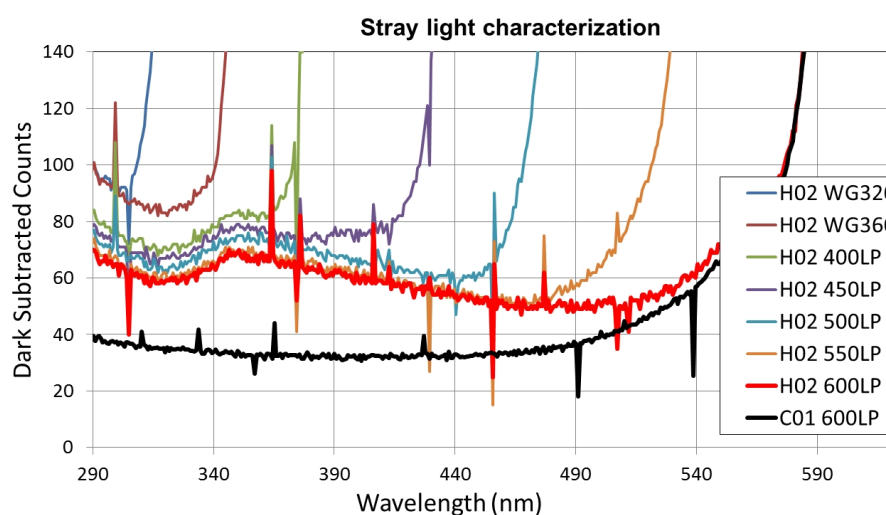
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## C3) CHARACTERIZATION OF ATMOSPHERIC RADIATION MEASUREMENT SYSTEMS

Many atmospheric chemical species are photochemically active, meaning they can be dissociated by sunlight. The Atmospheric Radiation and Measurements (ARIM) group deploys charged-coupled device (CCD) spectrometers for the determination of spectrally resolved actinic flux radiation and calculation of atmospherically relevant photolysis frequencies. The measurement is sensitive to solar elevation, clouds, aerosols, surface reflectivity and absorbing gases and is critical to understanding the evolution of ozone, greenhouse gases, and both natural and anthropogenic emissions.

The spectrometer creates a spectral measurement by dispersing incoming light with a grating onto the CCD detector. However, the detectors are sensitive to stray light interference due to the internal reflections. That is, photons intended for a particular wavelength are detected at other wavelength. Each spectrometer has its own stray light signature and thus they each must be characterized individually.

New filter sensitivity tests examined the spectral stray light signatures with NIST (National Institute of Standards and Technology) lamp sources and natural sunlight. Multiple spectrometers were compared to low stray light instruments and the NCAR/ACOM Tropospheric Ultraviolet and Visible (TUV) radiative transfer model. The tests provided a detailed spectral stray light signature. After the subtraction of a spectral dark current the stray light function is scaled by the stray signal at atmospherically dark wavelengths and removed. These updated UV-B (<315 nm) spectra have been used to improve past data sets (e.g. CONTRAST and WINTER) that previously used parameterized corrections for photolysis rates for species such as ozone. They also allow the use of spectrometers that were previously deemed insufficient for UV-B measurements.



**Figure 1.** Examples of long pass filter characterizations. The colored lines show a series of filters applied to a spectrometer with a non-linear stray light signature. The black line shows a spectrometer with a low and nearly linear stray light signature in the ultraviolet (<400 nm).

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C4) MANITOU EXPERIMENTAL FOREST OBSERVATORY (OBSERVATIONS OF OXYGENATED VOCS AND FIRE EMISSIONS)

The Atmospheric Chemistry and Observations Laboratory’s (ACOM) maintains a fixed field site at the Manitou Experimental Forest (MEF). This observatory is approximately 90 km southwest of Denver and 40 km northeast of Colorado Springs at an elevation of 7800 ft. (2377 m). It consists of a 27 m walk-up tower and 4 mobile laboratories used to investigate many themes relating to biosphere-atmosphere interactions. The site is a semi-arid ponderosa pine-dominated ecosystem that has periodic influences from the two major metropolitan areas, Denver and Colorado Springs. Each mobile laboratory has 6 20A circuits, which has been more than sufficient to support many researchers’ instruments in a number of large research campaigns. In addition to the two largest campaigns (BEACHON-ROCS in 2010 and BEACHON RoMBAS in 2011), NCAR has hosted a number of smaller measurement intensives during the past several years. During the summer of 2014, researchers from NCAR, the University of California, Berkeley, and the National Oceanic and Atmospheric Administration (NOAA) made intensive measurements of forest emissions of volatile organic compounds, with a specific emphasis on measuring “light” alkenes (e.g. ethene, propene, and butenes).

The 2015 growing season saw two measurement intensive campaigns at the observatory starting in July with researchers from Colorado State University measuring concentrations and fluxes of oxygenated VOCs from direct biogenic emissions as well as emissions that had been oxidized upwind of the tower site. ACOM provided the following instruments to the experiment:

- PTR-TOF-MS (Proton transfer reaction, including set up, operation, calibration and data analysis)
- Ozone (UV absorption)
- Carbon monoxide (IR absorption)
- NO and NOx (chemiluminescence)
- Particle size distributions from 4nm to 350 nm using (dual scanning mobility particle sizers)
- Meteorological variables at 4 heights on the flux tower (wind speed, wind direction, temperature, dew point, and pressure)
- 10 Hz sonic anemometer data at the top of the tower.

The latter instrument, along with fast (5 Hz) PTR-TOF-MS measurements, were necessary for determining fluxes using the eddy covariance method. CSU also provided other CIMS measurements and particle size distributions from the top of the tower using an Ultra-high sensitivity aerosol spectrometer (UHSAS). Figure1 below shows a picture of the chemistry flux tower and surrounding vegetation during July 2015.

The PTR-TOF-MS, trace gas measurements, and particle size distributions were kept on site after August 2015 to measure emissions from a prescribed burn during early October 2015. We augmented these measurements with a cavity ring-down spectrometer (CRDS) to measure water vapor, CO<sub>2</sub>, CO and methane from the fire. In addition, we took 1 hour samples (~12 L) on adsorbent cartridges for VOC analysis using GC-FID-MS in the Foothills laboratory. The combination of these VOC measurements



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combines the power of fast and sensitive measurements of the PTR-MS method with the chemical identification advantages of gas chromatography. The USFS has been more active in recent years in burning grasses, and understory litter in very safe and controlled scenarios on certain dedicated parts of the forests. The goals of these burns are to reduce total fuel loads that will lower future risks of catastrophic wildfires, which have devastated several Colorado forests and certain communities in the fires’ paths. The total prescribed burn area for this location was divided into 5 “plots” that totaled 626 acres. Of that, 4 of the 5 plots were ignited, and there were two days of active ignition (October 10, and 11) followed by about a week of smoldering activity. Several daytime and nighttime periods saw the fire and smoldering plumes travel directly into the tower space, providing valuable data on concentrations of all the chemical species measured as well as particles. There have been a number of ground-based and aircraft observations of wildland fires from fairly long distances. In contrast, this was a unique opportunity to sample emissions on a prescribed schedule where only the understory was burned. From this, we can provide data that is relevant to questions concerning how these prescribed burns can affect local and regional air quality as well as nutrient recycling. It was somewhat of a coincidence and fortuitous that the burn area is immediately north of our tower site. Data analysis for emission ratios and emission factors from the fuel loadings is ongoing to support a planned publication.



**Figure 1:** Chemistry flux tower at the Manitou Experimental Forest Observatory (MEFO). The walk-up tower is 27 m tall, and equipped with power and sensors at various levels as indicated in the text. The climate-controlled trailer that houses instruments can be seen to the left. Surrounding the tower is the forest’s dominant vegetation – ponderosa pine.



**Figure 2:** Prescribed burn smoke on October 13, 2014; ~11:30am local time (MDT). This picture was taken ~2 km south of the burn area from the chemistry flux tower at the Manitou Experimental Forest Observatory (MEFO). Approximately 1 hour after this picture was taken, the plume had drifted towards the tower where we observed elevated CO, CO<sub>2</sub>, volatile organic compounds, and NO<sub>x</sub>. Several other plumes were detected over the 3-day period capturing both active burning and smoldering behaviors.

< C3) Characterization of Atmospheric Radiation Measurement Systems	up	C5) Participation of ACOM scientists in the University-led WINTER (Wintertime INvestigation of Transport, Emissions, and Reactivity) campaign >
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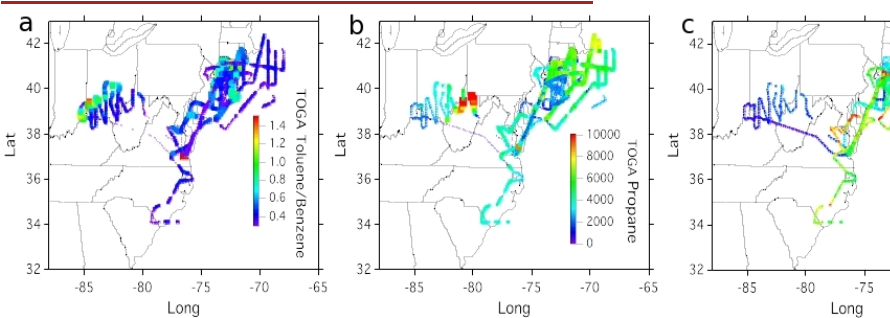
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C5) PARTICIPATION OF ACOM SCIENTISTS IN THE UNIVERSITY-LED WINTER (WINTERTIME INVESTIGATION OF TRANSPORT, EMISSIONS, AND REACTIVITY) CAMPAIGN

WINTER was an atmospheric chemistry campaign led by the University of Washington, with participation from ACOM scientists who provided key measurements of nitrogen oxides, ozone, methane, CO, CO<sub>2</sub> and VOCs. The campaign focused on wintertime emissions and chemical processes in the Northeastern US. The three main goals of the project were:

- (1) to characterize the chemical transformations of wintertime emissions with an equal focus on nocturnal and multiphase processes as on photochemistry;
- (2) to assess the dominant mechanism of secondary aerosol formation and quantify the geographical distribution of inorganic and organic aerosol types during winter; and
- (3) to provide constraints on wintertime emission inventories for urban areas, power plants and agricultural areas, and characterize the export pathways of primary pollutants to the North Atlantic.

WINTER used the NSF/NCAR C-130 based at NASA Langley in Hampton, VA to address these goals. Operation of the C-130 during winter in the Northeastern U.S. allowed comprehensive sampling, in one campaign, of 1) large urban/industrial plumes of nitrogen oxides, VOC, and sulfur from the Northeast corridor as it is advected off the coast, 2) coal-fired power plants throughout the eastern U.S. including the Ohio River Valley and along the East Coast, and 3) distributed emissions from oil and gas extraction, agricultural or biofuel burning, and vegetation in the mid-Atlantic and southeast U.S. The figure below shows the C130 flight tracks for flights 1-8 combined, colored by various tracers measured by the ACOM Trace Organic Gas Analyzer (TOGA) instrument.



**Figure 1.** Panel (a) shows measurements of the toluene/benzene ratio. Higher values indicate fresher emissions with lower values the result of chemical transformations. The freshest emissions were generally seen in the Ohio River valley and off of the Eastern seaboard. Panel (b) shows TOGA propane measurements showing very high values in northern West Virginia as a result of oil and gas operations but high values were also observed off of the coast of New England, apparently indicative of widespread use of LPG fuel in the area. Panel (c) shows TOGA HCN measurements (biomass burning tracer) showing evidence of widespread influence in the region from biofuel burning, most likely

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the result of many diffuse sources in the wintertime.

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< C4) Manitou Experimental Forest Observatory (observations of oxygenated VOCs and fire emissions)

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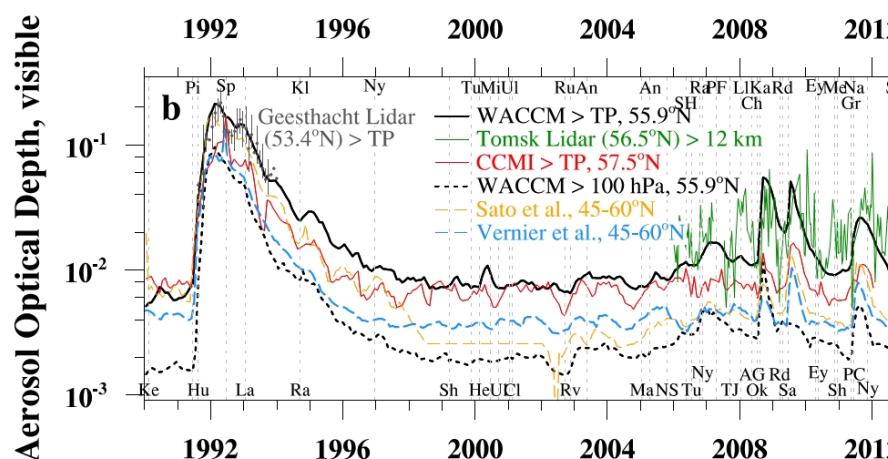
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## D1) DEVELOPMENT OF A NEW PROGNOSTIC CAPABILITY FOR STRATOSPHERIC AEROSOLS AND STRATOSPHERIC AEROSOL OPTICAL DEPTH IN CESM

Volcanic aerosols and solar variability are the dominant natural drivers of climate variability. Volcanic emissions of sulfur-bearing gases produce aerosol particles that scatter sunlight back to space, cooling the surface and atmosphere below them. When volcanic aerosols reach the stratosphere in significant quantities, such cooling effects can persist for several years and can become global in extent. The rate of stratospheric ozone loss due to human emissions of ozone-depleting gases is also modulated by chemical reaction on volcanic aerosols in the stratosphere.

Attribution of climate variability to volcanic activity is of particular interest in relation to the post-2000 slowing in the rate of global average temperature increases. Observations have recently revealed increases in stratospheric aerosol linked to a series of relatively small-magnitude eruptions since 2005. The coincidence of these increases with a slower rate of increase of globally averaged surface temperatures has led to attributions of their role in contributing to a reduced rate of global warming over the decade of the 2000s.

We have compiled a database of volcanic emissions for eruptions from 1990 to 2014, and developed a new capability for simulating stratospheric sulfate aerosols in the Community Earth System Model (CESM). We used these combined with other non-volcanic emissions of sulfur sources to reconstruct global aerosol properties from 1990 to 2014. Our calculations show remarkable agreement with ground-based lidar observations of stratospheric aerosol optical depth (SAOD), and with *in situ* measurements of stratospheric aerosol surface area density (SAD). These properties are key parameters in calculating the radiative and chemical effects of stratospheric aerosols. Our calculations represent a clear improvement over available satellite-based analyses, which generally ignore aerosols below 15 km, a region that can contain the vast majority of stratospheric aerosol extinction at mid- and high-latitudes. Our new capability for simulating volcanic input will greatly improve calculations of climate change and ozone loss variability.



**Figure 1:** Stratospheric aerosol optical depths calculated in CESM(WACCM5) are compared to observations. Model calculated

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zonal mean AOD above the tropopause compares very well to lidar observations, shown here from the Pinatubo period (1991-93) in Germany and for 2005-13 in Russia. Climate models generally prescribe volcanic aerosols based on analyses of satellite observations (Sato et al. and Vernier et al. shown here), which neglect aerosol below 100 hPa due to cloud interference with satellite retrievals. The model indicates that at mid-latitudes this approach misses about 80% of the stratospheric aerosols, which are between the tropopause and 100 hPa.

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D2) Ethane emissions inventory >

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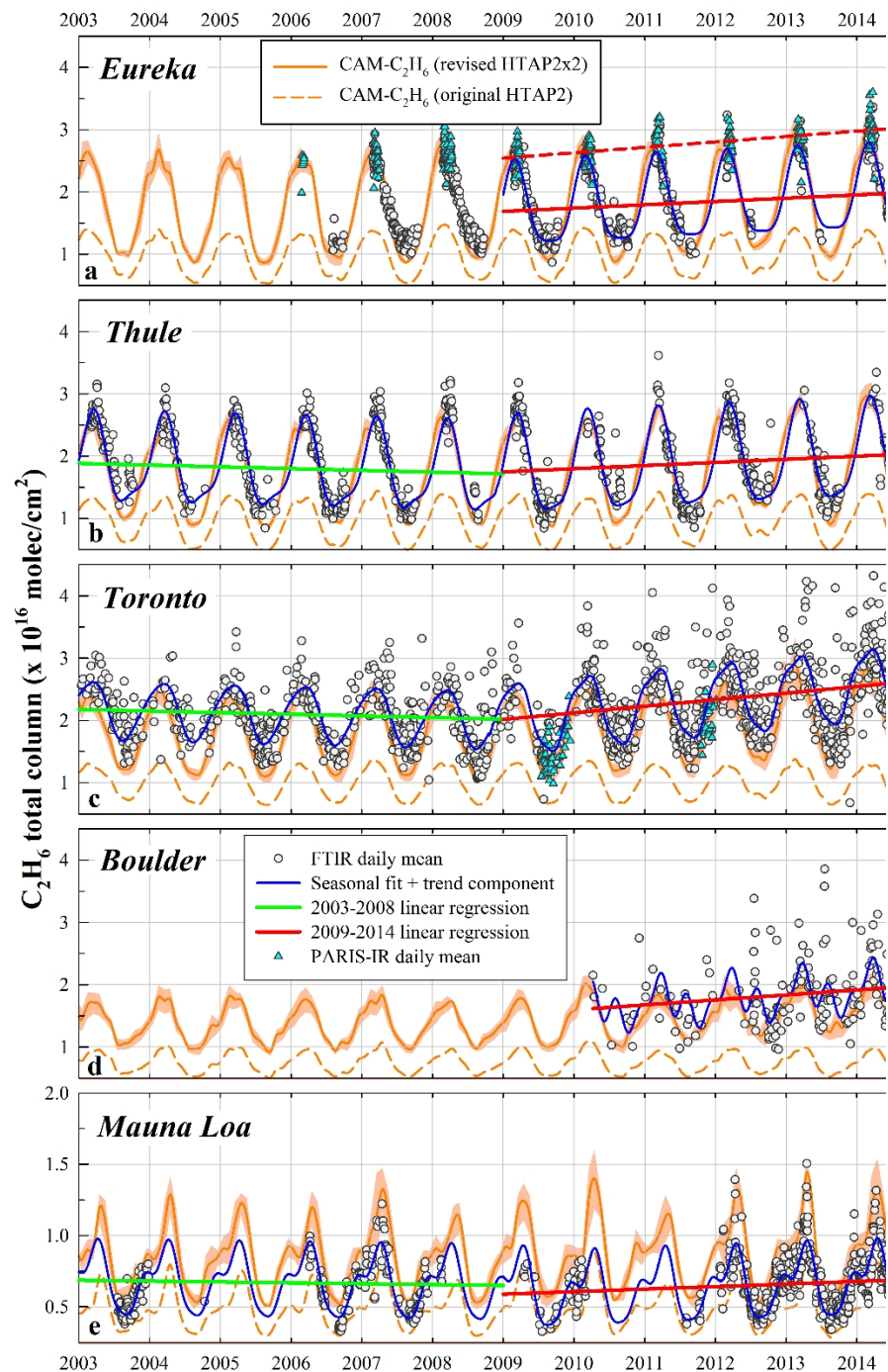
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## D2) ETHANE EMISSIONS INVENTORY

Ethane ( $C_2H_6$ ) is generally present in natural gas and its rate of emission to the atmosphere has increased in North America connected with the increase in oil and gas extraction activity. A variety of measurements have shown increased concentrations of ethane in the U.S. over recent years. Retrievals of ethane from FTIR measurements at several Northern Hemisphere (NH) sites (Thule, Boulder, Toronto, Jungfraujoch, Mauna Loa) have shown a consistent increase since 2009 while Southern Hemisphere sites (Lauder, Wollongong) have shown a slow decrease over the past couple of decades. Simulations with CAM-chem using standard inventories grossly underestimate the observed ethane amounts before 2009 and do not reproduce the NH increase since. Through these model-observation differences it was determined that the global anthropogenic emissions need to be roughly doubled. New simulations with this adjusted inventory, including an increase based on the observed trend, agree much better (see Figure 1). A linear increase of 0.2Tg/yr in North America emissions from 2009 accumulating to 1.2 Tg/yr by 2014 is required to match the observed secular increase. This implies an increase in methane emissions of approximately 15 Tg/yr from natural gas leakage and other activities related to oil and gas extraction.



**Figure 1.** Daily mean  $C_2H_6$  total columns derived from the FTIR (grey circles) and PARIS-IR (light blue triangles) observations performed between January 2003 and December 2014. The right y-axis scale converts the total columns into approximate surface mole fraction (see text for details). The blue curve visualizes the function (including seasonal modulation and trend component) fitted to all daily FTIR means over the periods 2003-2008 and 2009-2014, using a bootstrap tool (Gardiner *et al* 2008). The green and red lines are the associated linear regressions (as solid line for FTIR and dashed line for PARIS-IR). The dashed and solid orange curves are the monthly mean  $C_2H_6$  total columns simulated by CAM- $C_2H_6$ , implementing the original HTAP2 and revised HTAP2x2 (with increasing North American emissions) inventories, respectively. The shaded area corresponds to the  $1\sigma$  standard deviation. (from Franco *et al.*, to be submitted to Environ. Res. Lett.)

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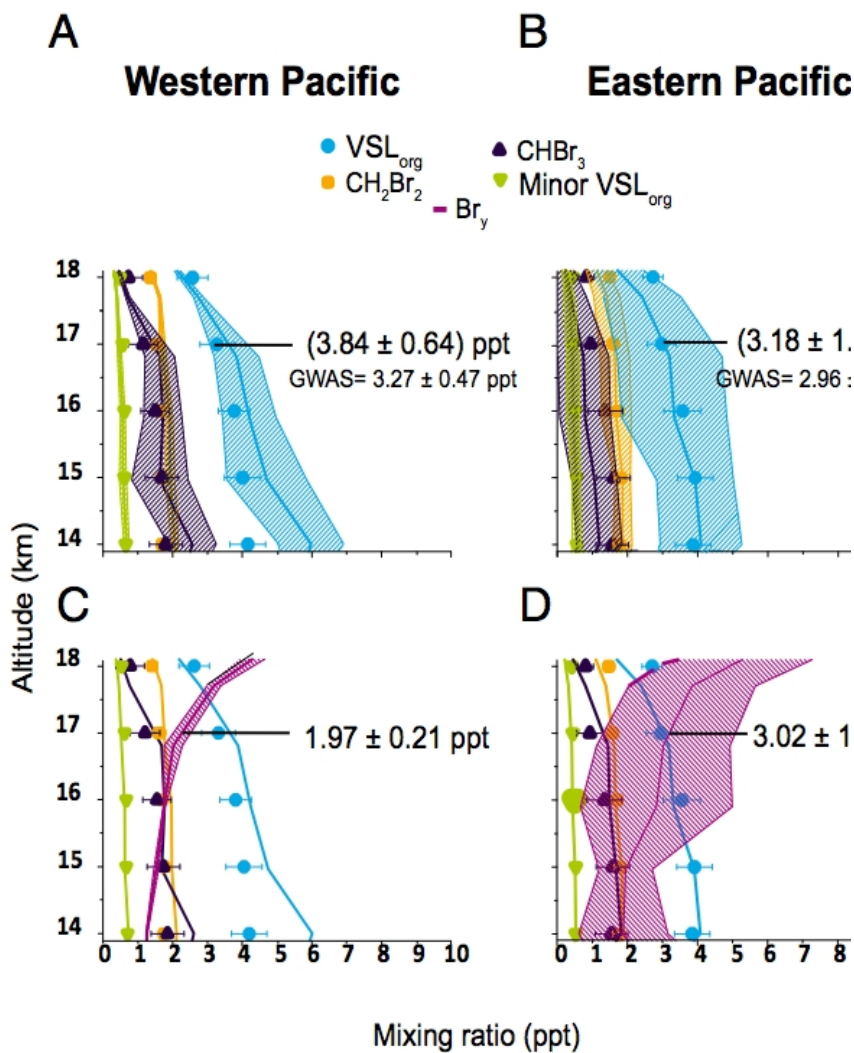
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## D3) EXPANDED REPRESENTATION OF HALOGENS IN CAM-CHEM

CAM-Chem is continuously being developed and applied to new research areas. In the example below, we are highlighting the expanded chemistry representation (to provide an explicit description of short-lived halogen species, Cl, Br and I, a long-term collaboration with A. Saiz-Lopez, Spain) and its use in analyzing the CONTRAST field campaign observations. In this case, the model can be evaluated against observations (see Figure below) and then applied to provide an understanding of the observed behavior. In particular, the recently published paper by M. A. Navarro and collaborators tackles the question of why the distribution of upper-tropospheric reactive bromine differs between the Eastern and the Western Pacific basins (<http://www.pnas.org/content/112/45/13789.full.pdf>). More specifically, this study reports an extensive set of in situ measurements of natural organic bromine species at the tropical tropopause. Compared with prior estimates, this study reduces the uncertainty of the contribution of reactive bromine to stratospheric ozone depletion. The study focuses on comparing measurements over the Eastern and Western Pacific, two regions characterized by different transport dynamics, to show the influence of convective events on the chemistry of the tropopause region. Using measurements and modeling, it describes the budget and partitioning of bromine at the tropical tropopause and evaluates the contribution of bromine to ozone destruction in the lower stratosphere.



**Figure 1.** GWAS measurements and CAM-Chem simulations  $\pm 1$  SD. Filled symbols are the 1 km average bins from GWAS measurements. Lines are the CAM-Chem simulation. Values from the arrows represent the mean mixing ratio (ppt) of VSL<sub>org</sub> and Br<sub>y</sub> at the tropopause level (~17 km) derived from CAM-Chem simulations. (A and B) Organic brominated species multiplied by their atomicity for (A) Western Pacific and (B) Eastern Pacific. (C and D) CAM-Chem estimations of inorganic bromine (Br<sub>y</sub>) from measured brominated VSLs with shaded  $\pm 1$  SD for (C) Western Pacific and (D) Eastern Pacific.

< D2) Ethane emissions inventory

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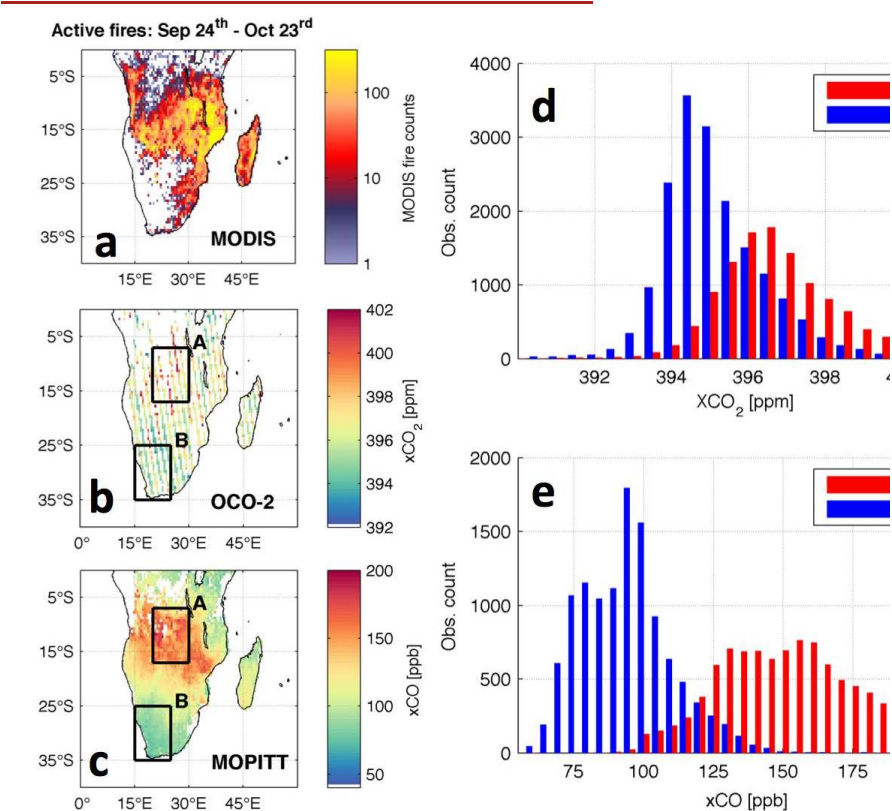
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E1) COMBINING MOPITT AND OCO-2 DATA TO ESTIMATE COMBUSTION EFFICIENCY OF SOUTHERN AFRICAN FIRES

MOPITT v5J multispectral carbon monoxide (CO) measurements were used with recently available OCO-2 carbon dioxide (CO<sub>2</sub>) measurements to study the combustion efficiency of Southern African fires. OCO-2 launched on 2 July 2014 and began global observations on 6 September 2014, allowing a unique satellite perspective on CO<sub>2</sub> emissions from these fires. MOPITT CO provides a critical constraint for both identifying enhanced CO<sub>2</sub> from fires and partitioning the carbon released from the burned biomass that is emitted as CO<sub>2</sub>, CO and other species. A first paper that exploits the combination of MOPITT and OCO-2 data was recently submitted to GRL by A. Bloom et al. This study estimates the CO<sub>2</sub>:CO emission factor ratio as 16:1 ± 56%(mol/mol), which is consistent with bottom-up fire emission inventories, model simulated fire plumes, and in-situ fire plume measurements.



**Figure 1.** (a) MODIS total fire counts (b) OCO-2 mean dry-column CO<sub>2</sub> concentration and (c) MOPITT mean dry-column CO concentration at 0.5°×0.5° during 24 Sep. - 23 Oct. 2014. Histograms of dry-column CO<sub>2</sub> (d) and CO (e) within areas A and B shown in panels b and c. From Bloom, et al., submitted to GRL, 2105.

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  - F1) Understanding the seasonal cycle and impacts of Black Carbon aerosols in India
- ▶ NCAR Imperative 6: Educate and entrain a talented and diverse group of students and early career professionals.

## F1) UNDERSTANDING THE SEASONAL CYCLE AND IMPACTS OF BLACK CARBON AEROSOLS IN INDIA

Black carbon (BC) aerosols in the atmosphere are a concern for climate because of its ability to absorb incoming solar radiation and for air quality because the fine particles affect human health. BC is emitted from burning of fossil fuels (such as diesel fuels) and biomass, such as crops and forests. BC aerosols are of special concern in Asia where emissions are significantly greater than the rest of the world. In India, observations show that black carbon concentrations at the surface are generally higher in winter than in summer.

ACOM scientists led a study to determine what controls the seasonal cycle of BC concentrations by conducting simulations over India with the Weather Research and Forecasting model coupled with chemistry (WRF-Chem). The study used BC mass concentration observations from 21 sites across India to validate the WRF-Chem results. Four conclusions were drawn from the model results. First, the seasonal cycle of BC surface concentrations is driven mainly by seasonal changes in meteorology and not by seasonal changes in emissions. Second, the model results showed that 60% of BC emissions are from the residential emissions sector; that is burning for cooking and heating in homes. Thus, the Indian government providing subsidies on liquefied petroleum gasoline (LPG) to the poor and its focus on boosting solar energy will immensely help bring down black carbon emissions. Third, the seasonal cycle of BC in the free troposphere (3-15 km altitude) is opposite to that of surface BC concentrations (the highest BC concentrations in the upper troposphere are in summertime). This result indicates that BC aerosols remain closer to the Earth's surface and can be more dangerous to human health during winter compared to during the summer monsoon period of June-September when they are distributed up to a higher height in the atmosphere. The fourth conclusion is that regional transport significantly impacts the BC distribution. For example, BC emissions from northern India contribute up to 30 percent to BC surface concentrations in southern India during the winter, while southern India makes a similar contribution to northern India during the summer monsoon season.

The regional contribution of BC to local regions is important for developing mitigation strategies to improve air quality in India. Individual states in India cannot design their own mitigation efforts alone to improve air quality, but instead regions, comprising several Indian states, must act together to reduce air pollution. For example, Bihar cannot mitigate its air pollution most effectively without support of the nearby states Uttar Pradesh and West Bengal.

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**Figure 1.** Haze from urban and industrial pollution, as well as agricultural and wildland fires (red dots), can be seen over northern India below the Himalayan mountain range in this satellite image from October 2014. (Photo courtesy [NASA](#).)

< NCAR Imperative 5: Develop and transfer science to meet societal needs. up NCAR Imperative 6: Educate and entrain a talented and diverse group of students and early career professionals. >

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G1) Atmospheric Composition and the Asian Monsoon (ACAM) Workshop and Training School

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G1) ATMOSPHERIC COMPOSITION AND THE ASIAN MONSOON (ACAM) WORKSHOP AND TRAINING SCHOOL

As a weather pattern, the Asian monsoon impacts the lives of more than a billion people. With rapid population and economic growth across the monsoon region, it is clear that monsoon convection coupled to surface emissions becomes a significant process, bridging regional air quality, climate change, and global chemistry-climate interactions. Collaborative efforts involving monsoon-region countries are a critical step in characterizing and quantifying the regional and global impact of the system. To facilitate collaboration and to connect scientists with diverse expertise and interests in understanding the complex interplay between monsoon dynamics and atmospheric composition, the Atmospheric Composition and the Asian Monsoon (ACAM) initiative is jointly sponsored by SPARC/IGAC. NCAR ACOM scientists are playing significant scientific and community and capacity building leadership roles in the formation of this initiative.

Building on progress from the initial workshop held two years earlier in Kathmandu, the 2<sup>nd</sup> Atmospheric Composition and the Asian Summer Monsoon (ACAM) workshop was held June 8-10, 2015 in Bangkok, Thailand. One hundred and seventy scientists representing 22 countries attended this workshop. Scientific discussions were focused on four themes:

- Emissions and air quality in the Asian monsoon region
- Aerosols, clouds, and their interactions with the Asian monsoon
- Impact of monsoon convection on chemistry
- UTLS Response to the Asian Monsoon.

Community building activities were through the formation and growth of four ACAM working groups:

1. Organize data for sharing ACAM relevant measurements
2. Form a partnership with the CCMi and AeroCom communities
3. Field campaign concept development and coordination
4. Develop training opportunities for ACAM regional young scientists on the use of models and satellite data

Following the 3-day workshop, the first ACAM training school was held on “Satellite and Model Data use for Aerosols and Air Quality”, hosted at the Asian Institute of Technology, Bangkok. Specific goals of the event were to train and build the capacity of early career scientists in Asia for effective utilization of satellite and model data relevant to studying aerosols and air quality in Asia, particularly in connection with the Asian monsoon. There were 33 participants (including 11 females), representing 12 Asian countries, at the training school. The school not only reached out to multiple countries but also to multiple institutions. The training school brought together international experts in satellite remote sensing and modeling to provide focused tutorials on aerosols, air quality, trace gases, emissions and transport.

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The ACAM workshop and training school were sponsored by a number of national and international organizations including IGAC (IGBP), SPARC(WCRP), NIES (Japan), ICIMOD (a Kathmandu based International center), IASS (Posdam, Germany), NSFC (China), IAMAS, NSF (USA) and NASA (USA).



**Figure 1.** International Sponsorship for ACAM workshop and training school.

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DIRECTORS MESSAGE

The mission of the Advanced Study Program is to help NCAR, and the university community it serves, prepare for the future. To do this ASP programs and activities strive to foster the professional development of early career scientists, promote advanced scientific educational opportunities at NCAR, focus attention on emerging areas of science and facilitate interactions between NCAR, universities, and the broader community.

The two-year ASP Postdoctoral Fellowships aim to further the development of early career scientists in the field of atmospheric and related sciences through their collaboration with NCAR scientists and research programs. Approximately 10 new appointments are made annually for positions across NCAR. Fellows' research advances are reported separately in the NCAR Laboratory Annual Reports.

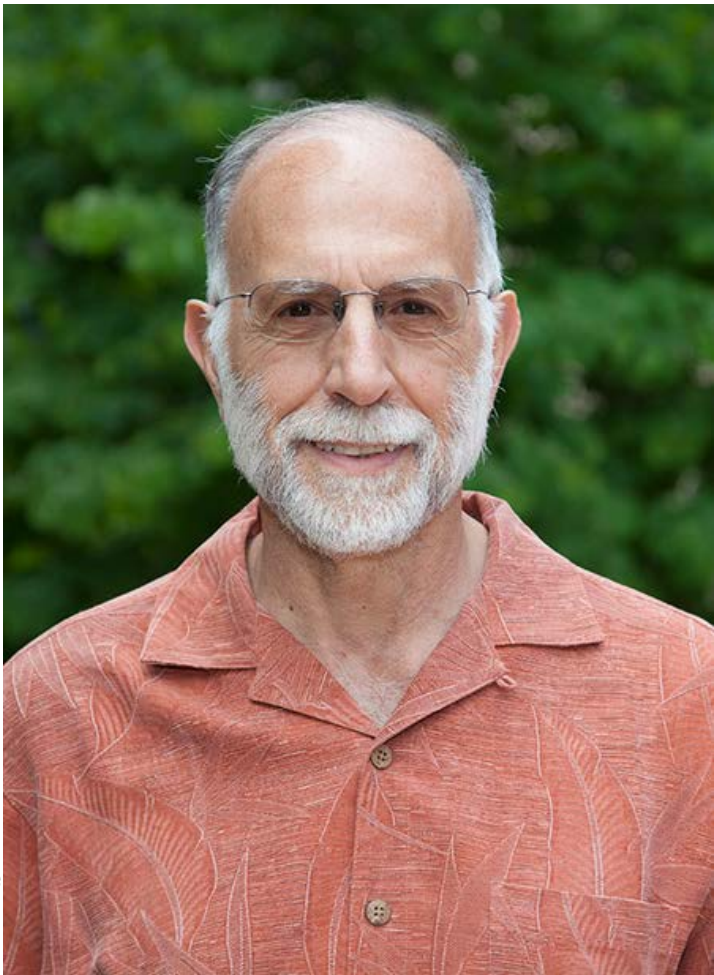
Through its remaining components, the Graduate Visitor Program (GVP), the Faculty Fellowship Program (FFP), and the Summer Colloquium, ASP promotes research activities, fosters graduate education, and develops partnerships between NCAR scientists and their colleagues in universities and other institutions.

ACCOMPLISHMENTS

The ASP awarded 11 new postdoctoral fellowships in Spring 2015. These new fellows have already begun to arrive and to participate in ASP activities, providing a boost to the ongoing program. Between the FFP and the GVP, the ASP supported 116 months of long-term visits to NCAR in FY15. Most of the GVP awards also include an advisor visit.

Finally, the ASP supported the Software Engineering Assembly (SEA) conference on scientific computing and software development that included 130 participants from NCAR, other scientific agencies and several students from Minority Serving Institutions (MSIs).

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



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FY2016 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, weekly Postdoc Teas, 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. Dr. Ian Faloona from the University of California, Davis will be here in December and Dr. Richard Seager from the Lamont-Doherty Earth Observatory at Columbia University will visit in Spring 2016.

The annual ASP Colloquium series will focus on the topic of *Advances in Air Quality Analysis and Prediction: The Interaction of Science and Policy*. Students will stay for two weeks to participate in lectures and hands-on activities.

ASP will support the NCAR Software Engineering Assembly’s fourth conference and also provide organizational support for the activities of the Early Career Scientists Assembly (ECSA).

ASP will continue to promote diversity in the atmospheric sciences by supporting travel of NCAR scientists to give seminars at MSIs, supporting teaching opportunities of NCAR postdocs at MSIs and encouraging participation in ASP programs of individuals from underrepresented groups. ASP will participate in and support an NSF-supported workshop on postdoctoral professional development in FY2016.

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

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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 fifty years and has sponsored over 500 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 FY15, the ASP appointed 11 new fellows (from over 120 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 FY2015, the ASP scheduled several events that included an education or career development aspect including a panel discussion entitled "Career Tracks for Ph.D.’s" at our annual retreat. These activities not only brought members of ASP together, but also included any postdoctoral fellow or graduate student within the organization who wished to attend.

The ASP aims to create a meaningful experience not only for ASP fellows, but for all fellows at NCAR. As part of this plan, NCAR/ASP is a sustaining member of the National Postdoctoral Association.

In FY2015, ASP plans to continue the core elements of the program, including monthly seminars, regular research reviews, regular career development activities, and the Thompson Lecture Series along with the annual research planning sessions and on-going mentoring that ASP postdocs receive.



*NCAR/ASP Phil Thompson Lecture Series, Dec. 9-12, 2014  
with Ulrike Lohmann, Swiss Federal Institute of Technology, Zurich*

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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 FY15, applicants submitted proposals and budgets for 3- to 12-month visits that occurred between 1 June 2015 and 31 May 2017. ASP received 11 viable applications. Seven applicants were extended offers for visits that began in FY15. Included with the faculty visits were six visits made by students. **We supported 18 months of faculty/scientist visits through this program in FY15.**

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.

One of the eleven applications was from an NCAR Scientist whose request was to go to Boston University to teach. That visit will begin in January 2016.

TESTIMONIALS FROM FY15 PARTICIPANTS:

**Guido Cervone**  
The Pennsylvania State University

Impact on Research:

I had a terrific time at NCAR, and it was very productive. First of all, I worked very closely with Drs. Haupt, Delle Monache and Alessandrini at RAL. I interacted with them daily, and they were very generous with their time, both during and after office hours. Our research led to two articles already published, and submitted two more that are currently under review. Furthermore, I was able to work closely with Dr. Del Vento from CISL, and he helped me parallelize my code to work on the Yellowstone supercomputer. I was able to take advantage of a scheduled downtime, and I run my simulations on 140,000 cores. This extreme level computing is paramount for my research, and I would have never been able to perform such simulations without the ASP program.

During my stay I was able to prove the the AnEn algorithm developed at NCAR/RAL scales to extreme scale computing. I profiled the algorithm, and showed that with a 95% parallelization we can achieve a 20x speedup over normal computations. This is an important result to use the AnEn algorithm operationally. Furthermore, because of this extreme parallelization possible, we have made plans to extent the AnEn to 2D. This is considered a very hard scientific and computational problem, that could not be solved without an efficient algorithm.

In addition to myself, ASP supported 1 graduate student — Laura Harding –

- who set the basis for her Ph.D. research. I was also able to support through various grants 6 more students (Yanni Cao, Elena Sava, Carolynne Hultquist, Anna De Angelis) and postdocs (Mark Coletti and Gabriella Ferruzzi), who spent between 1 and three months at NCAR. Overall, I was able to bring my

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entire group of 8 people to NCAR, and each achieved stellar research accomplishment. Although they were not directly supported by ASP, it is undoubtable that if I was not awarded the ASP, they would not have been able to spend time at NCAR. I am attaching a picture of us in front FL2. (I actually showed this picture to Eric Barron, the former director of NCAR and current director of PSU, and he was pleased of this collaboration).



### Impact on Career:

My relationship with NCAR is fundamental for my career. I am listed as affiliated scientist of NCAR, and my Department was recently added to the list of UCAR governing departments. Through this collaboration I am able to apply my research knowledge to problems related to renewable energy that are new research domains for me and my group. I believe this is a very symbiotic relationship in which I offer my geo-spatial analytics skills, and NCAR provides data and domain specific knowledge. Furthermore, I consider NCAR a 'well oiled machine', and it showed me how I should setup and operate my own laboratory. The program helped me by expanding my research horizons to new problems related to renewable energy, brining my entire laboratory to Boulder for about three months, and establish collaboration with top scientists in the fields. It also helped me meeting new people, who I consider very dear friends. It also allowed me to help NCAR, by providing solutions for geo-computational problem. I really believe that I was able to speedup the algorithm considerably, and thus prove its feasibility to problems that require efficient near real time computing. Furthermore, collectively me and my 7 post/docs and students wrote 12 journal articles in 3 months, most of which are co-authored with NCAR scientists, four of which have already been published.

It was a dream come true!!! I hope to be able to repeat this experience again. If I did not already love my job, I would certainly apply to NCAR!

**Diego Riveros-Iregui**  
University of North Carolina, Chapel Hill

As an early career faculty and ASP FFP fellow, I was able to focus on and make progress toward my research program for an entire semester. Thanks to the support from NCAR and the teaching release from my institution, this semester I was able to write and submit two research proposals and four research articles (one of which was accepted recently). The accomplishments of my visit at NCAR will be



central in the expansion of my research program in the coming years, and I am confident my current and future students will benefit from the achievements of this visit. Also, the FFP allow me to spend time in Boulder where I was able to interact frequently and explore new collaborations with scientists from CU Boulder, Colorado School of Mines, and Colorado State University, something very valuable for my career.

**Ken Minschwaner**  
New Mexico Tech

My involvement in the NCAR/ASP Faculty Fellowship Program for 2015 allowed me to make significant progress in two ongoing research projects and stimulated new work in at least two other research areas.

One of the most important aspects of being in residence at NCAR is access to an incredible diversity of knowledge and expertise within NCAR's staff and scientists. Within the Atmospheric Chemistry Observations and Modeling (ACOM) Division alone, I was able to attend at least two scientific talks per week, including Division seminars, bi-weekly Research Reports, bi-weekly satellite group talks, and weekly tropospheric chemistry talks. I also participated in monthly telecons with NASA's Discover-AQ project through a collaboration with ACOM scientists. Similarly, the Front Range's unique concentration of research in atmospheric science provided multiple opportunities for disseminating my research: two seminars/group talks at NCAR, two at NOAA's Earth System Research Laboratory, and one at Colorado State.

For my ongoing research projects, being in residence at ACOM allowed me to discuss ideas and obtain critical feedback for revising two scientific papers that were resubmitted during this time. One paper, "Signature of a tropical Pacific cyclone in the composition of the upper troposphere over Socorro, NM", was recently accepted for publication in Geophysical Research Letters. The other paper, "The Upward Branch of the Brewer-Dobson Circulation Quantified by Tropical Stratospheric Water Vapor and Carbon Monoxide Measurements from the Aura Microwave Limb Sounder", is currently under review in the Journal of Geophysical Research, Atmospheres. These two papers benefited tremendously from discussions with both staff scientists and visiting scientists at ACOM.

Two new research investigations were launched during my visit. The first involved comparisons between satellite measurements of nitric oxide in the thermosphere with results from the WACCM model. The model runs have been executed and the output sampled at the times and locations of the satellite measurements. Analysis of the results is ongoing. The second project involves a totally new research direction for me: analysis of the impact of oil and natural gas activity on air quality, and an assessment of fugitive methane release. This work involves analysis of aircraft and ground-based data from the 2014 FRAPPE mission. I anticipate that one or both of these projects may lead to opportunities for submitting future proposals to obtain support for graduate students to continue working on these problems.

**Greg McFarquhar**  
University of Illinois

My participation in the Faculty Fellowship Program (FFP) has been beneficial to research being conducted by myself and the 3 graduate students who are accompanying me on my sabbatical. Each student has had significant interactions with NCAR scientists. Student Wei Wu has been interacting with Xulin Xue of RAL and Wojtek Grabowski and Hugh Morrison of MMM to compare cloud microphysical properties observed by aircraft in the stratiform regions trailing deep convective systems against those produced by numerical models using both bin-resolved and bulk microphysical parameterization schemes. Wei has also been using the modeling codes to understand sources of discrepancies between model parameterization schemes. Student Joe Finlon has been working with Roy Rasmussen of RAL to compare measurements from the Meteorological Particle Spectrometer (MPS) recently purchased by the University of Illinois to those from several instruments at NCAR's Marshall site. He will use data to be collected in snow this winter to determine relationships for how snowflake mass varies as a function of its maximum dimension, a quantity needed for parameterizations for numerical models and remote sensing retrievals. And, graduate student Shichu Zhu has been working with Jeff Stith of RAF to improve algorithms used to process data collected by airborne cloud probes. In particular, he has been using data collected in liquid clouds during the Cloud Systems Evolution in the Trades (CSET) field experiment to determine differences in algorithms developed by NCAR, the University of Illinois, and a private company to derive cloud products. I have also been interacting with NCAR scientists to establish future collaborative

projects that will hopefully continue long after the FFP ends. With Wojtek Grabowski and Hugh Morrison of MMM, I have been developing a strategy for implementing relationships between cloud microphysical parameters that I have represented as volumes of equally realizable solutions into a stochastic framework within Morrison’s existing microphysical parameterization schemes. We are writing a proposal to the Department of Energy Atmospheric Systems Research (DOE ASR) program that we hope will support this research. With Andy Heymsfield and Carl Schmitt of MMM, I have also been developing research questions that would be appropriate for answering with deployment of the DOE Atmospheric Radiation Measurement (ARM) Program’s Mobile Facility on a glacier in Nepal: we hope to submit a proposal requesting support for this deployment within the next year. I will also work with Andy Heymsfield and Aaron Bansemer on analysis of data to be collected during the upcoming Olympic Mountain Experiment (OLYMPEX). With personnel at RAF, I have been developing flight sampling strategies and instrument payloads most appropriate for answering questions on the nature of ubiquitous mixed-phase clouds that form in pristine environments over the Southern Oceans in a project entitled the Southern Ocean Cloud Radiation Aerosol Transport Experimental Study (SOCRATES), for which we will request the use of the G-V in New Zealand in January 2018 from NSF. I am also working with Jeff Stith on analysis of small crystal shapes collected in the recent DC3 experiment to test whether aggregation of heterogeneous freezing is most responsible for the production of these small particles. It is also hoped that some more collaborations and student projects will emerge during the last half of my sabbatical visit.

**Leon Ofman**  
Catholic University of America

I am writing to thank the FFP program for the opportunity to visit HAO for three months this summer. The HAO is one of the greatest places in the world to work on solar physics research thanks to the leading scientists and experts that work there, inspiring research environment, and the nice location in Boulder, CO. During my visit, I collaborated with Dr. Scott McIntosh, and others on modeling the wave-driven solar wind in the lower corona using the numerical codes I have developed, guided by observational data from the CoMP instrument. This work is now in progress towards publication in a research paper. I have also collaborated with Dr. Sarah Gibson on implementing the results of the solar wind modeling with the FORWARD code under development at HAO that calculates how the corona would look in various instruments that observed the corona, such as CoMP instrument built at HAO. These collaboration helped develop my research in theoretical and computational solar wind modeling by providing connection to real coronal observations. I have enjoyed attending the many seminar, colloquia, and workshops in solar physics and related fields that took place at HAO this summer. These meetings expanded my horizons and I was inspired by hearing experts in solar physics and related fields share their knowledge. I have also benefited from the very friendly atmosphere at HAO, where I had many informal conversations with staff members and other visiting scientists during lunches, coffee breaks, and other informal gatherings. Finally, I would like to thank the staff that handled smoothly the administrative sides of my visit, in particular, Paula Fisher, Megan Delaney, the visitors' housing office at NCAR, and Chelsea Castellano for handling the Blue Bike request. I hope there would be another opportunity for a summer visit at HAO in the future.

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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 tenth 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.

The ASP made 16 awards in the GVP program as a result of our FY2015 GVP competition. ASP supported 99 months of GVP visits and 14 advisor visits in 2015.

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

FY15 TESTIMONIALS

**Emily Saunders**  
Howard University

During my time at NCAR I learned and grew so much as not only a scientist, but as a person as well. When my advisor, Dr. Stockwell, mentioned this program to me last year I must admit I was a little apprehensive. I had many doubts about how everything would play out when I arrived at NCAR. I had never heard of Boulder, Co and how was I going to accomplish all of my research goals during my time there. I was in a strange town and away from the comforts of my friends, family, and colleagues at Howard University. I must say that the moment I was accepted to the program I was welcomed with open arms by everyone I encountered at NCAR. Even though I was in a new town and working at a new place I felt like I had been working at NCAR for years. The administrative, housing, and travel offices made sure my transition into the NCAR family was smooth and that dedication made me feel like my time at NCAR would be a great learning experience.

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The graduate visitor program in my opinion pushes graduate students to figure out how to accomplish their research goals and learn new ways to carry out your research goals. During my time at NCAR I was able to successfully accomplish my research goal of creating a global atmospheric chemistry mechanism as well as learning how to use WRF-CHEM to test the validity of my mechanism based upon the output data I would receive from running a Wrf-Chem case. My time at NCAR helped my research immensely in terms of giving me the insight I need to continue my research towards my dissertation. The skills and tools I have obtained from my advisors at NCAR will be extremely beneficial to me throughout the rest of my graduate as well as professional career. My time at NCAR was one of the best learning experiences in my life and I highly recommend any future graduate students to be open to change and soak up all the knowledge they can during their time there.

**Lotte Bierdel**

Ludwig-Maximilians Universität München

The Advanced Study Program gave me the opportunity to visit NCAR for half a year and work on a specific research question related to my PhD work at the LMU Munich. The results of the study I conducted in collaboration with Chris Snyder deepened my insight into mesoscale dynamics and supported the results of my PhD thesis. Learning about the opinion of scientists working at NCAR about my PhD thesis and the study I conducted at NCAR as well as experiencing their working methods was very inspiring and instructive. Furthermore, the regular meetings of all the students participating in the ASP program with Rich Rotunno gave me the opportunity to get to know other international and motivated students with whom I could exchange my experiences regarding my PhD work and the work at NCAR in a more private setting. Being used to working on my PhD at a university institute, working at NCAR as a leading research institute in the field of atmospheric sciences was a unique opportunity for me to get to know a different very productive working environment. The research I conducted during my stay at NCAR resulted in a manuscript which will soon be ready to be published. I expect the scientific community to benefit from the results of my research through the new understanding of mesoscale dynamics that can arise from the application of the methods that were tested in my study. I consider publishing a study together with Chris Snyder as an excellent scientist from NCAR and having had the honor of being selected to participate in the ASP program as beneficial for my further career. Additionally, attending colloquia given by international speakers and meetings as well as talking to scientist working at NCAR broadened my scientific context and was an important personal experience. I expect the contacts I made with NCAR scientists and other international students that participated in the ASP program to lead to further collaborations and future visits or longer term stays at NCAR.

**Hrishikesh Chandanpurkar**

University of California, Irvine

The visit to NCAR mesa-lab facility under the ASP program has been a wonderful experience. The visit has been very beneficial to my PhD research, as I expect my work here to comprise about 1/3<sup>rd</sup> of my thesis. The facilities at NCAR provided me with sufficient infrastructure to conduct modeling experiments at a scale and speed which would have been difficult to achieve in my university. My ASP host, Dr. Steve Yeager, is always accessible for brainstorming, and has guided me through the nitty-gritties of ocean modeling (which is not my background) that would have taken a long time to learn on my own. Within a short time, thanks to my host and the infrastructure provided by ASP, I was able to conduct not just several ocean modeling experiments, but also learn the logistics of working with large clusters and dealing with large files. Plus, presenting my findings in section meetings and in CGD Research Reports evoked wide feedback which was extremely helpful for (and has been incorporated into) my research. Finally, the visit is giving me the experience of working in a non-university setting, and gives me insights into the work life of full-time scientists. The visit has helped me connect with several brilliant scientists and has facilitated discussions and collaborations, which I am sure will help my post PhD career.

**Xia Chu**

University of Wyoming

I found this to be a very valuable experience. University of Wyoming does not have expertise on WRF LES modeling, which meant that I couldn't move forward on this part of my research if I didn't participate in the Graduate Visitor Program in ASP. I not only get tremendous help from my host here, but also from a lot of other scientists. Because there are a lot of top scientists here, when I encounter a problem, I have

always been able to find someone who is expert in this area and ask for advice.

This is also a good opportunity to make connections with other researchers who could possibly become collaborators in the future.

**John Volk**  
University of Nevada Reno

I am very grateful for having the opportunity of the NCAR GVP. During my visit I was given the privilege to closely interact with leading scientists in my field as well as specialists who work with NCAR high performance scientific computing resources. As a result of their expertise, technical assistance, and the pleasant working conditions at NCAR I made significant progress towards my doctoral research. During my visit several new connections with colleagues and friends were made among NCAR researchers and fellow GVP participants. Getting to experience the unique culture of Boulder, CO was an added plus. Thank you for offering this great opportunity to all students.

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## ASP SUMMER COLLOQUIUM

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

In 2015, the summer colloquium was titled "Climate, Space Climate, and Couplings Between." This interdisciplinary colloquium included organizers from HAO, CGD, ACOM, and RAL.



The 2015 ASP summer colloquium was two weeks long and was attended by 25 Ph.D.. Sarah Gibson of NCAR was the key organizer along with co-organizers from NCAR Dan Marsh, Hanli Liu, Art Richmond, Giuliana de Toma, Rebecca Centeno-Elliott, Bette Otto-Bliesner, Wiebke Deierling, Jean-Francois Lamarque and Organizers from CU including Cora Randall and Peter Pilewskie

The ASP Summer Colloquium brought together graduate students from both Atmospheric Science and Solar & Space Physics programs to study the interrelated subjects of terrestrial and space climate, in



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particular regarding the response of both to long-term solar variability. The program began by laying a foundation of shared knowledge through basic subject tutorials on both sides. It continued with synthesis talks to explore concepts related to connections between these fields, and with focused research talks to build a picture of current hot topics and subjects of debate related to solar variability and climate/space climate research.



Students left with a stronger understanding not only of their own discipline, but of the other discipline be it Solar Physics or Atmospheric Science. Each student participated in hands-on tutorials and worked with a team on a relevant project which was presented at the end.



Group excursion to CU's Mountain Research Station

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## CGD DIRECTOR'S MESSAGE

The 2015 CGD-Laboratory Annual Report (CGD-LAR) highlights some examples of the exceptional results produced by Laboratory staff during the last fiscal year. This research significantly furthers the CGD mission "to discover the key processes of the Earth's climate system and to understand the interactions among them; to represent the knowledge in community models that effectively utilize computing advances; and to apply these models and observations to scientific problems of societal relevance.

This CGD-LAR focuses on activities that fall within the two NCAR Imperatives that most align with the CGD Strategic Plan; namely, Imperative 1 – Conduct innovative fundamental research to advance the atmospheric and related sciences; Imperative 3 – Develop, deliver and support a suite of advanced community models. Also included, as an illustration of the breadth of CGD, are activities related to Imperative 5 – Develop and transfer science to meet societal needs. CGD does contribute significantly to Imperative 6 – Educate and entrain a talented and diverse group of students and early career professionals. Related activities such as workshops and tutorials tend to be ongoing and are, therefore, described in the websites of both CGD (<http://www2.cgd.ucar.edu>) and of the Community Earth System Model, CESM (<http://www2.cesm.ucar.edu>). The correspondence of these CGD NCAR Imperatives to the CGD mission statement is not coincidental, but reflects the central role of CGD within NCAR.

In January 2015, the NCAR Earth System Laboratory (NESL) was dissolved and the Climate and Global Dynamics (CGD) became a separate Laboratory of NCAR. This reorganization should have been nearly transparent to most CGD staff, with minimal impact on its science. However, the transfer of administration functions from NESL to CGD, coinciding with the departure of CGD's lead Administrator as well as some Administrative support caused major upheavals and understaffing in the Administration team through to the end of FY2015. Although these issues are now being settled, the production of this 2015 CGD Laboratory Annual Report (CGD-LAR) was affected. In particular, previous mapping to NESL plans became obsolete, so it was decided to expend Administrative resources on mapping to the NCAR Strategic Plan as an investment in future reports. However, the scarcity of these resources means that only the base funded program has been included, leaving out about half the CGD science program supported by external awards. Activities within CGD often spread across two or more elements of the NCAR strategic plan, and in the CGD-LAR these appear only under the most appropriate topic.

Over the coming year, CGD will complete its transition to a Laboratory within NCAR with a fully staffed Administration Team. It will begin to produce its contributions to the Coupled Model Intercomparison Project (CMIP-6), update the Interdisciplinary Challenges of its strategic plan to better align with the NCAR Strategic plan, and continue its work on environmental issues that are already having significant



CGD Director: Bill Large.

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impacts on society. There will be new opportunities for collaborative research across NCAR and the wider community, prompted by the Grand Challenges issued in the NCAR Strategic Plan, which associated with prediction of hazards and their impacts, and with understanding the consequences of natural and anthropogenic climate and global change.

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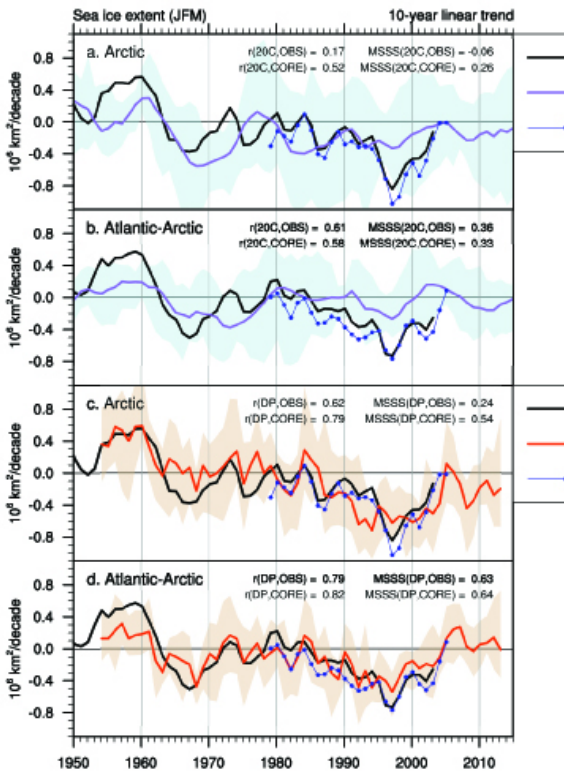
PREDICTABILITY LIMITS

CGD scientists discovered a striking pair of circumglobal teleconnection patterns responsible for heat waves over many regions in the Northern Hemisphere. These patterns are alternating series of upper level cyclonic and anticyclonic circulation centers. The anticyclonic centers are associated with heat waves.

Distribution and analyses of decadal hindcast and forecast simulations for the 1970-2024 period using CESM1 will facilitate comparison to available recent past climates for confidence in future decadal predictions. The model output will be made available to the community via the Earth System Grid Federation (ESGF). Accomplishments: Ten-member initialized decadal prediction ensembles using CESM1 (with CAM4) were run starting on January 1st of each year between 1955-2014, and integrated forward 10 years. The output from a subset of these simulations (corresponding to start dates 1961, 1966, 1971...1996, 2000-2006) has been made available on the ESG. This subset represents the CESM contribution to the CMIP5 decadal prediction protocol. A small subset of CESM1-CAM4 predictions initialized from ocean state estimates obtained using data assimilation (with DART) were also generated for comparison, but only for the start years 1975, 1980, ..., 1995, 200-2006. A new set of CESM1-CAM5DP simulations (spanning start years 1955-2014) that is currently underway will include prognostic ocean biogeochemistry and will be initialized from an improved ocean state estimate.

Completed hindcasts of seasonal 10-member ensemble forecasts initiated on a monthly basis from 1980 through 1996 as part of the calibration integrations for the CSEM1 contributions to North American Multi-Model Ensemble (NMME).

FY2015 efforts focused primarily on analysis of a set of CESM1-CAM4 decadal prediction ensembles (generated in FY2014) that were initialized each year between 1955-2014 (see description in section 6.1.1.2 above). This extended version of the CESM contribution to the CMIP5 decadal prediction protocol has helped to bolster the findings of Yeager et al. (2012) and Karspeck et al. (2014) that the subpolar Atlantic is a region of significant decadal-scale prediction skill. Recent work shows that significant decadal prediction skill extends to the marginal ice zones of the Atlantic, so that skillful forecasts of Atlantic (winter) sea ice extent trends seem feasible (Yeager et al. 2015). Analysis of the CESM1-CAM4 simulations has shed light on the mechanisms underpinning model skill in the North Atlantic as well as processes that limit forecast skill, such as poor near-term ENSO predictions that may be related to deficient ocean initial conditions. A new set of CESM1-CAM5 DP simulations (spanning start years 1955- 2014)



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that is currently underway will include prognostic ocean biogeochemistry, and will be initialized from an improved ocean state estimate.

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Spatial distributions of select 10-year trends in winter sea ice fraction and SST. Ten-year linear trends in winter (JFM) sea ice fraction (fraction/decade) and annual mean SST (°C/decade) over the periods a-h 1997-2007, and i-l 2007-2017 from observations (OBS), the CORE simulation (CORE), the CESM DP 10-member ensemble mean (DP), and the CESM 20C 6-member ensemble mean (20C). The trends in c,g (i,j) are computed from the single DP ensemble initialized on January 1 1998 (2008). Refer to supplementary text S1 for details of how CESM DP trends are computed. Shading gives the min/max range of the ensemble.

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## PROCESSES AND MECHANISMS

Incorporation of new components, parameterizations, and dynamical cores to continue to improve CGD's model representation of the Earth system. In FY 2015 CGD researchers plan to incorporate improved land-ice representation, ocean internal wave mixing, and Conservative Semi-Lagrangian Multi-tracer transport scheme (CSLAM) advection, respectively. Accomplishments: Implementation and extensive testing of two tidal-mixing parameterizations in the CESM ocean component model was completed. The first concerns incorporation of an algebraic redistribution of tidal dissipation energy in the vertical in contrast to the exponential redistribution (default in earlier schemes). The second scheme treats tidal constituents separately and includes a parameterization for subgrid-scale topography-dependent incorporation of tidal dissipation energy. We also evaluated new tidal-energy datasets; and added support to superimpose the 18.6-year lunar cycle on the tidal energy field. The addition of these features to the CESM ocean model required significant software restructuring of the tidal-mixing module and resulted in a flexible implementation that allows the mixing-and- matching of tidal mixing methods and options with various tidal energy fields. In addition, we developed new software tools to project tidal energy fields onto our model grid; expanded the existing ocean-model standard diagnostics package to create new tidal-mixing diagnostic plots; and developed new analysis tools to compare our solutions to published results.

CSLAM has been consistently coupled with the spectral-element dynamical core (CAM-SE) and is undergoing testing and optimization. The consistent coupling has required new algorithm development and implementation. The physics-grid version of CAM-SE (needed for CSLAM to couple parameterizations on the finite-volume CSLAM grid rather than the quadrature SE grid) is almost on the CAM trunk. Large infrastructure changes needed for the physics grid have already been committed to the trunk. CSLAM has been tested in CAM-SE using an idealized moist baroclinic wave and simplified chemistry and shows superior performance in terms of preserving linear relations between trace species (important for chemistry) as well as maintaining strong gradients in tracer distributions.

With respect to land- ice, the following major improvements have been made to CESM; all of which are now on the CESM development trunk:

- new version of the Community Ice Sheet Model (CISM), which includes a higher-order, parallel dynamical core ("glissade").
- improved representation of snow in the Community Land Model (CLM) so that the model can accurately simulate the deep (tens of meters) snow packs typically found on top of glacier ice.
- rewritten the coupling between CISM and CLM, moving this coupling into the CESM coupler. This rewrite allows the coupling to conserve fluxes, which is an important prerequisite to including CISM as a fully-active component in CESM.

Projection of societal trends relevant to assessing



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impacts and options for climate mitigation and adaptation; for example population shifts and land-use change. Accomplishments: Projections of future societal trends were carried out that are consistent with a new set of socioeconomic scenarios being used widely across the research community, known as the Shared Socioeconomic Pathways (SSPs). We produced spatial population projections consistent with five different SSPs for use by the wider community and within NCAR. We also used iPETS, the NCAR integrated assessment model, to produce projections of future economic growth, emissions, and land use consistent with two of the SSPs for use in climate impact studies.

Snowpack across Tuolumne River Basin, March 2015. (Credit: NASA/JPL-Caltech)

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ADVANCE COMMUNITY MODELS

We have moved much of the CESM infrastructure into a new component called CIME. The CIME component allows us to separate much of the infrastructure of the model such as coupling, IO and support scripting from the science components of the model. By doing this we hope to engage collaborators who are using models similar to CESM to share this infrastructure code thus increasing the size of the user and developer community. More users and developers should feedback with more testing, thus improving robustness of the model.

We have also moved the CIME source code repository from subversion to git. The git source code repository has proven to make collaboration and parallel efforts much easier. We have increased and improved the coverage of both unit testing and system testing. A database of test results, known problems and outstanding issues is maintained with the git source code repository. The user community is welcome to review this database, report new problems and even contribute solutions.

The Community Land Model version 5 has been compiled and includes many new parameterizations and features. The revised model, built on top of CLM4.5 incorporates revised snow and soil hydrology parameterizations, a new river model (MOSART), expansion of the crop model to global, revised treatment of urban surfaces, fully revised nitrogen processes and a functioning Ecosystem Demography model. This work has been completed in collaboration with University and DOE partners.

CGD scientists implemented new parameterizations of land surface physics, hydrology, and biogeochemistry for the Community Land Model. These model developments helped resolve critical model biases in surface fluxes, soil moisture, and the carbon cycle.



Close up of ripe wheat.

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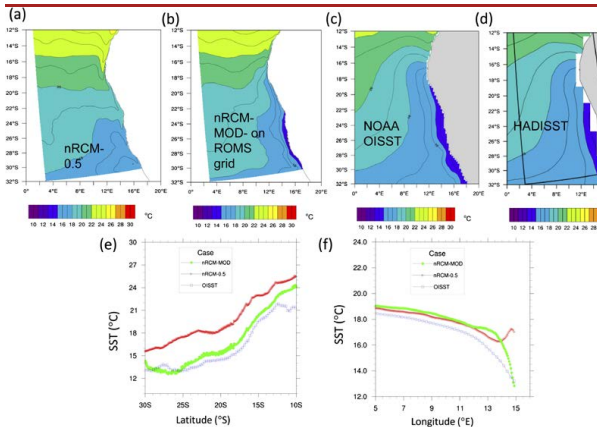
COMMUNITY ACCESS

Progress has been made on identifying important aspects of snow on sea ice that are not well represented in CESM but are in a state of readiness for model parameterization development. Considerable community input on this topic was gained through a workshop hosted by the Polar Climate Working Group in February 2015. Identified development needs include improvements to the spatial heterogeneity of snow conditions, incorporation of factors influencing snow metamorphism, and representation of the influence of snow conditions on summer melt pond evolution and structure. Sensitivity studies are underway to assess the influence of the snow cover spatial distribution on simulated polar feedbacks. This should provide guidance on model development needs moving forward.

The sensitivity of the mean climate and climate variability to CESM model component resolution was analyzed as a result of the Yellowstone Accelerated Scientific Discovery (ASD) period. A major result was that climatological mean sea surface temperature (SST) at the ocean's eastern boundaries was improved under higher atmosphere resolution, but not with higher ocean resolution (see below). In contrast, the midlatitude North Atlantic SST and precipitation were improved with higher ocean resolution, as well as Southern Ocean SST around the Antarctic Circumpolar Current, and, to a lesser extent, the Kuroshio/Oyashio system in the north-west Pacific. Regarding climate variability, it was found that the SST signature of ENSO was most similar to observations for highest model resolutions of 0.25deg. atmosphere and 0.1deg ocean, but the reasons are not fully understood. The well-known biases of a double ITCZ, and overly strong wind stress in midlatitudes, were present at all model resolutions, with just some local differences. Further, the ITCZ precipitation gets too strong at high resolution atmosphere, and the surface synoptic variability is too strong relative to free troposphere synoptic variability, at all atmosphere resolutions. (Small et al 2014 JAMES, 2015 in prep.)

The realism of coastal upwelling systems has been investigated in CESM and in embedded regional models. A major result is that improving atmosphere resolution with a standard resolution ocean leads to large improvements in model sea surface temperature (SST), but the upwelling currents (horizontal and vertical) are too weak and not localized at the coast. For the Benguela region, a realistic upwelling system has only been obtained by adjusting a high-resolution atmosphere model towards observations, to simulate the strong winds adjacent to the coast, together with a high-resolution ocean model to resolve the upwelling front. (Small et al. 2015). It was further noted in this paper and recently by other groups, that enhanced ocean resolution only improves the upwelling system if the modelled winds accurately represent the coastal wind structure.

We have incorporated several new sub-grid scale parameterizations in the CESM ocean component.



Top-level temperature (taken as SST), for JJA seasonal mean, from the (a) ROMS part of nRCM-0.5°, (b) ROMS part of nRCM-MOD experiment, (c) NOAA analysis of observed SST (OISST; Banzon et al. 2014), and (d) HadISST (1870–99) gridded onto POP grid. (e) The time-mean SST along the coast, as a function of latitude, using nearest grid cells to coast, for (see legend) nRCM-0.5°, nRCM-MOD, and OISST. (f) As in (e), but for a zonal section at 26°S, approximate latitude of Lüderitz.

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In addition to the tidal mixing parameterizations discussed above, these new parameterizations include an anisotropic formulation of the effects of mesoscale eddies; a new approach for the prescriptions of isopycnal and thickness diffusivities used for mesoscale eddy parameterization based on steering level arguments; inclusion of a wave model as a new CESM component along with the Langmuir mixing parameterization, and a parameterization of mixing processes in estuaries that modulates the introduction of terrestrial freshwater into the ocean model.

CESM solutions have been characterized by positive biases in surface ocean chlorophyll concentrations in sea ice covered regions during the spring bloom. These biases have been dramatically reduced through an improved treatment of photosynthesis that considers subgrid-scale variation in light. Grid-scale light distributions in sea ice regions can span a range from near zero light to the full downwelling irradiance. The default model computed photosynthesis as a function of grid-cell mean light; however, since the photosynthesis function is concave down, this resulted in a uniformly positive bias in photosynthetic rates. The new photosynthesis treatment accounts for subgrid-scale heterogeneity by changing the order of operations, computing light limitation terms under each ice category then averaging the result. This is a more accurate invocation of the underlying equations. In addition to reducing springtime chlorophyll biases, this new treatment reduces annual productivity significantly and yields greater sensitivity of regionally-integrated productivity to inter-annual variation in ice distributions.

Significant progress toward refactoring the ocean biogeochemistry component of CESM has been made. The previous code base was wholly dependent on the ocean model POP, limiting its invocation in other frameworks, including the next CESM ocean component. Furthermore, the code was not flexible with respect to process representation, challenging development and limiting the scope of scientific applications. The new ocean biogeochemistry model is called MARBL, the Marine Biogeochemistry Library. Phase 1 of MARBL development is near complete; this configuration will replicate existing functionality in a modular, base-model-independent framework. Additionally, following completion of phase 1, MARBL will be further modularized to enable more flexible process representation, permitting, for instance, ecosystem models spanning a range of complexity.

While there have been tremendous advances in the parameterization of mesoscale ocean eddies for non-eddy-resolving models, there has been very little progress in the area of subgrid-scale closure for those ocean models that resolve eddies. This despite the fact that the submesoscale regime is known to have important impacts on both the mesoscale and large-scale ocean circulation and property transports. A modified version of the Gent-McWilliams eddy parameterization scheme that accounts for anisotropy in the mixing tensor was implemented and tested in the high-resolution CESM ocean component model. This scheme has the strong advantage over standard practice of minimizing spurious diapycnal mixing. Results from sensitivity experiments indicate that with appropriate choices of anisotropy, the advantages of the adiabatic GM scheme and the scale-selectivity of the standard biharmonic scheme can be simultaneously achieved.

The CESM workshop was convened in Breckenridge, June 15-18. Attendance was 320 participants, lower than in previous years due a reduced participation from DOE scientists. Changes to the schedule were made to allow for more cross Working Groups sessions; this is aimed at fostering more communication on topics that span multiple research areas.

The annual CESM Tutorial was held August 10-14, 2015 at the Mesa Lab. The purpose of the CESM Tutorial was to provide graduate students and early career scientists the opportunity to learn the practicalities of running CESM as well as learn the science behind the code. We hosted 80 students this year from institutions all around the world with the objectives of introducing how physics is represented in each modeling component, and giving students hands-on experience in running and analyzing a basic fully coupled simulation. Science lectures were presented in the morning and practical labs in the afternoon. By the end of

the week, all students were able to run a short fully coupled simulation on NCAR's Yellowstone supercomputer and run diagnostic packages for at least one or more model component. Tutorial staff also instructed the students on the use of various CESM community resources such as documentation websites and community bulletin boards. Based on student survey responses after the completion of the tutorial, our goals were met and, in general, the students returned to their home institutions with excitement for their science and the practical knowledge necessary to begin or complete their research.

Four NCL tutorials (with CISL) were held in FY2015.

Attendance at the CESM Tutorial continues to be highly sought after and competitive. This year 135 people applied to attend the tutorial, and we were able to accept 80. These 80 people traveled from all over the world to Boulder, Colorado to attend the CESM Tutorial the week of 10-14 August 2015. Many of the staff in CGD volunteers to give lectures and assist in the classroom setting to provide a rich learning experience to the participants.

The 20th Annual CESM Workshop was held 15-18 June 2015 in Breckenridge, Colorado. It was a combination of plenary presentations, special interest presentations by the CESM working groups, and a poster session for participants to highlight their work. Jean-François Lamarque presented the annual 'State of the CESM'. Participants enjoyed two plenary talks by Dargan Frierson from the University of Washington – "An interconnected planet: How clouds, aerosols, and the ocean cause distant rainfall anomalies" and Jeff Kiehl from NCAR "CESM at 20." There were 327 participants at this year's workshop.

Ten of the twelve CESM Working Groups met during the winter months of 2015. These meetings are held at NCAR in Boulder, Colorado. Members from the various communities meet to discuss accomplishments and discuss plans on how to move forward with development of the various component models, etc.



CESM Tutorial.

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Advance community models

Community access

Multiscale Modeling Systems

- ▶ NCAR Imperative 5: Develop and transfer science to meet societal needs

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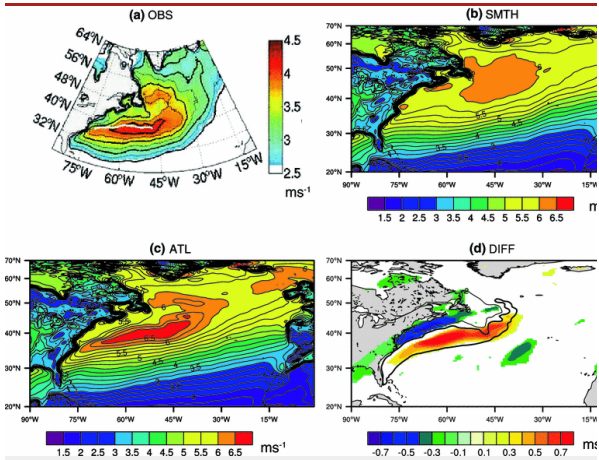
MULTISCALE MODELING SYSTEMS

The stretch-grid capability in the CESM has been expanded and more thoroughly tested in collaboration with scientists from U. Michigan (Zarzycki and Jablonowski). Also, numerical simulations have shown that the CAM5 physics parameterizations are much less-scale dependent than CAM4 physics. A significant development was the selection of the CLUBB approach to clouds for the new version of CAM and therefore CESM2.

CGD scientists implemented new parameterizations of land surface physics, hydrology, and biogeochemistry for the Community Land Model. These model developments helped resolve critical model biases in surface fluxes, soil moisture, and the carbon cycle.

The Oceanography Section continues to analyze fully coupled CESM results using the 1/10 degree horizontal resolution ocean component. Runs using a 1% per year increasing carbon dioxide forcing, and with a 50% stronger zonal wind stress in the Southern Hemisphere have been analyzed. Two journal articles have been submitted, both with young researchers from UCAR member universities as the lead authors.

Embedding of a regional ocean model in coastal regions has been performed for the California Current, Benguela Current, and Eastern US coast/Gulf Stream system. In the California Current, more accurate representation of the cold advection provided by the California Current in high-resolution ROMS, relative to 1deg. POP, as well as stronger coastal upwelling, led to a reduction of the SST bias by 1/3 to 1/2 off the coast, despite significant damping by air-sea fluxes. In the Benguela, as reported above, the realistic representation of the wind stress curl remains a challenge, and the model winds needed to be adjusted to give a realistic upwelling system (Small et al 2015). Finally, in the N. E. Atlantic, preliminary results from a regional ocean model of the Gulf Stream embedded in CESM does improve the coastal sea surface temperature off the US East coast (where a strong warm bias exists in standard resolution models), due to a better resolved Gulf Stream current and pathway. However this improvement is only local, and the sea surface temperature downstream in the North Atlantic Current, outside the ROMS domain, degrades. This contrasts with use of a global high-resolution ocean model where the central mid-latitude North Atlantic SST bias is reduced (Small et al. 2014a). In this case it is likely that a basin-wide regional model is required to get good results (e.g. Bryan et al 2007). Finally, it is noted that improving SST off the US East coast gives rise to a localized improvement of the storm track in that region, pushing the strongest winds offshore, to the real location of the Gulf Stream, as observed (Small et al. 2014a,



Surface storm track in the North Atlantic shown as long-term, seasonal-mean of the standard deviation of filtered meridional wind variability. a At 10 m, from ECMWF analysis (reproduced from Booth et al. 2010, with permission of the American Meteorological Society), b at 60 m from SMTH simulation, c at 60 m from ATL experiments and d difference field ATL minus SMTH. In d only values significant at 95 % according to the t test are shown in color. In d the corresponding SST anomalies of +2 °C (−2 °C) are shown as thick (thin) solid lines.

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2014b).

Coupled comparisons integrations with scale robust convective scheme and scale robust moist boundary layer turbulence schemes.

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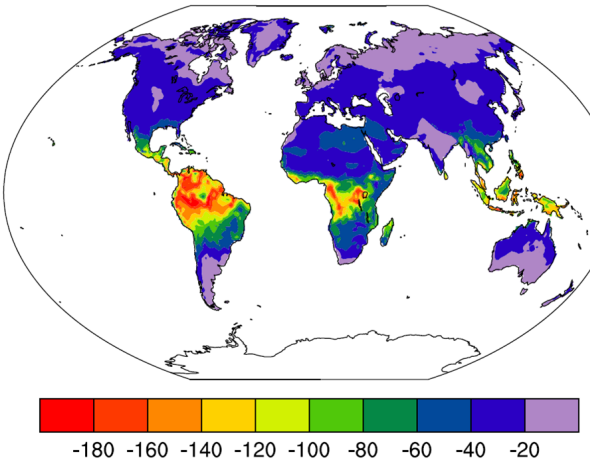
SUPPORT DECISION MAKING

NCAR supplied Rutgers colleagues with high resolution (1km) hourly surface meteorological data for all power stations in the New Jersey electric power generation system as part of our EaSM 1 collaboration. The data was provided for historical as well as RCP 4.5 and RCP 8.5 projected climate scenarios simulated with CESM 1.0 following the CMIP5 protocol. Rutgers colleagues used the high- resolution temperature projection data in a power sector capacity expansion model that incorporated changes in sectoral composition of electricity demand over time along with the effects of climate change and variability on both the demand and supply-side of power sector. These changes informed a macro-economic model that accounted for price elasticity of demand and other effects on the broader macro-economy. The study found that scenarios that included climate variability, climate change effects and high economic growth rates required higher electricity generation capacity, along with higher supply costs, wholesale/retail prices and total ratepayers' costs. This work is currently under review in the journal Energy Policy as the manuscript: "LP-CEM: A modeling tool for power systems planning incorporating climate change effects and macro- economic trends."

In FY15 the Climate and Human Systems Project continued work on its study on the Benefits of Reduced Anthropogenic Climate change (BRACE), which is producing a special issue of the journal Climatic Change that investigates the differences in impacts between a high future climate change scenario (RCP8.5) and a moderate climate change scenario (RCP4.5). Over the course of the year, 18 out of 23 total papers were submitted to the journal, and four have now been accepted. Outputs/Outcomes/Impacts: Responses to climate change must factor in more than environmental and atmospheric dynamics. To attain a more scientifically informed response to climate change questions also requires developing a better understanding of how socio-economic factors may evolve in the future and how such factors will affect society's reactions to managing a changing environment.

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RCP4.5 (2061-2080) - RCP8.5 (2061-2080)




Projected reduction in the average number of heat wave days per year in 2060-2080 if climate change followed a moderate rather than a high warming pathway, based on CESM simulations.



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CISL DIRECTOR'S MESSAGE



CISL Director Al Kellie

2017.


Welcome to the FY2015 CISL Annual Report. These highlights include an overview of CISL's broader impacts on the research community. CISL operates NCAR's unique supercomputing and data services that are tailored to the atmospheric, geospace, and related science communities including some 200 universities. This year's report draws attention to the broad scope and high quality of CISL's work.

CISL conducted the NWSC-2 supercomputing procurement for a multi-petaflops supercomputer to replace the Yellowstone system at the NCAR-Wyoming Supercomputing Center (NWSC). During this process, CISL worked with scientific, business, and technical experts from across NCAR and UCAR to determine the best value from among the various offerings to enhance scientific productivity for the next four years. The NWSC-2 system will be put into production by January

CISL again stepped up to NCAR leadership activities by co-leading the NCAR-wide Data Stewardship and Engineering Team (DSET), whose goal is to define cross-NCAR data management engineering practices that lead to a better integration of NCAR's data services. In addition, along with participation of scientists from across NCAR, CISL also co-led the creation of an NCAR Data Assimilation Initiative that defined a coordinated DA path forward, building on the software framework provided by the Data Assimilation Research Testbed (DART).

Significant progress was made in speeding up scientific workflows as well as data analysis and visualization software. The fall 2015 release of The Community Earth System Model (CESM) will for the first time include pyAverager and pyReshaper as climate data workflow tools. FY2015 saw one major and one minor release of the NCAR Command Language (NCL) graphics software continuing the theme of Python integration. Over 2,000 copies have been downloaded of the new Version 2.4 of the Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers (VAPOR) 3D visualization software package that features support for GRIB data and global circulation model outputs from the Community Atmosphere Model (CAM).

The Application Scalability and Performance Group's (ASAP) acceleration efforts are producing significant results in refactoring NCAR applications for performance on future architectures. The Strategic Program to Optimize Computing (SPOC) is also helping to lead the way in more efficiently exploiting Yellowstone. ASAP optimized routines in CAM for a 1.5-2.0x speedup, which is an important improvement because CAM represents 70% of the CESM execution time. Other compiler optimizations by SPOC resulted in a 15%-20% improvement in the execution of dynamics in the Model Prediction Across Scales (MPAS)

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model.

The 2015 class of the Summer Internships in Parallel Computational Science (SIParCS) program was the second largest in its nine-year history, with 17 students participating. It was also the most diverse, with three interns from Minority-Serving Institutions (MSIs), five female interns, and eight interns from seven different EPSCoR states.

In 2015, CISL's Institute for Mathematics Applied to Geosciences (IMAGE) produced five conferences designed to help Earth science researchers cope with the ever-increasing challenges of Big Data. In May, the Summer School in Data Assimilation organized by IMAGE and the Statistical Methods for Atmospheric and Oceanic Sciences (STATMOS) brought together graduate students, early-career scientists, and senior scientists in environmental statistics and related fields to explore topics in applied environmental data modeling. In June, IMAGE presented a week-long Data Analytics Bootcamp for High School Students, an opportunity for 10 Boulder high school sophomores and juniors to learn about being a data scientist. IMAGE presented three more conferences in July, August, and September to continue developing researchers' skills in Environmental Data Analytics, Ensemble Data Assimilation, and Climate Data Informatics. These conferences support the research communities' need for help in coping with the Big Data challenges of today's research environment.

As you read this FY2015 CISL Annual Report, I hope you can appreciate the importance of the progress we are making and how proud I am of the work being accomplished by our staff.

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## CISL SERVICES

CISL has a proud tradition of providing world-class supercomputing and data services to its user community. From CISL's services and support web pages, users can access CISL's help desk and consulting services, as well as complete information about HPC systems, storage systems, data analysis and visualization systems, data collections, user documentation, and training. The quality of these services is and will remain a core value of the laboratory. However, the makeup of these services is not static: they continually change in concert with rapid changes in the underlying technologies and the scientific demands of our users:

- CISL maintains and operates the physical facilities and cyberinfrastructure needed to support the atmospheric and related sciences.
- A rich set of data collections is curated, managed, and archived for free and open access.
- CISL creates essential, widely used software cyberinfrastructure such as data analysis and visualization tools and frameworks for modeling and science gateway construction.
- User support and training are provided for all of these services.
- All of these resources and services are integrated with regional and national cyberinfrastructure and services, and with the organizations that maintain them, such as the Front Range GigaPoP (FRGP), the Rocky Mountain Advanced Computing Consortium (RMACC), and NSF's eXtreme Science and Engineering Discovery Environment (XSEDE).

In FY2015 CISL continued to operate the data-centric petascale Yellowstone supercomputing environment at the NWSC, including the 1.5-petaflops IBM iDataPlex supercomputer, the 16-petabyte central disk storage system known as NCAR's GLOBally Accessible Data Environment (GLADE), two data analysis and visualization systems, the HPSS data archive, high-speed wide-area networking, and high-performance data transfer and sharing services. A wide range of computing projects pursued the research frontiers of weather phenomena, climate change, space weather, solar physics, and more. Three years into Yellowstone's production lifetime, CISL also began the NWSC-2 procurement effort in FY2015, which will lead to the NWSC's next supercomputing system.

CISL's software CI capabilities continued to make important advances in FY2015 as well, including a new version of DART being used in production by real-time WRF forecasters that uses the remote memory access (RMA) capability of MPI-2 to allow much larger models to work with DART; a new release of the NCAR Command Language (NCL) that included several new computational routines and improvements to internal parallel code for drawing raster graphics; two releases of PyNIO enhanced for parallelized workflows in climate model diagnostic packages; and improvements to the Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers (VAPOR) that include adding support for ocean modeling data and refactoring VAPOR's architecture to facilitate third-party code enhancement. All of these tools are heavily used – for instance, NCL's software was downloaded 21,547 times in FY2015.

This work is supported by NSF Core funding and other sources as specified in the following individual reports.



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CISL COMPUTING FACILITIES

From the NCAR Strategic Plan, “High Performance Computing (HPC) is one of the foundational elements of NCAR’s scientific research and publications.” Within CISL, providing capable, flexible, and efficient facilities continues to be the cornerstone of this foundation. NCAR is moving forward with plans for both NWSC and the ML in the coming fiscal year.

During FY2015, a CISL team focused on installation planning for the NWSC’s next HPC system to be installed in FY2016. Early in FY2015, CISL requested that key HPC vendors respond to a brief set of questions designed to obtain power, cooling, and facilities infrastructure requirements for the systems they would propose. The facilities and infrastructure information indicated that the projected power consumption of ~2-4 MW would consume all of the NWSC’s available electrical capacity on the low end and exceed the electrical capacity on the high end of the range. To prepare for systems at the higher end, CISL developed a statement of work and RFP process around the build-out of Computer Room Module A as the best path forward. This process proceeded in parallel with the NWSC-2 procurement as there was considerable schedule risk to procure long-lead components such as the 3-MVA transformer needed to energize Module A. Later, as the proposals came in for the NWSC-2 procurement, CISL determined that all vendor proposals were trending toward the low end of ~2 MW. As a result, CISL re-evaluated and moved forward with simply augmenting Module B.

In a similar fashion, another CISL team has been focused on the retrofit and upgrade of the Mesa Lab Computing Facility (MLCF). This effort has been a partnership with UCAR Facilities Management, Safety, and Sustainability (FMS&S) to first develop a master plan to further develop construction documents and retrofit the MLDC in a phased effort to enhance reliability and greatly improve energy efficiency. The master planning was completed in the summer of FY2015.

NSF Core funds support the NWSC efforts. UCAR indirect funding has supported the work for MLCF efforts.

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NCAR-WYOMING SUPERCOMPUTING CENTER

The NWSC entered its third full year of production in FY2015. The NWSC is designed to meet the rapidly growing high-performance computing (HPC) needs of Earth System scientists and to encourage broader participation in this scientific enterprise. Earth System scientists need petascale computing, data analysis, and visualization resources combined with exascale data management capabilities to support greater model resolution, increased model complexity, better statistics, more predictive power, and longer simulation times. The NWSC has been designed and built with a focus on sustainability and energy efficiency consistent with NCAR's and the University of Wyoming's strong commitment to environmental stewardship.

The NWSC is fully aligned with NSF's vision for 21st-century cyberinfrastructure and directly contributes to the creation of a national petascale computing capability. The facility is a peer with other NSF facilities and serves as a "stepping stone" for Earth System science investigators to fully utilize the largest systems available, such as NCSA's Blue Waters. CISL's first strategic imperative is to provide HPC facilities for the Earth System sciences: "A foundational element of CISL's mission is to deploy and operate the physical and virtual computational facilities needed to support the science community. Essential to this mission is the design, construction, and operation of a new data center capable of meeting future scientific computing challenges in the atmospheric sciences."

CISL continually optimizes and improves the efficiency and operability of the facility. This year CISL piloted an effort to monitor waste water output with the Cheyenne Board of Public Utilities (BOPU). Because much of the water loss for NWSC is evaporative, we minimize pressure on the water treatment facility and have reduced our waste water charges by ~60-75%.

The other major focus for the staff at NWSC has been preparation and planning for the next HPC system. Procurement efforts for design build services were nearly completed in FY2015. In addition, some modifications to security cameras, card readers, etc., were made to maintain physical access controls during construction. This minimizes opportunities for mistakes to impact the production computing environment by ensuring construction crews don't have access to critical production areas.

The operational expenses for NWSC during FY2015 were met using NSF Core funds

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MESA LAB COMPUTING FACILITY

The Mesa Lab Computing Facility (MLCF) has been repurposed to house the majority of the enterprise-class IT equipment for NCAR and UCAR. It will therefore continue providing significant value to researchers for many years into the future.

At present, the MLCF provides servers and services for NCAR divisions and UCAR programs including ACOM, CGD, CISL, COSMIC, F&A, Globe, HAO, IIS, JOSS, and RAL.

CISL, along with UCAR Facilities Management, Safety, and Sustainability (FMS&S), completed a master planning effort for the MLCF in FY2015. Late in FY2015, the effort shifted to a design and phasing plan that divides the MLCF upgrade into three phases. Construction documents should be complete early in FY2016.

During FY2015, CISL worked with FMS&S to develop a plan for upgrading and right-sizing the Uninterruptible Power Supply (UPS) system at the MLCF. The current UPS systems will reach their end-of-service life in calendar year 2016, and support plus spare parts will likely become difficult to procure. Completing this work is consistent with the master plan and removes a significant item from the critical path and simplifies the coordination required during any MLCF construction.

Funding for the MLCF is supported by UCAR overhead funding out of the UCAR Communications pool.

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## CISL HARDWARE CYBERINFRASTRUCTURE SERVICES

CISL deploys and operates NCAR's high performance computing (HPC) environment on behalf of the atmospheric and related sciences community. The integrated petascale computing, analysis, visualization, networking, data storage, and archival systems constitute a world-class HPC resource for about 2,000 researchers from institutions throughout the U.S. and abroad.

While more details about the cyberinfrastructure managed by CISL appear in subsequent sections of this report, the primary resources include:

- The Yellowstone compute cluster based on IBM's iDataPlex architecture: a 1.5 PFLOPS system composed of 4,536 two-socket Intel Sandy Bridge nodes connected by a full fat-tree FDR InfiniBand interconnect.
- The Globally Accessible Data Environment (GLADE) high-performance parallel file system capable of over 90 GB/second of sustained bandwidth with a data storage capacity of 16.4 PB.
- A data-sharing environment based on Globus Plus software with a capacity of 1.5 PB.
- A high-performance data archival system based on IBM's High Performance Storage System (HPSS). Current data holdings exceed 50 PB, with a capacity of 160 PB.
- Data Analysis and Visualization resources:
  - The Caldera computation and visualization cluster comprised of 16 nodes based on the same two-socket Sandy Bridge architecture as Yellowstone, but augmented with two NVIDIA K20X GPGPU accelerators per node, and a 16-node Pronghorn system based on the same node-level architecture as Yellowstone.
  - The Geyser data analysis and visualization cluster comprised of 16 nodes based on the Intel Westmere processor and featuring 1 TB of DRAM per node and NVIDIA K5000 GPUs.
- The Erebus cluster comprised of 84 nodes and based on the same node-level architecture as Yellowstone. Erebus is operated by CISL on behalf of the U.S. Antarctic Program's Antarctic Mesoscale Prediction System (AMPS) project.
- CISL's HPC Futures Lab, a range of smaller systems for pre-production testing and evaluating future and emerging HPC hardware and software technologies.

Yellowstone and its associated complex of HPC systems and storage resources operated in full production



Yellowstone's end panels highlight one of the geological wonders of the national park after which it was named.

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status throughout FY2015. CISL currently plans to continue operating Yellowstone through calendar year 2017.

NWSC-2 procurement

In concert with UCAR during FY2015, CISL conducted the NWSC-2 procurement which was designed to obtain a high-performance computing system to replace Yellowstone and augment the GLADE parallel file system. Draft technical specifications were released for vendor comment early in the fiscal year, followed by an early release of the NCAR benchmarks that will continue to exist and be enhanced outside of CISL procurement efforts. The NWSC-2 RFP was publicly released in April, and proposal evaluation was conducted during the summer. At the end of FY2015, final negotiations were conducted to provide the following new NWSC-2 resources for production use by January 2017:

- A new high-performance computing system with a peak computation rate exceeding 5 PFLOPS.
- Augmentation of the GLADE storage system with over 20 PB of additional storage capacity and 200 GB/second bandwidth to the new HPC system, with the capability to expand GLADE storage capacity beyond 56 PB and incrementally enhance bandwidth.

Funding

NCAR’s supercomputers are managed by CISL under the UCAR/NSF Cooperative Agreement and are supported by NSF Core funds.

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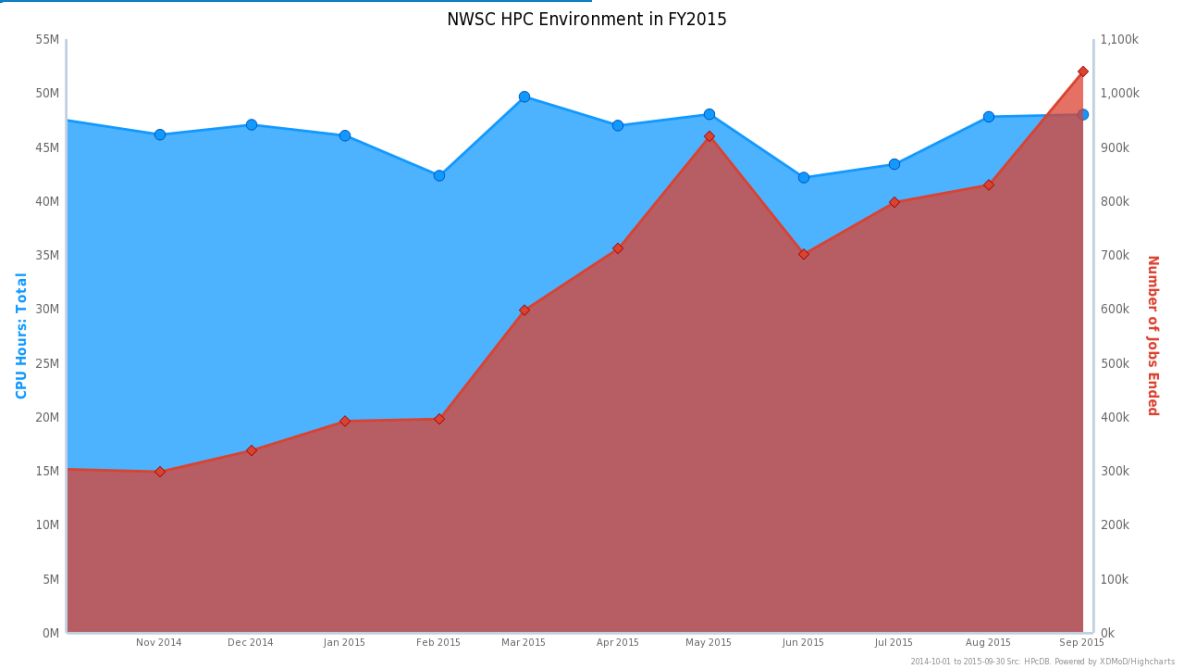
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NWSC DATA-INTENSIVE COMPUTING ENVIRONMENT

The NWSC HPC environment includes petascale high-performance computing (HPC) resources, the Globally Accessible Data Environment’s centralized file system and data storage resource, and data analysis and visualization resources. The systems that were initially deployed within the NWSC in late 2012 have now been in production use for nearly three years, having enabled new science and discovery in the atmospheric and related sciences.



Monthly profile of the number of jobs and core-hours delivered by the NWSC HPC systems during FY2015. (This plot was produced by Open XDMoD, authored by the University of Buffalo under NSF grants ACI 1025159 and ACI 1445806 for the development of technology audit service for XSEDE.)

FY2015 was again a highly productive year for the NWSC data-intensive computing environment. Over the past year these systems have supported 555 million core-hours of computing for over 7.3 million jobs.

GLADE

The centerpiece of NWSC’s data-centric supercomputing environment is NCAR’s Globally Accessible Data Environment (GLADE), which provides a shared, high-speed (90 GB/second), high-capacity (16.4 PB) central file system connecting all the computing and support systems required for scientific computation and associated workflows. This centralized design, independent of the HPC resources, improves scientific productivity and reduces costs by eliminating the expense (time and energy) of moving and maintaining multiple copies of data.



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## Yellowstone

The Yellowstone HPC resource, with peak processing power of 1.5 PFLOPS (1.5 quadrillion floating point operations per second) and 72,576 Intel Sandy Bridge (E5-2670) processing cores, was ranked as the 13th most powerful supercomputer in the world when it was installed. It dropped to 29th place in June 2014, and it was ranked 49th on the June 2015 TOP500 list. Yellowstone's design and configuration target the data-intensive computing needs of the Earth System sciences, disciplines that push the limits of computational and data systems.

## Geyser, Caldera, and Pronghorn

Rounding out the resources of the NWSC's HPC environment are the Data Analysis and Visualization (DAV) systems Geyser, Caldera, and Pronghorn, the first two of which are specifically configured for DAV tasks and equipped with NVIDIA graphics processing units (GPUs). The 16-node Geyser cluster, with 1 terabyte of memory and a single NVIDIA K5000 GPU per node, was designed for data synthesis, analysis, and visualization tasks; while the 16-node Caldera cluster, with two NVIDIA K20X GPGPUs per node, was designed for computationally intensive, GPGPU-accelerated parallel applications and data analysis tasks. Pronghorn was initially an Intel Phi accelerator evaluation system, and after decommissioning the Phi adapters, has been repurposed to augment the Caldera system, but without computational accelerators.

## Data sharing services

Launched last year, CISL continued to operate the the NCAR Data Sharing Service during FY2015. Based on the Globus Plus software (a tool that emerged from a partnership with the University of Chicago and Argonne National Laboratory), the NCAR Data Sharing Service provides researchers a way to share large data sets with collaborators around the world using a simple web-based interface. The service provides 1.5 PB of storage, data movement servers, and high-speed network connectivity to external research networks.

CISL's commitment to a data-intensive computing strategy extends beyond the Yellowstone environment and includes a full suite of science gateway and data portal services. CISL continues to lead the community in developing data services that can address the future challenges of data growth, preservation, curation, and management. CISL also leads in supporting NSF's requirement for data management plans. Our disk and tape-based HPSS archival storage systems provides an efficient, safe, and reliable environment for long-term offline hosting of datasets, yet provides user-friendly interfaces for quickly retrieving stored data. CISL has streamlined and improved its data services through the data-centric design of the NWSC environment, and particularly via the GLADE file systems.

## Erebus/AMPS

During FY2015, CISL continued to operate the 84-node supercomputing cluster Erebus that is based on the same architecture as Yellowstone. Erebus delivered 8.9 million core-hours during FY2015 and is used exclusively by the Antarctic Mesoscale Prediction System (AMPS) for producing twice-daily numerical weather predictions over the Antarctic continent. Primary users of these simulations are forecasters who support the U.S. Antarctic Program flight operations and polar observatory, and to support research and education activities involving Antarctic meteorology.

## NWSC-2 procurement

This past year UCAR, on behalf of CISL, issued the NWSC-2 RFP for the acquisition of a new HPC resource and augmentation of the GLADE environment. With input from internal and external advisory teams, CISL established a set of requirements for the new systems and benchmarks for their evaluation. The RFP was issued in April 2015, and proposal evaluation was concluded at end-FY2015. While formal announcement of the award will occur early in FY2016, the HPC system to be acquired that will ultimately replace Yellowstone will have a peak computational rate exceeding 5 PFLOPS, and the storage system, which will enhance GLADE, will have an aggregate I/O bandwidth of 200 GB/second, an initial storage capacity of 20 PB, and will be expandable to beyond 40 PB (thus potentially expanding GLADE's total capacity to over 56 PBy). The NWSC-2 HPC and storage resources are planned to be deployed for production use by the end of calendar 2016. CISL plans to operate Yellowstone through calendar 2017, thus providing a one-year overlap with the new NWSC-2 HPC system.

## Funding

The NWSC environment, including HPC, GLADE, and DAV resources, was made possible through NSF Core

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funds, with supplemental support from the University of Wyoming. AMPS computing was supported by NSF Special funding.

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PRODUCTION SUPERCOMPUTING STATUS

In FY2015, CISL focused its efforts on ensuring that Yellowstone and related systems – GLADE, Caldera, Erebus, Geyser, and Pronghorn – were operated at the highest levels of performance, availability, and utilization. This section describes some major events and highlights from FY2015.

Balanced supercomputing environment

Throughout the year, CISL continued to deliver on its computing imperative for hardware and software cyberinfrastructure. CISL's efforts remained substantially focused on providing robust, reliable, and secure high-performance computing resources in a production research environment, and on supporting that environment for thousands of users and hundreds of projects spanning NCAR, UCAR member universities, and the University of Wyoming in a wide variety of disciplines related to the Earth System sciences. CISL resources empower the research community to pursue more innovative investigations, and CISL itself provides the organizational focus, capabilities, and skill sets to support these investigations, including meteorological field campaigns and computational projects of other NCAR laboratories.

CISL's production supercomputing environment is designed, administered, and managed to provide data-centric computational resources that are balanced to meet the needs of its numerical simulation and data-analysis communities. Further, CISL strives to provide the most effective and useful combination of computational and data storage capability and capacity, augmented by scientific data analysis, visualization, and archival services. CISL works to provide equitable access to these computing and storage resources while achieving high reliability, minimizing job wait times, and maximizing resource throughput and utilization. These objectives require CISL to continuously monitor system usage and performance and to continuously work to balance resource allocation with priority-based intelligent job scheduling, a well-tuned job queue structure, and single-job resource limits.

System software upgrades

The NWSC software environment was very stable throughout FY2015 with a minor upgrade to the LSF resource manager and job scheduler late in the year. The only other software changes involved a series of minor upgrades to the InfiniBand routing algorithm, including the implementation of "routing engine chains" to allow Yellowstone to be routed as a full fat tree while InfiniBand connections to the Globally Accessible Data Environment (GLADE) and the DAV resources can be treated differently.

System specifications

The following table provides the technical details for the supercomputing systems maintained by CISL during FY2015.

	Yellowstone	Caldera	Geyser	Pronghorn	Erebus (AMPS)
Peak FLOP rate (TF)	1509.6	21.8	14.4	37.7	28.0
Total number of nodes	4536	16	16	16	84

Advanced Study Program	Primary node architecture	IBM dx360 M4	IBM dx360 M4	IBM x3850 X5	IBM dx360 M4	IBM dx360 M4
Climate & Global Dynamics	CPU type	Intel Xeon E5-2670	Intel Xeon E5-2670	Intel Xeon E7-4870	Intel Xeon E5-2670	Intel Xeon E5-2670
Computational & Information Systems Laboratory	CPU microarchitecture	Sandy Bridge EP	Sandy Bridge EP	Westmere EX	Sandy Bridge EP	Sandy Bridge EP
Earth Observing Laboratory	CPU frequency (GHz)	2.6	2.6	2.4	2.6	2.6
High Altitude Observatory	CPUs per node	2	2	4	2	2
Mesoscale & Microscale Meterology Laboratory	Cores per node	16	16	40	16	16
National Center for Atmospheric Research	Node memory capacity (GB)	32	64	1024	64	32
Research Applications Laboratory	Node memory type	DDR3-1600	DDR3-1600	DDR3-1066	DDR3-1600	DDR3-1600
STRATEGIC PLANS	Interconnect network	InfiniBand 4x FDR	InfiniBand 4x FDR	InfiniBand 4x FDR	InfiniBand 4x FDR	InfiniBand 4x FDR-10
	Interconnect topology	3-tier full fat tree	1-tier full fat tree	1-tier full fat tree	1-tier full fat tree	2-tier full fat tree
PREVIOUS CISL REPORTS	Network ports per node	1	1	2	1	1
	System bisection bandwidth (GB/sec)	31,100	109	104	109	407
 Printer-friendly version	Accelerator/GPU	-	NVIDIA K20X	NVIDIA K5000	-	-
	Accelerator peak single-precision FLOP rate (GF)	-	3,950	2,150	-	-
	Accelerator peak double-precision FLOP rate (GF)	-	1,310	90	-	-
	Accelerators per node	-	2	1	-	-
	Accelerator memory capacity (GB)	-	6	4	-	-
	Accelerator memory type	-	GDDR5	GDDR5	-	-
	Number of compute racks	63	0.5	2	0.5	1

HPC Futures Laboratory

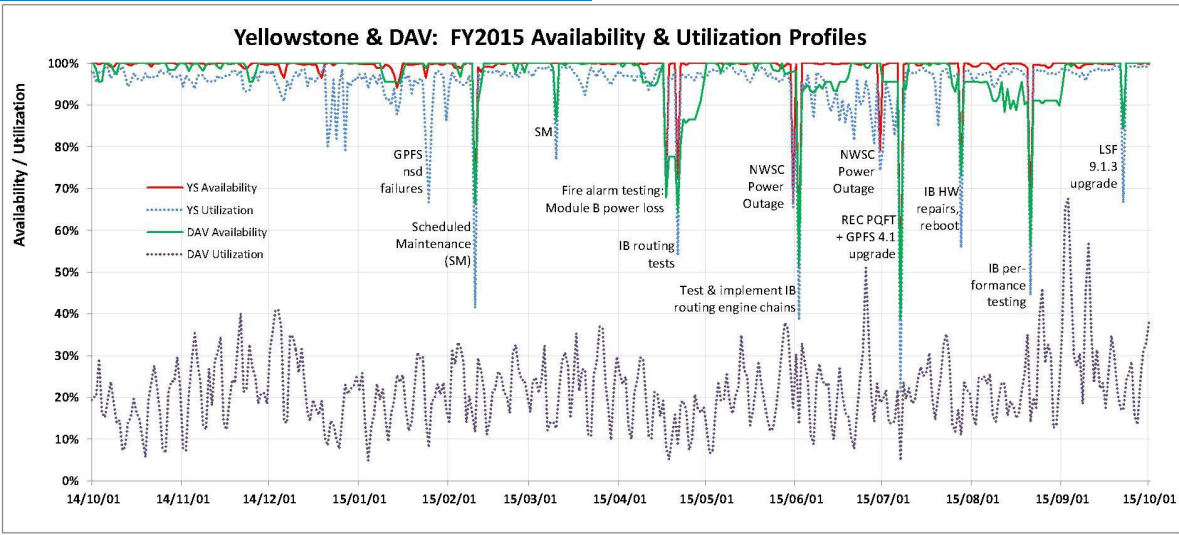
CISL continued running its HPC Futures Lab that focuses on HPC research, something that is relevant for improving the current environment and helping CISL assess new technologies that may be present in future systems. The HPC Futures Lab provides system administration, consulting staff, and scientists with a ready-to-use environment where cutting-edge technology can be deployed and tested. Some of the current research is examining areas such as heterogeneous architectures, GPGPUs, coprocessors, resource managers, job schedulers, Message Passing Interface (MPI) software, benchmarks, performance tuning, file systems, and a variety of computation-intensive applications.

System availability

During FY2015, Yellowstone had an average scheduled availability of 99.8% and user utilization of 94.8%, while the Data Analysis and Visualization systems (Caldera and Geyser) averaged 97.8% scheduled availability and 21.7% user utilization.

FY2015 Availability Metrics	GLADE	Yellowstone	DAV
Total user availability	99.7%	98.9%	97.1%
Downtime: Scheduled maintenance and environmental	0.3%	0.9%	0.7%
Scheduled availability	100%	99.8%	97.8%

Stability and utilization of Yellowstone and the DAV resources reached new peaks this year. The figure below shows the availability and utilization profiles for FY2015, with annotation of those days where availability was less than 90%.



The availability and utilization profiles for the HPC (Yellowstone) and DAV (Caldera and Geyser) resources during FY2015, showing downtimes due to power outages and for scheduled maintenance, InfiniBand testing and routing algorithm changes, and software updates.

System optimization

Throughout FY2015, CISL’s system administration and consulting services staff continued to focus on stabilizing, refining, and optimizing the user environment and on working with end users to improve application resilience and performance.

Funding

This work is made possible through NSF Core funds, including CSL funding, and NSF Special Funds were used for the AMPS resources.

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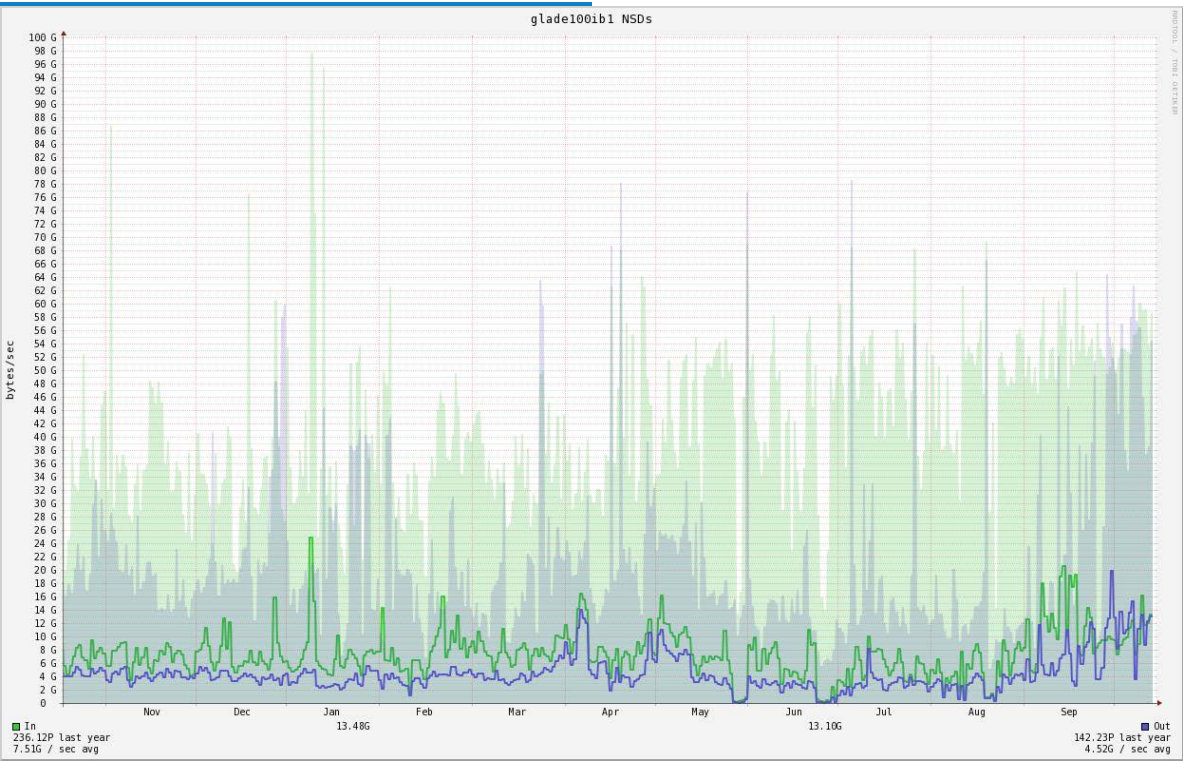
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GLOBALLY ACCESSIBLE DATA ENVIRONMENT

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



GLADE usage for FY2015 showing 236 PB of data written and 142 PB of data read.

GLADE's architecture shifts user workflows from a design that centers on serving the supercomputer to a more scientifically efficient design that facilitates the flow of data. Through a globally accessible storage infrastructure, users now arrange their workflows to use stored data directly without first needing to move or copy it. Additional services like high-performance data transfer protocols enhance CISL's ability to bring computational data from other sites to NCAR for post-processing, analysis, and visualization.

In FY2015 GLADE resources continued to provide stable centralized file services for all CISL HPC resources. GLADE resources were fully allocated in FY2015, and bandwidth usage has begun to show regular spikes at maximum throughput. The new Globus data sharing service was moved from a proof-of-concept environment to the production GLADE environment enabling collaborative data sharing for all projects.

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This work supports CISL’s computing imperative for hardware cyberinfrastructure by provisioning storage and networking systems customized to support efficient workflows for the atmospheric and related sciences. Specifically, GLADE facilitates typical user workflows plus special efforts like supporting data flows for the IPCC AR5. GLADE also advanced CISL’s computing imperative for facilities by demonstrating high-performance data services that were critical for the next-generation resources that now operate at NWSC and will continue to be critical as we move toward next-generation resources in FY2016.

GLADE equipment was purchased with NSF Special funds, and it is supported by NSF Core funds including CSL funding.

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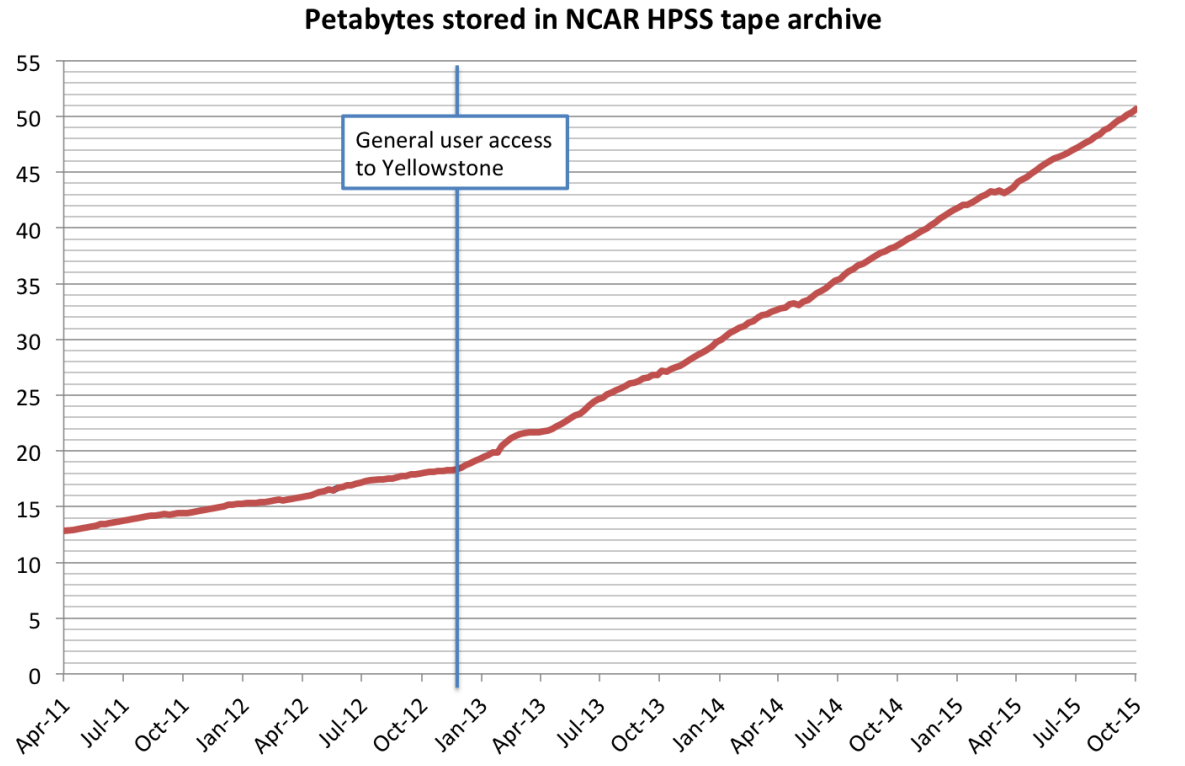
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ARCHIVAL SYSTEMS

The High Performance Storage System (HPSS) provides data archive services for the HPC system Yellowstone, as well as for divisional servers at other NCAR laboratories and UCAR programs. HPSS usage grew throughout FY2015 with over 12 PB of new data and 32 million files added to the archive during the year.



HPSS growth in petabytes.

CISL's HPSS has supported offsite duplication for CISL's [Research Data Archive](#) (RDA) based on CISL's FY2013 business continuity plan. The primary data copy is resident at the production NWSC facility, while the secondary copy is stored at the Mesa Lab Computing Facility (MLCF) in Boulder. This ensures both data replication and geographic separation for disaster recovery support. In FY2014, this service was also extended to EOL's high-value, irreplaceable data collections. It is anticipated that more labs and programs will make use of this service in the future.

In FY2015, the HPSS system was augmented with a further 20 T10K-D drives to augment the 30 additional drives that were installed in FY2014.


A limited migration from Oracle T10K-C tapes to T10K-D formatted tapes was conducted in FY2015. The D-tapes offer a 60% capacity increase over the C-tapes. Further migration will take place in FY2016. All

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Oracle T10K-B equipment residing at the MLCF was decommissioned.

After continued analysis of the growth and performance of the archive and assessment of the technology landscape, and also to benefit from early experience with the NWSC-2 supercomputer, CISL postponed the release of the tape library procurement until mid-2017. To meet the expected data load increase from the new supercomputer in 2017, further analysis and projection exercises were conducted to size an augmentation of the current HPSS equipment.

To help manage cost, CISL implemented and currently executes policies for orphaned file processing to ensure that older data either leaves the system or is adopted by funded projects to cover the cost of keeping them. In FY2015, a further step was taken to target abandoned files for deletion, prior to the next tape technology migration.

The HPSS effort supports CISL’s computing imperative for hardware cyberinfrastructure by deploying a production HPSS instance that supports NWSC archival services requirements. The NCAR HPSS is managed by CISL under the UCAR/NSF Cooperative Agreement and is supported by NSF Core funds and CSL funding.

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DATA ANALYSIS AND VISUALIZATION ENVIRONMENT

The Data Analysis and Visualization (DAV) environment enables scientific workflows by providing UCAR's research community with state-of-the-art systems tailored for the specialized needs of parallel data post-processing, analysis, and visualization. This environment also supports the research community by developing algorithms for relevant visualization and analysis methods and by producing animations and imagery in collaboration with and on behalf of scientific staff.

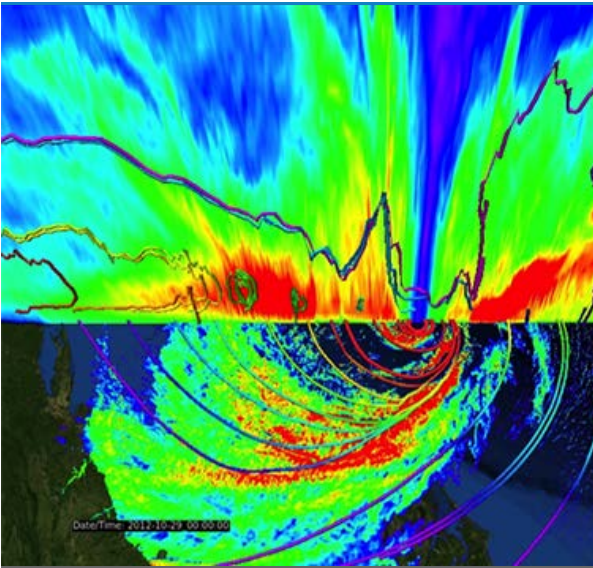
NCAR's DAV environment consists of two clusters each designed to complement the other in meeting the diverse needs of climate and weather DAV applications. Caldera is targeted for use by general-purpose applications that can be accelerated via high-performance graphics processing units (GPUs) and parallel graphics/visualization applications. Geyser is targeted primarily at traditional interactive dataset manipulation, reduction, analysis, and visualization applications and for large, data-intensive applications requiring GPUs and/or large shared memory. Both systems share a dedicated, high-bandwidth I/O network path to Yellowstone's filesystems on the GLobally Accessible Data Environment (GLADE). Caldera and Geyser are also used extensively for production and on-demand regridding, data subsetting, and curation of NCAR's Research Data Archive (RDA) sholdings.

Caldera is a 16-node cluster comprised of IBM dx360 M4 nodes, identical to the Yellowstone compute nodes except that they are augmented with two general-purpose graphics processing units (GPGPUs). Each Caldera node contains two 8-core Intel Sandy Bridge processors, 64 GB of memory, and two NVIDIA Tesla K20X accelerators. Each K20X accelerator is capable of 1.31 TFLOPS double-precision calculations or 3.95 TFLOPS single-precision calculations, giving Caldera a peak double-precision floating point rate of over 47 TFLOPS. The same peak computation rate requires over 140 Yellowstone nodes.

Geyser is a 16-node cluster comprised of IBM x3850 X5 nodes, each equipped with four 10-core Intel Westmere processors, one terabyte of memory, and one NVIDIA Quadro K5000 graphics adapter. The K5000 accelerator is designed for high-speed graphics rendering, with a single-precision floating point rate of 2.1 TFLOPS.

Additional details of the Geyser and Caldera systems are contained in a table in the LINKProduction supercomputing status section of this annual report.

In addition to supporting CISL's computing imperative for hardware cyberinfrastructure (CI), the DAV



This unprecedentedly high-resolution WRF simulation of Hurricane Sandy was created on CISL's Geyser cluster with CISL's VAPOR software. As shown in the figure, this 500-meter simulation revealed features previously unseen in other coastal cyclones, such as a surface-based warm jet that propagates as fast as wind speed. Producing hundreds of terabytes of data, this simulation demanded substantial DAV resources for analysis.

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environment supports CISL’s software CI computing imperative by supporting, developing, and enhancing software specific to the simulation, analysis, and forecasting needs of the atmospheric and related sciences. Furthermore, the DAV resources help to advance CISL’s science frontier in understanding large and heterogeneous data sets by developing new methods and tools such as VAPOR to extract and visualize information from such data sets.

CISL currently plans to continue operating Geyser and Caldera through calendar year 2017.

NCAR’s DAV environment and services are supported by NSF Core funds including CSL funding.

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NCAR'S DATA-SHARING SERVICE ON GLOBUS PLUS

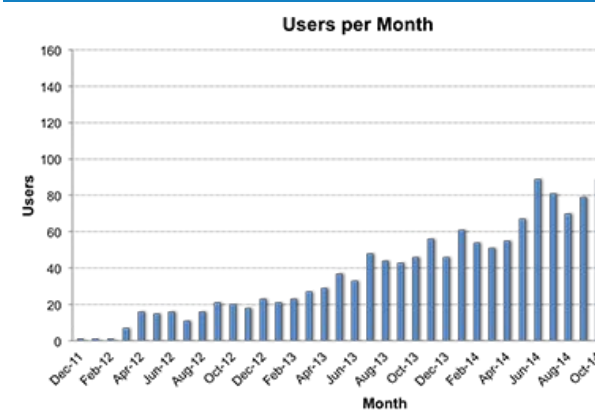
The GLOBally Accessible Data Environment (GLADE) provides centralized high-performance file systems spanning supercomputing, data post-processing, data analysis, visualization, and HPC-based data transfer services. Additional services like high-performance data transfer protocols, including a new data-sharing service, enhance CISL's ability to bring data from other sites to NCAR for post-processing, analysis, and visualization and to share data easily with external collaborators.

The data sharing service leverages the capabilities of Globus Plus to increase customization options for storage as well as data sharing. Globus, a project of the Computation Institute (a partnership of The University of Chicago and Argonne National Laboratory), is a software service that has been described as a "Dropbox for big data." It is broadly used in the scientific community. "Plus" refers to a feature that allows researchers to share data with colleagues outside of their home institutions, greatly facilitating collaborative work.

In FY2015 the small proof-of-concept data-sharing service built upon Globus Plus was moved to the production GLADE service allowing data-sharing from both a dedicated data-sharing space and the larger GLADE project spaces. In addition to making data available to external colleagues, Globus Plus allows users of CISL's HPC environment to control the users or groups of users to which the data are accessible. With the sharing service, outside users need only a free Globus account, not a UCAR username/token, to access shared data. An additional joint project between CISL/DSS and the Globus team integrated Globus Plus features into the RDA data service. Part of this integration allows RDA users to access data-sharing with their RDA username and credential instead of a Globus account.

This work supports CISL's computing imperative for hardware cyberinfrastructure by provisioning storage and networking systems customized to support efficient workflows for the atmospheric and related sciences. GLADE also advanced CISL's computing imperative for facilities by demonstrating high-performance data services that were critical for the next-generation resources that now operate at NWSC and will continue to be critical as we move toward next-generation resources in FY2016.

GLADE equipment was purchased with NSF Special funds, and it is supported by NSF Core funds including CSL funding.



Globus Usage per month, showing the number of users from December 2011 to April 2015.

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CISL SUPERCOMPUTER USER SERVICES

CISL has a strategic commitment to provide robust, accessible, and innovative services and resources to researchers in the atmospheric and related sciences, including the broad university community, Climate Simulation Laboratory (CSL) users, NCAR researchers, and University of Wyoming users. As part of that commitment, CISL provides its users with responsive and knowledgeable support services. CISL's success in supporting scientific goals and enabling scientific impact depends in equal measure on understanding the needs and research objectives of its user community, and on integrating CISL's resources, capabilities, and services in response to those needs. Our success can be measured in part by the high demand for current and future CISL resources in FY2015.

NCAR is one of only a small number of institutions with the resources and support services necessary to conduct high-end climate research, model development, and support for field campaigns. As a discipline-specific computing center, CISL is able to provide the capabilities and skill sets required to support important computational campaigns with on-demand resources that include those driven by unfolding natural disasters.

In FY2015, CISL user services expanded its efforts in working with NCAR developers to improve the performance of NCAR's flagship models and contributed benchmarking and technical expertise to inform and evaluate the NWSC-2 procurement process. CISL user services also continued to enhance the production Yellowstone environment, supported Yellowstone users as the system delivered ongoing daily utilization in excess of 95%, and increased training opportunities to help users make effective use of this powerful resource.

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

< NCAR's data-sharing service on Globus Plus

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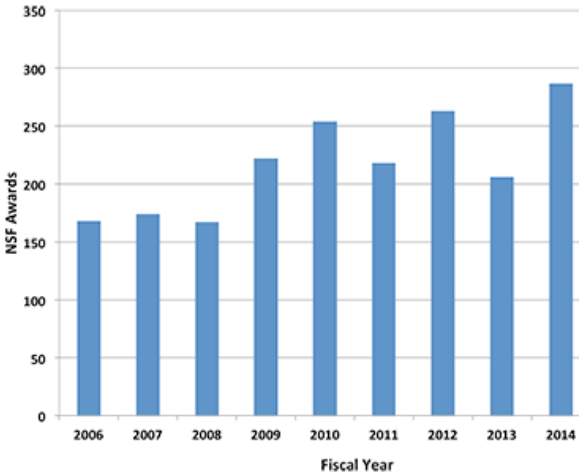
USER COMMUNITY OVERVIEW

CISE’s success in supporting scientific goals and enabling scientific impact depends in equal measure on understanding the needs and research objectives of its several user communities, and on integrating CISE’s resources, capabilities, and services in response to those needs. In FY2015, these user communities included more than 1,600 users at more than 240 universities and other institutions who benefited from using CISE’s high-performance cyberinfrastructure (CI) and services. In FY2015, nearly 500 new users joined the CISE computing community.

A discipline-specific approach to supercomputing allows CISE to tailor system design and services for our user community and to satisfy the highly specialized technical requirements of scientific applications such as climate system models. More than 70% of CISE’s HPC system use is related to running NCAR-developed climate and weather applications, and this well-defined workload allows CISE and NCAR scientists to optimize the most heavily used models and applications on current and future systems. It also ensures that model development and research in Earth System processes can occur in a controlled yet responsive environment where researchers can prepare complex models and perform the computationally demanding tests required to validate them.

The size, breadth, and disciplinary pursuits of the CISE user communities offer perspectives on the scientific impact enabled by CISE’s HPC, data analysis, and archival resources. These user communities reported more than 320 publications and 57 dissertations and theses resulting from CISE HPC support in FY2014 (the timeframe of our most recent survey). Scientifically, our user communities span 17 areas of interest in the atmospheric and related sciences.

CISE works to provide equitable and efficient access to several distinct communities of researchers in the atmospheric and related sciences, including the broad university community, Climate Simulation Laboratory (CSL) users, NCAR researchers, and University of Wyoming researchers through the Wyoming-NCAR Alliance. In FY2015, CISE continued to manage several allocation processes to distribute resources and ensure access by the most meritorious projects.



CISE allocations to university researchers have supported the scientific objectives of more than 150 different NSF awards each year for the past decade. In FY2015, active projects supported more than 300 unique NSF awards.

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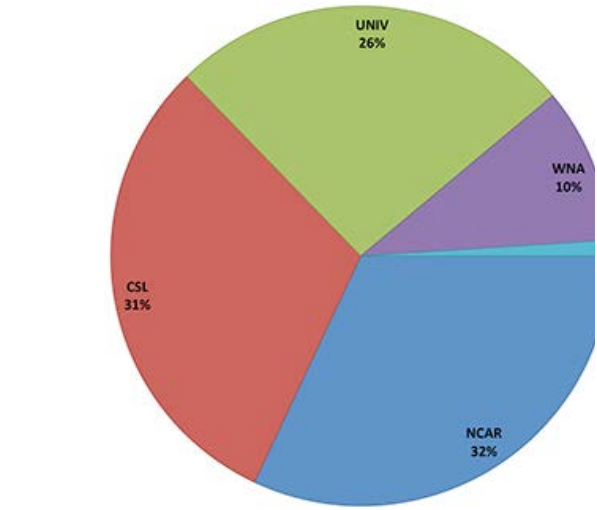
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Approximately 29% of Yellowstone is available to U.S.-based University researchers with NSF awards in the atmospheric or related sciences. University requests are reviewed twice per year by the CISL HPC Allocation Panel (CHAP). In October 2014 and April 2015 combined, the CHAP reviewed 90 requests for 472 million core-hours on the Yellowstone system, while university researchers also submitted nearly 230 small allocation requests during FY2015, indicating a growing demand for resources well beyond Yellowstone’s current capacity.



The FY2015 usage of Yellowstone by CISL’s major user communities showed strong increases by both the University and Wyoming communities, bringing the actual usage very close to the targets for each area.

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In geographic scope, CISL’s university users represent hundreds of different universities and collaborating institutions, primarily in the U.S. as defined by our HPC mission. CISL allocations to university researchers have supported the scientific objectives of more than 150 different NSF awards each year for the past decade. In FY2015, active projects supported more than 300 unique NSF awards, and 780 university projects were open during the year on CISL resources (an 11% increase over FY2014).

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A comparable portion (29%) of Yellowstone is also allocated to NCAR researchers in support of the computational needs of the NCAR laboratories, including NCAR Strategic Capability (NSC) projects. A new cohort of these large-scale projects was reviewed in April 2015 by a panel of NCAR computational scientists and approved by the NCAR Executive Committee.

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About 28% of Yellowstone is available to the CSL at NCAR; in FY2015, the CSL review process was the responsibility of the CHAP. In addition to supporting the CESM community allocation, CSL projects engage researchers funded by NSF awards to pursue climate-related science questions requiring large-scale simulations of Earth’s climate system.

The Wyoming-NCAR Alliance (WNA), which targets geosciences collaborations among the University of Wyoming, NCAR, and institutions in other EPSCoR states, convened the Wyoming Resource Allocation Panel (WRAP) in February and July 2015. In FY2015, the WNA awarded 55.6 million core-hours to nine large projects, and initiated nine small allocations; 33 different WNA projects used nearly 50 million Yellowstone core-hours.

This work is a crucial part of CISL’s computing imperative to provide hardware cyberinfrastructure customized for the atmospheric and related sciences. This ongoing service for users is supported by NSF Core funds including CSL funding. The Wyoming Resource Allocation Panel (WRAP) is supported by funding from the University of Wyoming.



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SPECIAL COMPUTATIONAL CAMPAIGNS

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

The table below lists the special computational campaigns supported by Cisl during FY2015. The efforts included support for two projects that involved demonstrating operational capabilities for improving weather and climate forecasting with NCAR flagship models.

FY2015 Special Campaign	Project Lead	Begin	End
MPAS global 3-km hindcasts for HIWPP	W. Skamarock	01-Jun-2014	31-Dec-2014
Testing and applying WRF-Solar for irradiance and solar power prediction	S. Haupt	16-Jun-2014	30-Sep-2015
Impacts of climate change on coral reef ecosystems of the Coral Triangle Region	J. Kleypas	17-Jun-2014	30-Apr-2015
Completion of atmospheric model development for CAM5.5 and the North American Multi-Model Ensemble hindcast suite	J. Tribbia	23-Dec-2014	30-Jun-2015
Real-time evaluation of extended guidance provided for SPC applications by a global convection-permitting model	W. Skamarock	17-Mar-2015	31-Dec-2015
A large-eddy simulation study of Southern Ocean boundary layers	P. Sullivan	01-May-2015	30-Jun-2015
The North American Multi-Model Ensemble (NMME) Phase II seasonal system	J. Tribbia	15-May-2015	31-Jul-2016
Regional climate ensembles project	C. Bruyère	01-Nov-2014	03-Sep-2016
Real-time high-resolution ensemble analyses and forecasts of high-impact weather with NCAR's DART facility and WRF model	G. Romine	01-May-2015	30-Apr-2016

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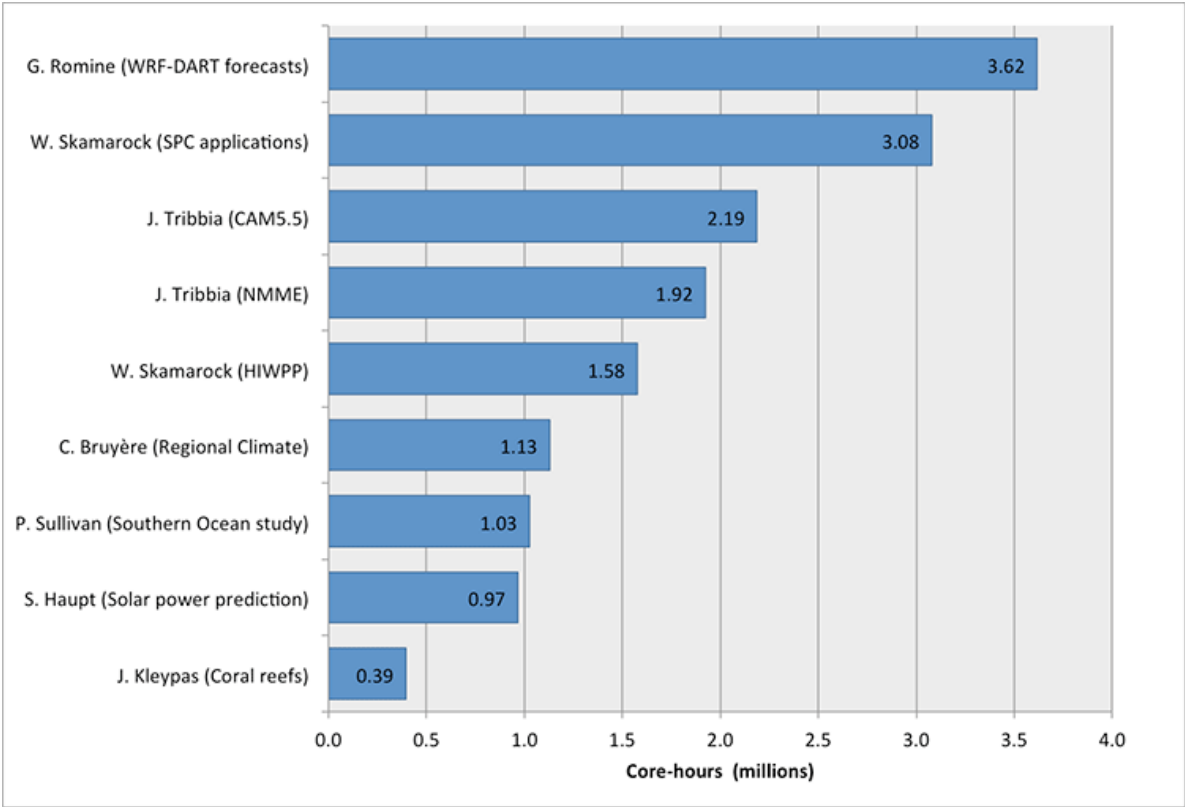
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CISL works to accelerate scientific discovery through numerical simulation by providing a portion of the Yellowstone system to special campaigns. The image shows usage of Yellowstone for special computational campaigns during FY2015.

Building on their demonstrated success producing real-time ensemble forecasts during the Mesoscale Predictability Experiment (MPLEX) in 2013, the same team has begun conducting real-time 48-hr, 10-member, 3-km WRF-based ensemble forecasts over the entire contiguous United States for a full year, running daily on Yellowstone starting in April 2015. This data set will permit evaluation of high-resolution ensemble predictions across a variety of weather regimes including events not typically studied with convection-permitting ensembles, such as snowstorms. Thus, this data set will be useful to university researchers studying topics ranging from data assimilation to physical processes and predictability. The year-long aspect of this work will help WRF model developers understand seasonal WRF model climatology and biases. Furthermore, the team will objectively verify probabilistic ensemble forecasts and develop new methods to evaluate high-impact weather events ranging from supercell thunderstorms to winter-weather hazards. A system of this scope is unprecedented considering the scales involved. Limited-area continuously cycled ensemble data assimilation for a year-long period has never before been attempted, and this will be the only such high-resolution ensemble in the world.

In spring 2015, the MPAS team from the Mesoscale and Microscale Meteorology (MMM) lab used Yellowstone to produce extended-range convection-permitting forecasts in support of a collaborative effort with NOAA and the University of Oklahoma, part of the Next Generation Global Prediction System (NGGPS) project. Using the MPAS model and a variable mesh with 3-km resolution over the continental United States, the team produced five-day forecasts for the 2015-2016 Spring Forecast Experiments conducted at the NOAA Storm Prediction Center and evaluated these forecasts as part of ongoing efforts to provide extended range, five-day guidance for severe weather. The Yellowstone computations tested whether the use of a multi-scale global model provided more information about the potential, mode, and intensity of convective activity to storm forecasters for Day 2 and beyond, over and above what the current NCEP modeling suite provides. The 2015 NOAA/SPC Hazardous Weather Testbed spring experiment spanned five weeks in May and June, and the MPAS team conducted one 5-day forecast per day for the weekdays during those five weeks.

These special computing campaigns serve CISL’s computing imperative to provide on-demand and real-time services support for hardware cyberinfrastructure. This work is made possible through NSF Core

funds, including CSL funding.

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HELP DESK AND CONSULTING

CISL’s strategic commitment to providing robust, accessible, and innovative information services and tools to our customers includes end-to-end services for NCAR’s supercomputer users with 24x7 frontline user support, extensive online documentation, and consulting services for providing in-depth expertise. CISL’s User Services Section (USS) unites four functions – the CISL Help Desk, Consulting Services, Documentation, and Accounts and Allocations – to streamline and coordinate user-oriented procedures and support activities.

User support efforts in FY2015 by the Consulting Services Group (CSG) focused on helping the user community make full, efficient use of the Yellowstone system’s capabilities, and planning for its successor system at the NCAR-Wyoming Supercomputing Center (NWSC). During FY2015, CISL’s consulting staff provided expertise and one-on-one, customized service for special campaigns, including workshops and field campaigns, and benchmarking and testing in support of the NWSC-2 procurement effort.

CSG also provided staff expertise to a CISL-wide effort aimed at improving the performance of NCAR flagship models on Yellowstone with an eye toward preparing the models for future systems. These models included the Community Earth System Model (CESM), the Weather Research and Forecasting model (WRF), and Model Prediction Across Scales (MPAS). The Consulting Services Group also continued to support users of these models on the Yellowstone system and taught several training courses for users of CISL’s supercomputing and storage resources.

USS continued its ongoing dedication to providing up-to-date documentation that helps users compute efficiently on Yellowstone and other CISL-managed systems. USS staff created or updated more than 160 web pages in FY2015 to ensure the continued accuracy, relevance, and timeliness of CISL’s documentation and supporting video presentations. The website pages that support users’ computation and data management efforts received 127,000 unique page views in FY2015.

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## Start the TurboVNC *client*

Run the TurboVNC client on your local system, following these examples.

### Linux and Mac OS X

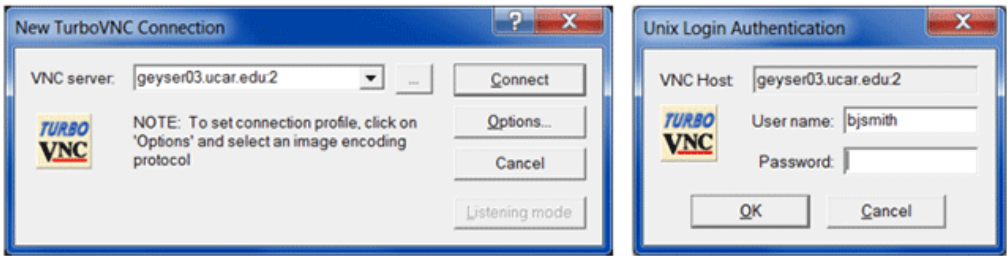
Open an X terminal application and run **vncviewer** on your command line. Include the host name and display number, as in this example.

```
vncviewer geyser03.ucar.edu:2
```

### Windows

Select *TurboVNC Viewer* from the *Start Menu* TurboVNC group on your desktop.

Type the host name and VNC display number in the dialog box.



This excerpt from a CISL documentation page describes one step in the process of running visualization applications in the Yellowstone environment. Documentation complements the services that CSG and Help Desk staff provide to the end-user community. Such documentation contributes to efficient use of scientists’ supercomputing and data storage allocations.

CISL tracks user support activity for this growing community using an ExtraView trouble ticket system. In FY2015, the ticket system recorded 10,843 tickets to the CISL Help Desk, a 12% decrease from the FY2014 total. The average number of log entries per ticket was 4.43, and communication with users was highest on complex cases. Of the total tickets submitted, the Help Desk team closed 2,608 tickets in an average of 3.57 days (median, 0.72 days), or 217 per month on average. In the same period, Consulting Services staff resolved 1,303 more complex requests with an average response time of 14.5 days (median, 5.0 days). An additional 535 user support tickets that were fielded related primarily to managing allocations and accounting, with an average response time of 5.6 days (median, 0.81 days).

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



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OPTIMIZING MODEL PERFORMANCE ON NCAR SUPERCOMPUTERS

In recent years, the amount of performance that can be extracted from supercomputers through software optimization has become at least as important as that coming from hardware improvements. Significant factors driving this trend include the stagnation or even reduction of the speed of a single thread of execution, the aggressive introduction of vector/SIMD instruction sets, the increased core count per processor socket which requires careful parallel programming to properly utilize, and the introduction of heterogeneous architectures composed of both conventional processors and accelerator coprocessors.

In FY2015 CISL continued to augment its efforts to optimize NCAR codes, focusing first on NCAR's flagship community models. This strategic optimization thrust is two-pronged, with one effort (called SPOC) aimed at optimizations of current model code bases for Yellowstone-like systems (i.e., conventional multi-core processors) and a second (called IPCC-WACS) housed in TDD's ASAP group focused on the future challenges of the accelerator space. The SPOC effort is described below, and the IPCC-WACS effort is described in the section titled [Evaluating many-core and accelerator-based architectures](#).

Strategic Parallel and Optimization Computing (SPOC) initiative

In FY2015, CISL's Strategic Parallel and Optimization Computing (SPOC) initiative continue its NCAR-wide efforts to increase the performance and efficiency of NCAR's community codes—CESM, WRF, and MPAS—on Yellowstone. In addition to benefits on current Yellowstone hardware, the SPOC efforts are targeting code optimizations that are expected to translate to performance benefits on future processor architectures. In addition to support within the Consulting Services Group (CSG), CISL identified additional resources for this work and embedded them directly with the model development teams. Key activities this year include:

- CESM performance was targeted on a number of fronts. A CSG staff member worked to make the CESM internal performance timing infrastructure consistent across models, essential groundwork for identifying future optimization targets and for better understanding the benefits of performance improvements. CISL and CGD staff also supervised a summer intern from Louisiana State University, who focused on parallel I/O optimizations in the POP ocean model.
- SPOC supported an external optimization expert who worked with the MPAS development team on the MPAS dynamical core. Specifically, through changes to only about 200 lines of code and experimentation with Intel compiler options, this work resulted in 15% to 20% improvement in the dynamics, which translates to an 10% to 15% improvement for MPAS overall.
- Work with the WRF team involved two SIParCS interns who identified several optimization opportunities that potentially represent a 15% performance improvement for WRF and 25% for WRF-Chem. The students also began exploring performance optimization possibilities for running WRF on Xeon Phi and demonstrated 50% performance improvement in a carefully crafted, idealized WRF case, run in symmetric host-Phi mode. The students have been hired by CSG as student assistants to continue pursuing WRF optimizations.
- CSG staff investigated potential system software and architectural changes. A comparison of different MPI libraries suggested possible performance improvements, and CSG continues efforts to understand the usability and performance benefits for the full CESM suite. An InfiniBand topology

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study was conducted on Yellowstone and a number of external HPC systems to quantify performance tradeoffs for NCAR’s flagship models and inform the NWSC-2 procurement process.

- Training has also been identified as a key contribution from the SPOC initiative toward building the relevant skills in the NCAR developer community. To that end, SPOC-supported staff conducted workshops on finding hotspots and bottlenecks in code and an introduction to performance tuning and optimization. CISL also hosted vendor-led training events by Intel, on their analysis tools and compilers, and by Allinea, with an overview of their debugging and profiling tools.

The SPOC initiative is supported by NSF Core funds.

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CISL'S BIG DATA SERVICES AND SOFTWARE TOOLS

CISL provides our research community with Big Data tools and services for locating, accessing, and analyzing a variety of observational and model research data collections. These data are served through data gateways over high-speed wide-area networks and are also accessible from disk and tape storage on the Yellowstone computing complex. These tools and services combine to support our communities' efforts to extract scientific knowledge from the petabytes of data available on NCAR's cyberinfrastructure. These tools and services include:

- Research Data Archive (RDA) – The climate and weather research communities' data needs continue to grow, so CISL adds new content and access features to the RDA. More than 11,000 unique users acquire 1.1 petabytes of data yearly through the RDA web portal. In addition, hundreds of internal users access substantial amounts of data directly from NCAR's Globally Accessible Data Environment (GLADE).
- Data Gateways – Data gateways expand scientific collaboration by connecting research communities and new climate data consumers with data products and tools. The Science Gateway Framework (SGF) is a unified portal for scientific data users, and it helps researchers use new supercomputing environments. The SGF underlies CISL's [NCAR Earth System Grid](#), the [ACADIS](#) Arctic Data Repository, and the [Community Data Portal](#).
- Data Assimilation Research Testbed (DART) software – DART supports community researchers and improves their prediction skill for and understanding of the Earth System by collaboratively developing and applying data assimilation methods across a wide range of geophysical problems.
- Data Analysis Tools – CISL's portfolio of data analysis tools provides an ever-growing community of scientists with unique capabilities tailored to the disciplines we serve. The scalability and performance of these tools are increasingly important in the era of Big Data. The Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Research (VAPOR) offers the capability to efficiently explore enormous or complex 3D data sets. The NCAR Command Language (NCL) is an open source scripting language for geoscientific data analysis and visualization. NCL reads and writes several geoscientific data formats and creates publication-quality graphics. PyNIO and PyNGL are Python modules built on top of NCL's component libraries, providing Python users with the same file I/O and visualization capabilities as NCL. PyAOS is an atmospheric and oceanic-based computational library with contributing partners from universities, national laboratories, and commercial enterprises.
- [NCAR Data Sharing Service via Globus Plus](#) – NCAR's Data Sharing Service uses Globus Plus to augment CISL's existing Globus-based data transfer services with user-managed big-data sharing capabilities.

Through parallelism, end-to-end workflows employing these tools and services are used by scientists to produce results more quickly and to a broader audience of researchers.

The funding for each of these efforts is specified in the sections below.

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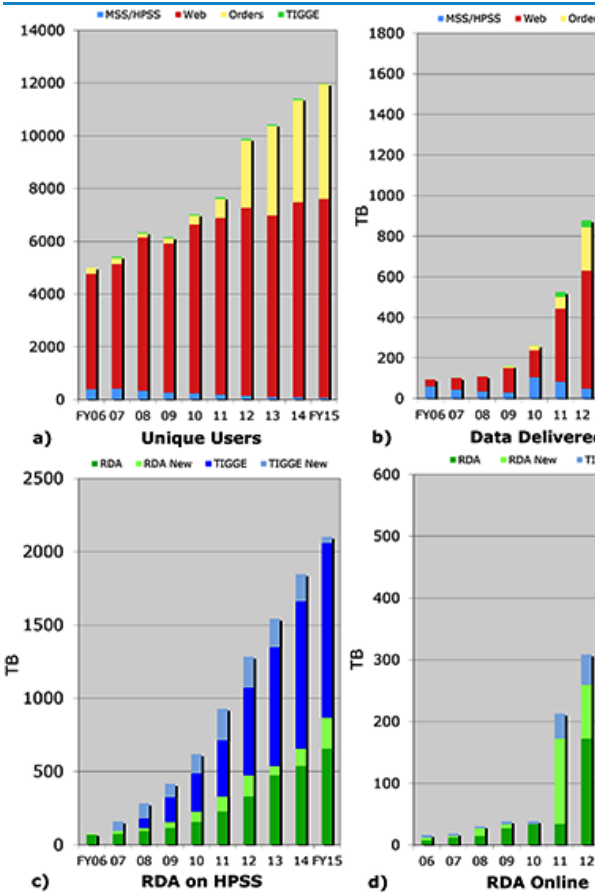
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RESEARCH DATA ARCHIVE

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

In FY2015, over 12,000 unique persons were provided about 1.5 petabytes of data through various primary access pathways: the NCAR HPSS, public servers on the web, one-time special requests prepared for individuals, and the THORPEX (The Observing system Research and Predictability EXperiment) Interactive Grand Global Ensemble (TIGGE) archive (see charts a and b). The TIGGE project stopped active data collection during FY2015 and now has minimal impact on these metrics. The number of unique users increased steadily from 2012 through 2015. One-time requests (subsetting, format conversion, and HPSS file restaging to disk) and full file downloads increased.

CISL is making it easier for users to access terabyte-sized archives on their own. Orders were automatically prepared for over 4,300 individuals, and they received over 500 terabytes of data. Web users form the largest group, with 7,500 people downloading over 1,000 terabytes (1.0 petabytes) of data. There are fewer users of the HPSS (71 requesting 21 terabytes) and TIGGE (16 requesting 3 terabytes) services. The newest and most-used RDA collections are directly available from NCAR's Globally Accessible Data Environment (GLADE) to the HPC environment. We currently cannot estimate the metrics for this pathway, but it is substantial because the access from the HPSS (tape-based) has dropped, and anecdotally, our local users are pleased. These metrics indicate that the RDA is an important growing data resource for a broad community.



These charts show the data access and growth metrics for the RDA during FY2006-FY2015. a) The number of unique RDA users specified by access pathway: the NCAR HPSS, publicly available web servers, one-time special requests (orders) prepared for individual users, and TIGGE. b) The amount of data delivered to customers, by access pathway. c) The amount of data in the HPSS archive, showing annual growth and not including backups. d) The amount of data on public web servers, showing annual growth. Charts a) and b) indicate the RDA's significance to the community. Charts c) and d) show the annual progress toward building more valued content into the RDA.

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The RDA content expanded by over 200 terabytes in FY2015 (see charts c and d). The complete RDA is now over 2.1 petabytes, and over 550 terabytes of it is readily available via GLADE (chart d). NCAR users can access the portion of the RDA not available on GLADE directly from the HPSS, and the Data Support Section provides automated procedures to assist outside users with data access from HPSS.

The RDA is constantly changing. Curation extends and adds to existing datasets, and stewardship improves the documentation, creates systematic organization, applies data quality assurance, and develops user access. Many routine tasks and background infrastructure developments are necessary to maintain the RDA. Major accomplishments for FY2015 include:

- Added Globus access as an RDA service, including for both static datasets and one-off orders.
- Expanded automated systems that use CISL HPC and GLADE to give users better access to terabyte-sized datasets. More than 41,000 individual data requests were processed.
- Added significant data assets to the RDA:
  - The International Surface Pressure Databank version 3
  - Japanese Reanalysis 55 year, Atmospheric Model Intercomparison Project
  - Japanese Reanalysis 55 year, Conventional Data Only
  - NCEP Final 0.25-Degree Global Tropospheric Analyses and Forecast Grids
  - Final 30km Arctic System Reanalysis
- Expanded Thematic Realtime Environmental Distributed Data Services (THREDDS) Data Server (TDS) to over 35 popular GRIB-formatted datasets, creating metadata and data access for scientific tools using standard interoperable protocols such as Open-source Project for a Network Data Access Protocol (OPeNDAP).
- Expanded HPC-driven spatial, temporal, and parameter subsetting with data format conversion options to 55 datasets.
- Increased formal data citation potential by assigning and maintaining DOIs on 55 RDA datasets.

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

RDA maintenance and development within CISL are almost entirely supported by NSF Core funding. A small NASA grant supplemented development of ICOADS.



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SCIENCE GATEWAY SERVICES

CISL builds and operates science gateways that provide sustainable access to shared cyberinfrastructure for diverse scientific communities. Our projects span climate science, regional climate research, arctic science, solar science, digital preservation, and international efforts to develop metadata and knowledge infrastructure. Many of these efforts are tied to major interagency, national, and international initiatives, including the Intergovernmental Panel on Climate Change (IPCC), the International Polar Year (IPY), the World Climate Research Program (WCRP), and the Library of Congress' National Digital Information and Infrastructure Preservation Program (NDIIPP). Most of these projects use open source, web portal infrastructure based on the Science Gateway Framework (SGF). CISL's contributions to this suite of science gateway services is supported through NSF Core funding and augmented by special funding as noted below.

Our contributions to science gateways support CISL's computing imperative for software cyberinfrastructure by maintaining, operating, and supporting 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 operating science gateways and other technologies that provide critical cyberinfrastructure (CI) to broad communities. Finally, operational services provided for the NCAR Earth System Grid gateway (ESG-NCAR), ACADIS, WMO, and other collaborations address CISL's strategic action item to meet the challenges posed by large and heterogeneous environmental data, and to establish metadata standards for diverse collections of data and models.

Detailed updates on our portfolio of Science Gateway services follow:

Earth System Grid Gateway at NCAR (ESG-NCAR)

CISL operates the ESG-NCAR gateway that provides data discovery and access services for global and regional climate model data, knowledge, and software. The ESG-NCAR gateway participates in the Earth System Grid Federation (ESGF), which is a globally distributed petascale data management environment for CMIP5/IPCC-AR5 and U.S. climate science. The ESG-NCAR gateway supports community access to data products from many of NCAR's community modeling efforts, including IPCC, PCM, AMPS, CESM, NARCCAP, and NMME data products. The ESG-NCAR gateway is heavily used by over 1,200 users monthly and delivers over 30 terabytes monthly of scientific data to the community.



**ACADIS**  
Advanced Collaborative Arctic  
Data Information Service

NSF Arctic projects  
Self publishing tools  
Many disciplines  
Long term preservation



**ESGF & ESG-NCAR**  
Climate Data at NCAR

Climate models  
RCMs (NARCCAP)  
Large data volumes  
Heavily accessed

Shown above are two prominent science gateway services operated by CISL. These systems provide access to shared data management cyberinfrastructure for diverse scientific communities from petascale “big head science” to the “long tail” of small individual investigator-based projects. Combined, these services support over 1,250 active users monthly with annual downloads of over 2 petabytes.

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In FY2015, the ESG-NCAR gateway capabilities were extended primarily to support simpler end-user data product access and address the needs of increased data publication volume. CISL also provided considerable end-user support through the ESG-NCAR help desk, answering over 300 end-user inquiries. We moved to a more continuous software delivery process, releasing and deploying updated versions every two weeks, bringing end-user value early and often via our Agile Scrum software development process. Other FY2015 accomplishments include refining data provider workflows; publishing performance enhancements, tools, and services for DOI assignment; an updated user interface framework; simplified security workflow; and open data access.

CISL continued to work closely with our community of data managers to process and publish data products from AMPS, CESM, CCSM4, NARCCAP, and NMME projects. Over 725 terabytes were published to ESG-NCAR during FY2015, raising the full volume of ESG-NCAR to 4.3 petabytes and 6.4 million files.

NSF Core funds support the operational ESG-NCAR gateway as well as special funding from the National Multi Model Ensemble (NMME) and High Impact Weather Prediction (HIWPP) projects.


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**Advanced Cooperative Arctic Data and Information Service (ACADIS)**

ACADIS is a collaboration between CISL and NCAR’s Earth Observing Laboratory, the National Snow and Ice Data Center, and Unidata. ACADIS is a community data service that provides project data management planning, data archival, preservation, and access for all projects funded by NSF’s Arctic Science Program (ARC). CISL’s contributions to ACADIS include the ACADIS gateway, which provides an end-to-end service where NSF-supported data providers can publish their data collections and make them available to the broad community of researchers.

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Accomplishments in FY2015 include expanding REST-based data management APIs, adding tools for DOI assignment, and extending ISO-19115 metadata record support. The data provider workflow was significantly enhanced based on end-user feedback and usability studies to provide easier and faster metadata authoring, bulk file upload, and efficient creation of metadata-rich records. An automated archive export and storage process was developed to store a copy of the repository data and metadata in the Amazon S3 service. A Cloud Service-based Gateway and services were deployed and tested to assess the costs associated with potential future cloud-based operations. The ACADIS gateway supports a community of over 200 principal investigators and receives an average of 50 provider-self-published datasets monthly.

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The ACADIS project is supported by NSF Core and NSF Special funds.

**Community Data Portal (CDP)**

The CDP offers a broad range of scientific data collections that includes observations, climate, atmospheric chemistry, space weather, field programs, models, analyses, and more. Many programs and projects at NCAR, UCAR, and UCAR Community Programs (UCP) are represented in the portal. CDP provides a self-publishing model that offers data management tools directly to projects and PIs. Roughly 2,200 registered CDP users are discovering, accessing, and using 8,000 collections representing over 6.5 terabytes of managed data holdings. Data discovery is enhanced worldwide by automatically sharing these metadata with other portals and international centers.

In FY2015 we developed a plan for replacing the CDP services with an open source solution that has a lower maintenance cost. This work was based on input from the nearly 50 active CDP data providers and the NCAR Data Stewardship Engineering Team (DSET). In FY2015 we continued to provide operational support, security upgrades, and critical bug fixes for the CDP services.

CDP is supported by NSF Core funding.

**Chronopolis: Federated Digital Preservation over Space and Time**

There is a critical and growing need to organize, preserve, and make accessible the increasing number of digital holdings that represent vital intellectual capital, much of which is precious and irreplaceable. Chronopolis is a strategic collaboration among the San Diego Supercomputing Center (SDSC, lead

organization), NCAR/CISL, the University of California Library System, and the University of Maryland. It is aimed at developing national-scale digital preservation infrastructure that has the potential to broadly serve any community with digital assets for science, engineering, humanities, and more. In addition to community collections, Chronopolis CI is being used to provide digital preservation services for the ACADIS project.

In FY2015, CISL replaced our Chronopolis production node with a new 325 TB storage system and related server and software services. CISL developed a new web-based dashboard tool for system monitoring and federation-wide reporting and capacity planning. CISL continued to provide operational support of the NCAR storage node which currently manages 25 terabytes and over 2.3 million managed objects.

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

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DATA ASSIMILATION RESEARCH TESTBED SOFTWARE

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

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.

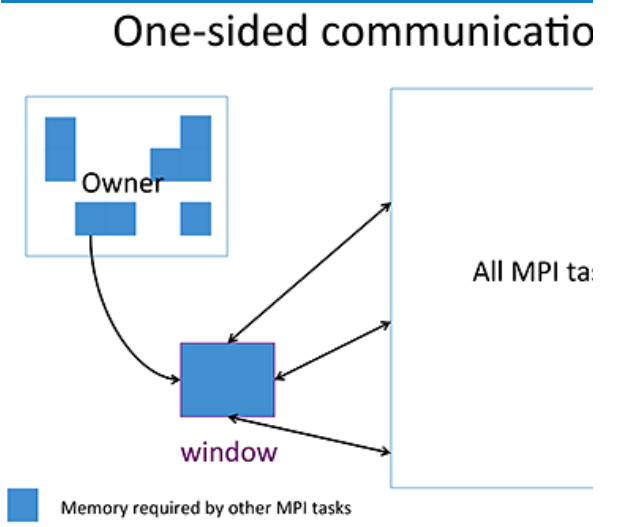
A new version of DART that uses the remote memory access (RMA) capability of MPI-2 has been developed and is in production use by several groups producing real-time forecasts with WRF. The DART RMA version eliminates the need to store a complete model state vector in the memory space of a single process and allows much larger models to work with DART. Work has begun on merging the previous DART software that computed all forward observations locally with the RMA version into a single source that will work efficiently for models of all sizes.

An initial implementation of a cross-component assimilation system for fully coupled CESM has been completed. This implementation has revealed a number of new software engineering challenges, in particular, allowing simultaneous use of observations like temperature that exist in more than one model component (e.g., atmosphere, ocean, land).

The interfaces between DART and the CAM family of models (CAM-FV, CAM-SE, WACCM, CAM/Chem) have been updated to work efficiently with the latest versions of the models and DART.

A fundamentally new data assimilation algorithm, the fourth-order-accurate quadratic ensemble filter developed by Dan Hodyss at NRL, has been implemented in DART. The quad filter was tested with both low-order models and GCMs and will work with any model for which a DART interface exists.

DART interfaces to a number of new models were developed in collaboration with model developers and users. New models include: the WRFHydro hydrological modeling system, the CM1 non-hydrostatic convective model in collaboration with the University of Washington, the Joint UK Land Environment Simulator (JULES) land surface model in collaboration with the University of Bristol, the Laboratoire de



The remote memory access (RMA) version of DART uses MPI2 one-sided communication to allow any MPI task access to any part of the model state vector that is placed in a memory window by the task that "owns" it. This means that DART can now compute the expected value of observations while the state vector is distributed across many MPI tasks. This removes a previous limitation that the entire model state must fit in the memory of a single MPI task and allows DART to run with much larger prediction models.

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Meteorologie Zoom (LMDZ) atmospheric GCM in collaboration with the Indian Institute of Technology, and the Unified Curvilinear Ocean Atmosphere Model / General Curvilinear Ocean Model (UCOAMS/GCOM) in collaboration with San Diego State University.

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NCL DATA ANALYSIS AND VISUALIZATION SOFTWARE

The NCAR Command Language (NCL) is a data analysis and visualization environment developed primarily at CISL in deep collaboration with a number of core scientific groups. NCL enables scientists to easily and effectively read, analyze, and visualize their geoscientific data on platforms ranging from personal laptops to high performance computers. PyNIO and PyNGL are Python modules based on NCL's file input/output and visualization capabilities; these modules offer NCL's software components to a wider and more mainstream user base.

The NCL and Python tools have been embraced broadly across the international Earth System sciences community spanning research, education, operational, military, government, and commercial organizations. They are used for data analysis and display to generate publication-quality visualizations for journals, for post-processing and comparing data from a wide range of Earth System models, for real-time data access and display at operational centers, and by hundreds of graduate students as the primary tool for their research. Critical to the importance of these tools is that they are free, well supported, and run across a wide variety of UNIX systems, allowing students and scientists to continue their research uninterrupted as they change organizations.

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

In FY2015 we released a major version of NCL with over 20 new computational and visualization routines and major improvements to internal OpenMP code for drawing raster graphics. We laid some of the research groundwork for developing a web-based GUI for NCL. We released two versions of PyNIO for use in parallelized workflows for climate model diagnostic packages, and for eventual incorporation into "xray," an extension of a popular high-performance data analysis library for scientific Python ("pandas").

Also in FY2015 we added Python-based task parallelism to a large suite of NCL scripts in the Climate Variability Diagnostics Package (CVDP) – an analysis tool that documents the major modes of climate variability in models and observations – resulting in a 4x to 6x speed-up. We released a beta version of PyNGL that incorporates the latest graphical features of NCL with contouring support for complex grids and the new color model. We put PyNIO under "conda," a package manager that allows for very fast and easy installation of Python packages that require complicated dependencies. We created an NCL / Python Power Users Group called "nclpy-group."

There were 21,769 downloads of NCL, PyNGL, and PyNIO software in FY2015. Our email lists had 3,156 total postings on 1,210 unique subjects.

Our core development and maintenance of NCL and Python tools is primarily supported by NSF Core funding.



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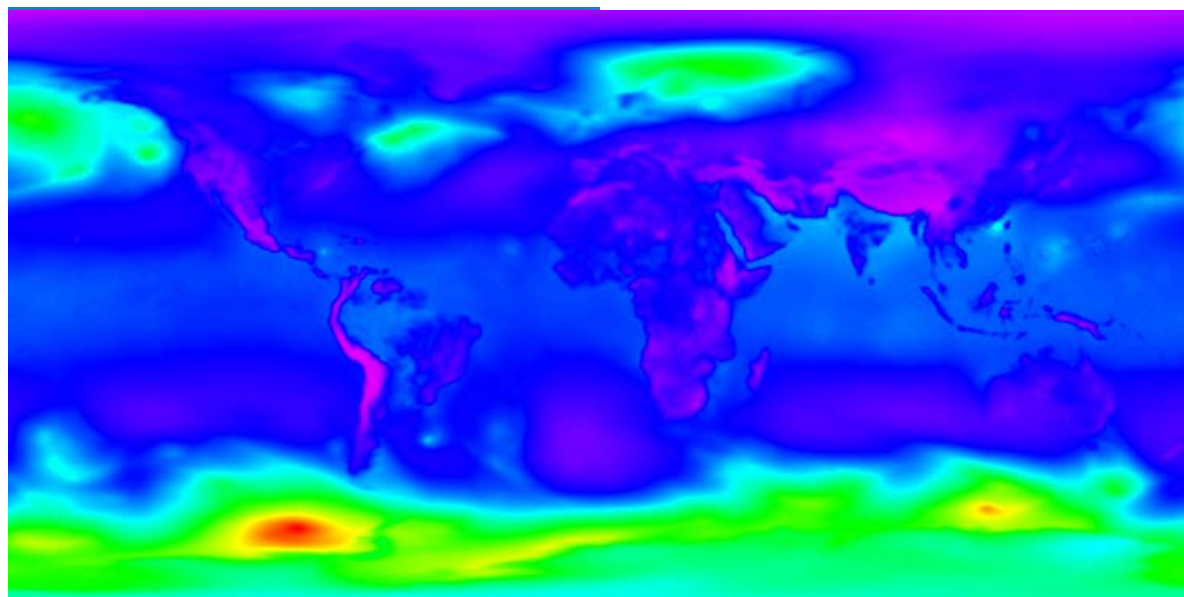
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## VAPOR VISUALIZATION SOFTWARE FOR VERY LARGE DATASETS

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 at Davis and the Ohio State University. With subsequent support from the NSF, and the Korean Institute for Science and Technology Information (KISTI), VAPOR has transitioned from a research project into production, and it has become a strategic priority for CISL. Though VAPOR's origins are strongly rooted in geophysical turbulence, more recent work on VAPOR has focused on expanding its capabilities to support the needs of the broader Earth System sciences community, particularly in the areas of numerical weather prediction, climate, and ocean modeling.



This image demonstrates VAPOR's new MPAS data reader, developed in collaboration with DKRZ. With the pending release of VAPOR version 2.5, users of the MPAS-A and MPAS-O models will have the ability to interactively explore high-resolution MPAS outputs.

Development of VAPOR is closely guided by a steering committee comprised of Earth scientists from around the world that sets development priorities, dictates software requirements, and serves as friendly users for testing and evaluating new software features. VAPOR's unique features include its use of a wavelet-based, progressive-access data 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.

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

Climate & Global Dynamics

Computational & Information Systems Laboratory

Earth Observing Laboratory

High Altitude Observatory

Mesoscale & Microscale Meteorology Laboratory

National Center for Atmospheric Research

Research Applications Laboratory


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

VAPOR’s FY2015 efforts were focused on meeting the contractual obligations of grants from the Korea Institute of Science and Information Technology (KISTI) and the NSF, as well as on developing and enhancing core capabilities. The KISTI award funded the development of numerous enhancements to VAPOR’s suite of visualization tools such as support for OSGeo Tile Mapping Service high-resolution cartographic maps, improved contour and hedgehog plots, and stereoscopic rendering. With support from a two-year NSF SSI2 grant, the VAPOR version 3 refactoring efforts – which focus on third party extensibility and improved ease use – were significantly advanced. In particular, VAPOR’s wavelet-based data model was restructured to facilitate use by other communities (and is now the basis for bioimaging data analysis development efforts underway at UCSD’s Center for Scientific Computation in Imaging), and a working, limited-functionality prototype of the new GUI was completed. Other highlights include:

- The number of registered VAPOR users worldwide has reached nearly 8,000, and VAPOR was cited by 13 scholarly journals to date in CY2015.
- Development work was completed and version 2.5 of VAPOR was on track to be released in November 2015.
- A fifth year of funding to support further enhancements was secured from KISTI.
- A collaboration with DKRZ led to the development of data importers for the MPAS and ICON global models.
- A visualization of LES data produced by NCAR was accepted into and shown at the XSEDE Visualization Showcase.

This project is supported by NSF Core funds, a subaward from the University of California at San Diego, 54067252, and KISTI grant C15012.

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CISL’S ENTERPRISE ARCHITECTURE

Enterprise Architecture (EA) is the name of the discipline of translating an organization’s vision and strategy into effective business practices and information technology (IT) infrastructure to support those practices. EA is a relatively young and still-evolving discipline, but it has been adopted by a wide variety of public and private organizations. The U.S. Government has developed a set of reference models called the Federal Enterprise Architecture.

Under the auspices of the UCAR Information Technology Council (ITC), co-chaired by Anke Kamrath (OSD director) and Shawn Winkelman (Finance and Administration IT Director), and at the direction of the UCAR President’s Council, a UCAR-focused Enterprise Architecture Team (EA Team) was formed at the beginning of FY2013. The team meets biweekly to discuss IT topics of significance to the institution and recommend courses of action.

During FY2015, the EA Team oversaw the completions of UCAR’s Google Apps for Government rollout. The EA Team has also been heavily involved in developing an appropriate framework for Project Portfolio Management (PPM). Classic PPM methodologies are a concern because of the heavyweight process. EA has been exploring Agile-based methodologies as possibly a better fit for the organization.

Enterprise Architecture has completed reviews and made recommendations on the Identity Management strategy for the organization. The EA team has also reviewed service management plans and is actively involved in a phased effort to move UCAR to security best practices. Many of the UCP and NCAR entities are now being required to adopt Federal Information Security Management Act (FISMA) requirements. Finally the EA team has been actively involved in developing the UCAR IT strategic plan.

Development of an EA for UCAR supports the Science and Collaboration Fabrics of the CISL Strategic Plan, and is a joint effort between CISL/OSD and UCAR Finance and Administration IT. This effort is supported by UCAR indirect funds.

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NETWORK ENGINEERING AND TELECOMMUNICATIONS

Networking infrastructure is essential technology vital to UCAR's ability to function and prosper in a rapidly evolving scientific and technical environment. Networking infrastructure enables many aspects of the scientific enterprise to flourish: business processes, scientific investigations and analysis, communication, global collaborations, and educational and outreach missions. Network infrastructure is literally the backbone of all other IT infrastructure and services. A sound and reliable network infrastructure is critical to building stable IT infrastructure at the higher levels. It is the goal of the Network Engineering and Telecommunications Section to provide this fast, robust, and flexible infrastructure to support all other IT services.

Networking is a critical component of cyberinfrastructure. Networks are interconnected and interoperate at the campus, metropolitan, regional, national, and international levels. Networking is a global endeavor. Being well connected has become a requirement for successful business operations, but it is especially important for a national research center such as UCAR/NCAR. Networking provides a vital service enabling all functions at UCAR. UCAR's scientific mission is enabled and supported by networking. UCAR's business operations, including interactions with funding agencies, also depend on networking. Collaborative science would not happen today without networks, just as UCAR's business operations would not function.

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 and each other. These activities are essential for the effective use of UCAR/NCAR 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.

NETS pursued these **Local Area Network (LAN)** and general support projects in FY2015:

- UCAR network infrastructure re-cabling
- WASP inventory system
- GIS
- Softphones
- ML Room 034 remodel and NETS shop relocation
- Cellular support
- Network monitoring
- Netflow
- Extraview
- Filemaker
- Multicast support activities
- Business continuity
- Everbridge Emergency Notification System (ENS)
- UPS, grounding, wireless networking, IPT, Collocation Facilities Management (CFM)
- ML 29 infrastructure design
- IPT server replacement
- Spring and fall power downs
- Cisco 6500 to 4500 replacement
- Equipment maintenance
- Budget support



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- Purchasing support
- HAO MLSO network upgrade design
- OpenDCIM documentation
- NWSC Module A & B design
- NWSC2 procurement
- CG1 Library remodel
- EOL Executive Conference Room
- ARUBA Clearpass design
- Maintenance of NETS servers
- Replaced Vidyo systems with Chromebox
- Replaced Wiki Projects with Smartsheets

NETS pursued these **Metropolitan Area Network (MAN)** projects in FY2015:

- Boulder Point-Of-Presence (BPOP)
- Boulder Research and Administration Network (BRAN)
  - BRAN Table Mesa Flood Mitigation
- City of Boulder CG4 inter-building cabling

NETS pursued these **Wide Area Network (WAN)** projects in FY2015:

- Front Range GigaPoP (FRGP) ongoing management and engineering
  - Expanded Google peering to 20 Gbps
  - Netflix regional caching and upgrade
  - DREAM 20G upgrade
  - FRGP BiSON utilization
  - I2 NET+ support investigation
- New FRGP participants: I2/USDA
- City of Denver and USAP departed
- Internet2
  - Gender Diversity Initiative Co-chair
  - Network/Connector Liaison
- Bi-State Optical Network (BiSON)
  - Implemented Golden ring
  - Implemented BiSON South
  - UW NSF CC\*NIE 100G upgrade
- XSEDE
- Western Regional Network (WRN)
  - 100G upgrade implementation
- NOAA Research Network (NWAVE)
  - Boulder TIC design
  - 910 colocation design and support
  - WRN lambda addendum
- The Quilt Project – National Regional Networks Consortium
  - Jeff Custard – Executive Committee/Vice-Chair and Secretary
  - Marla Meehl – Nominations Committee
  - Marla Meehl – Finance Committee
  - Marla Meehl – CC\*IIE Regional Collaboration Working Group
- NSF CC\*DNI UH Mauna Loa Instrument Proposal to provide high speed wireless networking support

NETS pursued these **special projects** in FY2015:

- NSF RCMOA CC\*IIE Grand and WINS Supplement
  - Two RCMOA workshops
  - Women in IT Networking at Supercomputing (WINS) awardee process
- Westnet meeting support
  - January 2015
  - June 2015
- Enterprise Architecture Technical Advisory Board (EA-TAB) participation

NETS will continue to provide support and enhancements for all of these essential networking services. NETS activities are primarily supported through UCAR Communications Pool indirect funds, the FRGP/BiSON, NSF Core funds, and NSF proposal funds.

Detailed project descriptions appear below for three of these projects: Cisco 4510 upgrade and deployment, Aruba Wireless access point upgrade and deployment, and BiSON R7 upgrade.

### Cisco 6509 emergency replacement with Cisco 4510s

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UCAR networking depends on Ethernet switches at all locations including the NWSC. These switches provide 1 Gbps network service to all offices, conference rooms, public spaces, etc. and in addition, the switches provide Power over Ethernet (PoE) to power all Cisco IPT phones and many building services like PoE cameras. A little over a year ago, in the process of ordering update Cisco 6509 interface cards, we were notified, without prior warning, that Cisco was no longer supporting PoE on the 6509 platform. This required a rapid redirection of plans to efficiently order and replace all end-of-service hardware in a timely and cost-effective fashion.

Team lead Teresa Shibao worked closely with Cisco to identify and clearly define the problem, evaluate multiple solutions with the network engineering and management team, and worked with management to develop a creative, efficient, and cost-effective solution that has been deftly executed and implemented. The Cisco 4510 was identified as the appropriate technical solution, and Teresa, NETS management, Ellen Martinez, UCAR Contracts, and Dan Wilson, were able to work with Cisco to craft a cost-effective and creative solution (deep discount) and zero interest four-year capital lease (a new and unique solution for UCAR). The capital lease allowed UCAR to fund a multi-year bond equipment expense in one year. This will save UCAR money in the short term with the up-front deep discount and in avoided interest and depreciation expenses. Long-term will also accrue because maintenance for the Cisco 4510 is much less expensive than the 6509 maintenance. It also freed up bond funds for other uses across UCAR.



Rick Mumford and Carlos Rojas-Torres unpack a Cisco 4510 ethernet switch for installation.



Led by Teresa Shibao (Network Engineer, not shown), Network Infrastructure Team members Armando Cisneros, Paul Dial, Susan Guastella, Jerome Martinez, Mike Martinez, Rick Mumford, Carlos Rojas-Torres, put in the long early-morning hours and hard work on this project. The team received SCD special recognition awards from Al Kellie, CISL Director, on 20 August. From left to right: Armando Cisneros, Network Technician; Rick Mumford, Network Technician; Al Kellie, CISL Director; Ellen Martinez,

Administrator; Paul Dial, Network Engineer; Carlos Rojas-Torres, Network Technician; Susan Guastella, Administrative Assistant. Other team members not shown: Jerome Martinez, Network Technician and Mike Martinez, Network Technician.

Susan Guastella and Ellen Martinez worked deftly through the complicated and new process of ordering under a capital lease, a learning experience for everyone. They set up the capital lease depreciation and four-year management process, again new to everyone involved. They did a splendid job with much patience, creativity, and attention to detail.

There were 20 communication closet switches to be installed. Teresa and her team committed to expedite the installation requiring a switch installation every other week, which is an aggressive schedule with extensive planning and prep work for each installation required to ensure success. Teresa and Paul agreed to alternative switch installations as lead to spread the load and provide important technical and leadership experience to Paul Dial.

It was critical that this work get completed within schedule, and the nature of the work requires a level of quality in planning, design, and execution to ensure continuity of the network. The closet switches are the backbone and core of the UCAR network. This work at some point impacted all UCAR network and phone users and the NI Team ensured that the impact was minimal by their excellent quality and execution of their work. The NI Team committed and adhered to an aggressive schedule that demanded that they work outside their normal schedules and perform a magnitude of work that is far beyond normal done in parallel with their regular jobs. The scope had far-reaching impacts that demanded an exceptional commitment to excellence to minimize downtime and impact to users.

### **Wireless Local Area Network (WLAN) upgrade to Aruba**

If there is one technological advancement that has defined the past five years, it is undoubtedly the advent of mobile connectivity. The constraints of connectivity have dissolved in recent years, resulting in an “always on, always connected” society and workplace. The pace of this change has been staggering and its implications are unquantifiable.

In 2015, NETS evaluated various WLAN replacement alternatives to bring our WLAN technology up to the state of the art and better serve the UCAR WLAN users including easier support for the UCAR system administrators who support a myriad of wireless devices and access levels. After multiple demonstrations and cost and technical comparisons, Aruba was chosen as the WLAN vendor.



Mike Martinez, Jerome Martinez, and Paul Dial finalizing a 4510 installation.



Rick Mumford installs a new Aruba Access Point.



Aruba ClearPass access management was chosen to offer new options for “onboarding” of wireless clients as well as certificate management. This integrated system from Aruba provides UCAR with several advantages.

First, the AP management system is a “controllerless” model meaning NETS did not have to purchase several pairs of redundant hardware appliances per campus but instead can leverage an “Aruba Instant” configuration that provides deployment flexibility and software-based redundancy using existing AP hardware with no single point of failure.

Second, Aruba offers technology to distribute wireless users across APs and frequency bands, enhanced channel interference management for increased overall WLAN capacity, and protection against failed APs and outside interference sources.

Third, AirWave management provides centralized monitoring and management with network-wide visibility and enhanced correlation and classification options.

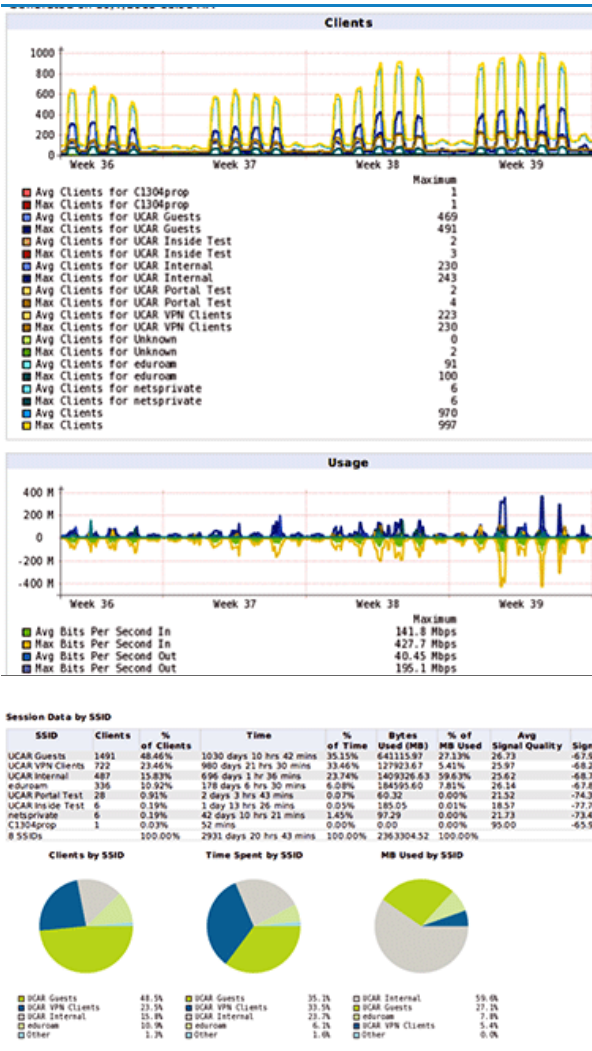
Fourth, ClearPass provides a policy platform as well as an improved UCAR wireless user experience due to guest and visitor management portal options.

NETS purchased 802.11ac Aruba Access Points (APs) along with Aruba AirWave network management to control the AP infrastructure.

BiSON R7 Upgrade

High Performance Networking (HPN) and the other components of advanced CyberInfrastructure (CI) are key enabling technologies vital to each university, college, and research organization’s ability to function and prosper in a rapidly evolving scientific and technical environment. HPN enables scientific investigations to flourish, along with analysis, communication, global collaborations, education, and outreach missions. Advanced networking infrastructure is an essential enabler of all key elements comprising CI. HPN, commensurate network security, throughput performance, High Performance Computing, data movement, file storage, and retrieval management are all rapidly changing aspects of CI.

The Networking Engineering and Telecommunications Section (NETS) has constructed, operated, and maintained the Bi-State Optical Network (BiSON) for over 10 years. BiSON is the Regional Optical Network (RON)



AirWave is now providing detailed ongoing usage information on over 1,000 wireless client devices connected to the UCAR WLAN.



John Hernandez, project lead, shows a completed ADVA R7 installed and active.

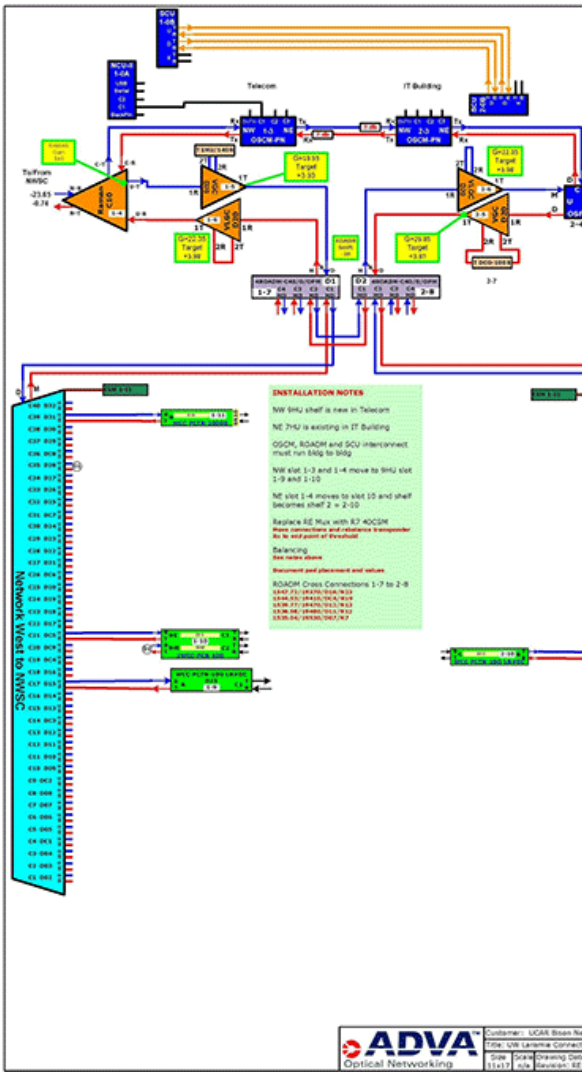
serving Colorado and Wyoming. The BiSON collaboration is an extremely successful partnership among the universities, research, and educational organizations in the region and enables advanced networking in a geographically challenged area (large distances, low population density, and limited State funding). Continued investment in BiSON is critical to meeting the growing and expanding demands of CI in the region.

John Hernandez, Scot Colburn, Pete Siemsen, Bryan Anderson, and Carlos Rojas-Torres were responsible for all design, installation, and documentation of every component of this multi-year project. This included working closely with the optical wave division multiplexing (WDM) equipment vendor ADVA and the constituents on determining unique technical and budgetary requirements and designing the network to meet those requirements. This process requires multiple iterations and technical and negotiation skills. The installation included establishing schedules to minimize interruption and impacts over multiple days and team travel for the multiple physical installations throughout the multi-phase project.

The NETS team has upgraded the full BiSON ring to a state-of-the-art ADVA WDM system that is enabling 100G lambda paths, less costly and more flexible 10G lambda paths, and more flexibility in point-to-point paths. The NETS team worked with UW and the State of Wyoming to install the first 100G lambdas as part of a successful NSF CC\*IIE grant enabled by this BiSON upgrade. As part of this grant, UW and the FRGP were able to upgrade the wide area paths serving the FRGP to 100G as well, directly benefitting all FRGP and BiSON participants including UCAR.

The teamwork on the BiSON upgrade resulted in substantial, innovative achievements in service to the FRGP, BiSON, and UCAR constituents and customers. UCAR directly benefits from this project in our use of BiSON infrastructure supporting scientific research and administrative activities. BiSON is used for UCAR network access intra-UCAR to the NWSC and to the broader Internet for all of UCAR, including all national and international network connectivity. Through BiSON collaboration, considerable cost savings are realized by UCAR and all BiSON participants by leveraging the economies of scale realized by shared resources.

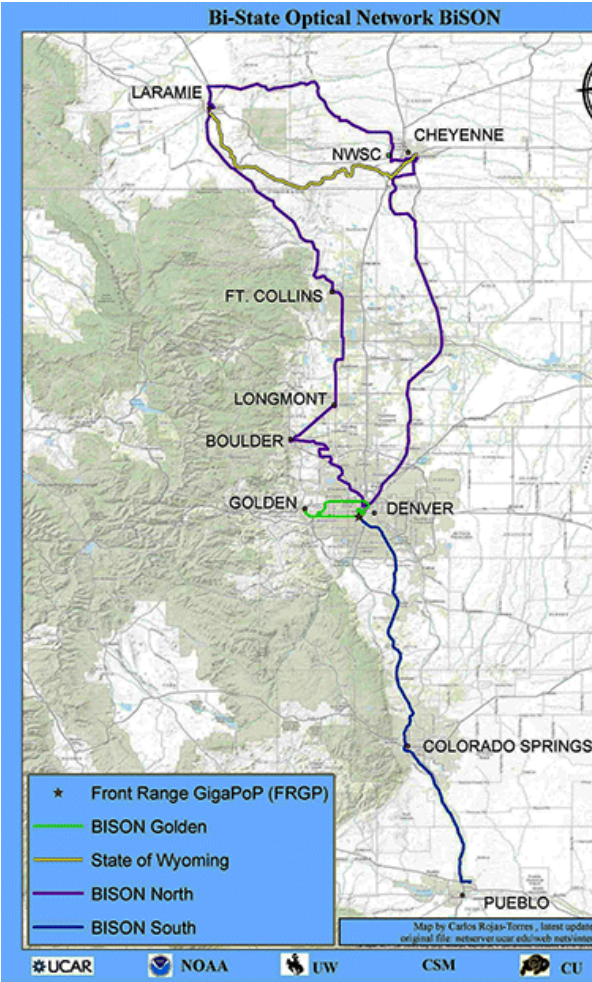
Fiber optic paths and WDM equipment are very costly to acquire and maintain. By maximizing the



Detailed plan for the installation of the University of Wyoming ADVA R7 ADVA node in Laramie.

relationships and purchasing power of 10 major R&E organizations in the region, we have all been able to do more with less – higher speed, more flexibility, more geography, more grant funding, and more collaboration within the region and the broader Internet. This, in turn, enables more science, education, and research.

Through the FRGP and BiSON, regional and national collaboration and positive exposure for UCAR are also realized. An example of regional collaboration enabled and supported directly by BiSON is the Rocky Mountain Advanced Computing Consortium (RMACC). HPC across the region utilizes BiSON to share computing and storage resources. The Quilt and Internet2 are examples of national collaborations where UCAR/FRGP/BiSON participate and UCAR benefits directly from the national exposure of technical and regional leadership.



BiSON network after upgrade and expansion.



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CYBERSECURITY

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

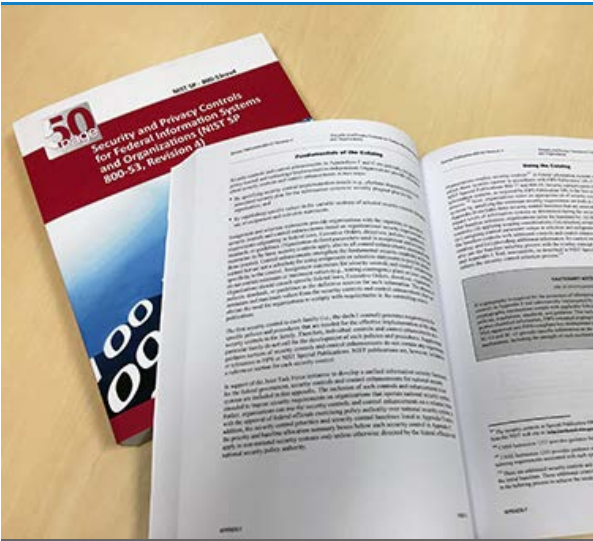
Providing secure information technology systems within CISL and across UCAR supports CISL’s computing imperatives to provision hardware and software cyberinfrastructure for the atmospheric and related sciences. Cybersecurity is also critical to CISL’s computing imperative for data curation and to its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

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

In FY2015, changes in contractual arrangements with some UCAR sponsors (particularly federal and other government agencies) required the organization to begin implementing measures to comply with FISMA, the Federal Information Security Management Act of 2002. In support of that effort, funds were identified to support new staff and contract staff to develop the required controls and documentation to achieve compliance.

Beginning in FY2015 and continuing into FY2016, CISL Security Engineering Group (SEG) and compliance staff are assisting COSMIC staff in developing and implementing the System Security Plan for the COSMIC-P/GD system, which will support a new constellation of satellites scheduled for launch in 2016. That system is required to implement the Moderate level of FISMA controls. The experience gained during that effort will be leveraged to support a UCAR-wide FISMA compliance level of Low, expected to be achievable in the FY2016-FY2017 timeframe. Any required higher-security network segments will also be addressed.

Another major effort underway with SEG involvement is implementation of a new Identity and Access Management (IAM) infrastructure. This will support better control of access to UCAR resources by



One of the foundational documents for implementing FISMA, NIST Special Publication 800-53 R4. This document describes the security controls that must be implemented to achieve FISMA compliance levels of Low, Moderate, or High.

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providing a more comprehensive source of authentication and authorization information for UCAR staff and collaborators. Background investigation and architecture efforts took place during FY2015, with initial implementation coming in FY2016.

At the same time, SEG continues its historical work of providing guidance to the organization in the maintenance and monitoring of a secure networked computing environment.

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

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DISTRIBUTED SERVICES AND WEB ENGINEERING

The CISE Enterprise Services Section (ESS) provides the hardware and software infrastructure – including development, deployment, configuration, monitoring, and maintenance – for a variety of Information Technology (IT) services used across UCAR. Examples of these services include organization-wide DNS and DHCP, incoming and outgoing e-mail via SMTP, web content hosting, development and production instances of the Drupal web Content Management System (CMS), and distributed software revision control systems, among others. ESS also provides system administration support for other CISE groups such as the Data Support Section and the Software Applications and Gateway Engineering group.



The Enterprise Infrastructure Operations team use the Agile/Scrum methodology to plan work. Implementing this methodology has allowed EIO to improve productivity and transparency while maintaining focus on the team’s highest priorities.

In FY2015, ESS’s Enterprise Infrastructure Operations (EIO) group was faced with a growing number of systems to support, including providing technical support for UCAR’s Google Apps for Government domain and deploying new Infoblox appliances to provide DNS and DHCP services. To ensure that EIO was able to respond appropriately to the highest-priority needs, they adopted a formal Agile/Scrum methodology, dividing project work into two-week “sprints” that permit staff to focus on the most important tasks at any given time. This methodology has been successful in improving productivity and clarity for staff and reducing the number of projects that need to be managed concurrently while giving enhanced transparency to stakeholders in the projects.

Other groups have also adopted Agile processes. The Software and Web Engineering Group (SWEG) has been using Agile/Scrum for some time, and the Security Engineering Group (SEG) has now begun to use it as well. Beyond CISE, various groups within UCAR are seeing value from these efforts, and Agile

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processes are starting to be applied at the enterprise level.

Also during FY2015, SWEG has continued its work improving the SAM software in support of CISL/USS, particularly in the areas of stability and reporting, and will work next on the synchronization processes for PeopleDB, which in turn are connected to the Identity and Access Management (IAM) efforts described in the [Cybersecurity](#) section.

ESS provides enterprise services in support of the Service, Innovation, and Collaboration sections of the CISL Strategic Plan. Support comes from NSF Core and CSL funding, as well as from UCAR indirect funds because the services provided are available to all UCAR/NCAR labs and programs.

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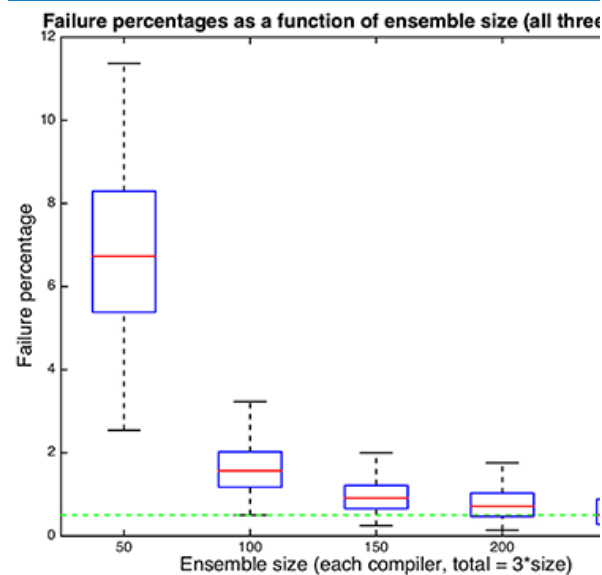
## CISL SCIENCE

CISL research activities support scientific computation, numerical methods, geophysical modeling, and the analysis of geophysical data and model experiments. These activities are chosen to lead the geophysics community in adopting new computational methods and mathematical tools to improve research.

Diverse scientific disciplines often share common tools and numerical methods. The kind of mathematical, computational, and physical sciences housed in CISL focus on areas that have broad application across scientific computation in the geosciences. Hallmarks of this research are innovative and standout contributions that not only have relevance for the overall NCAR scientific program, but also are significant in their specific area of mathematical, computational, or data science.

The figures shown here illustrate some of the diversity of scientific research in CISL. One interesting theme that unifies much of this research is the interplay between seemingly deterministic physical models and algorithms and the use of statistics and random processes to manage uncertainty. The first example illustrates probabilistic forecasts of severe weather to suggest the uncertainty in the forecast. Although probabilistic forecasts are acknowledged to be more useful for supporting decisions, they are also challenging to calibrate, so this is part of CISL's research in data assimilation. The example shown by the second figure is in the context of software engineering. Here the consistency of CESM being run under new hardware or compiler conditions can be tested using the distribution of results under known conditions that are correct. Statistics and probabilities are used to calibrate this test in a way that addresses the particular issues in Earth System modeling and the practical constraints in software development.

Some notable highlights in CISL research during FY2015 include:



The Ensemble Consistency test was jointly developed between IMAGE and TDD and provides an objective and fast way to test if new CESM runs such as those coming from a different hardware system or even from a different set of compiler options are consistent with an ensemble of runs obtained from Yellowstone using different initial conditions and three different compilers. Although the test has already been successfully implemented in the latest CESM release, we are still working to optimize the ensemble size and composition that is the benchmark for testing CESM consistency under other conditions. A practical question is how large should the benchmark ensemble be? The figure shows results from a Monte Carlo Study selecting 10,000 hypothetical samples that should all pass the Ensemble Consistency Test (ECT) for CESM. The variable is the benchmark ensemble size. It can be seen that an ensemble size of 250 runs from each of three compilers is required to achieve the theoretical (and desired) false positive rate of 0.5%, which is shown as a green horizontal dashed line. That is, a version of CESM that is completely consistent with the benchmark distribution will only be rejected by this test 1 out of 200 times. Such a large ensemble size (3x250) is required because the consistency test depends on the estimation of principal components (e.g., EOFs) from the global annual means of 114 variables. In this case, principal component analysis requires a large sample size to be robust.

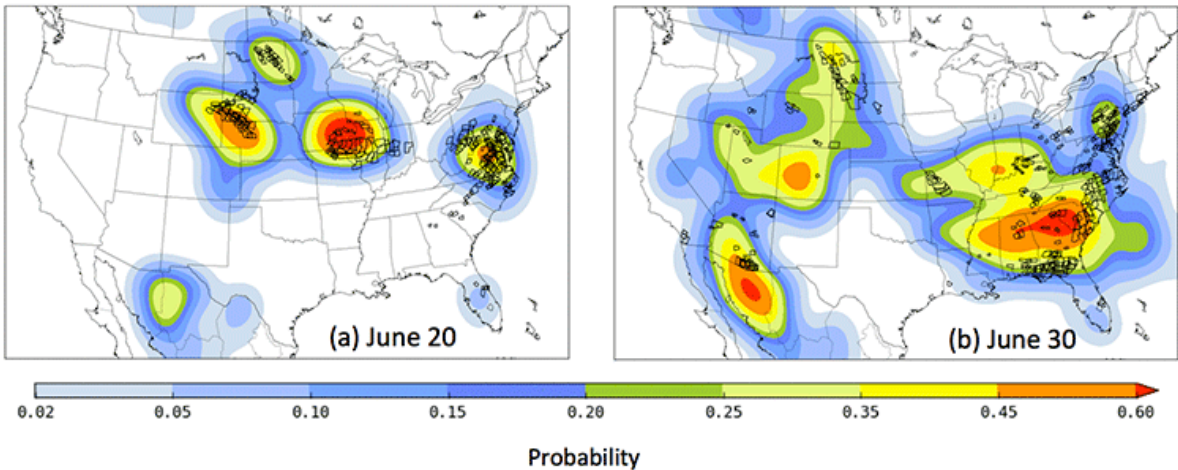


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- Data-centric research that extends tools for data assimilation and data analysis of complex observational data, processing of large simulations, and visualization of model output.
- Algorithm developments that accelerate the simulation of geophysical processes and make better use of computational and storage resources.
- Developing and evaluating computational strategies for new architectures to anticipate how codes and workflow may have to adapt to future systems.



Examples of forecast probabilities of daily hazardous local storms during June 2015 from NCAR’s real-time ensemble prediction system. These results are based on NCAR’s Data Assimilation Research Testbed (DART) and a high resolution version of the Weather Research and Forecast model (WRF) to produce forecasts of severe storm events. In this study a 10-member ensemble is used to identify representations of individual storm hazards. These are then combined to generate probabilistic severe storm guidance for a 24-hour forecast period. Higher probabilities (warmer fill colors) indicate a higher forecast probability of hazardous storms occurring within a particular region. The two plots in this figure illustrate different distributions of severe storm events for the U.S., highlighting the range of skill that these ensemble forecasts have in predicting high-impact weather events. Overlain in black polygons are areas where local National Weather Service (NWS) forecast offices issued either tornado or severe thunderstorm warnings. Probabilistic forecasts of weather hazards based on ensembles is an active area of research, and this study evaluates how some new measures of severe weather vary over the full area of the the conterminous United States. In particular, this work is novel in using a regional-scale ensemble method as the initial conditions to make the forecasts, and also in using new diagnostics to assess the forecast skill. Future activities planned for the ensemble system include plans to compare this work to the operational GSI system and to consider forecasting winter weather hazards.

The funding sources for these many projects are specified in the following individual reports and subsections.



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DATA-CENTRIC RESEARCH

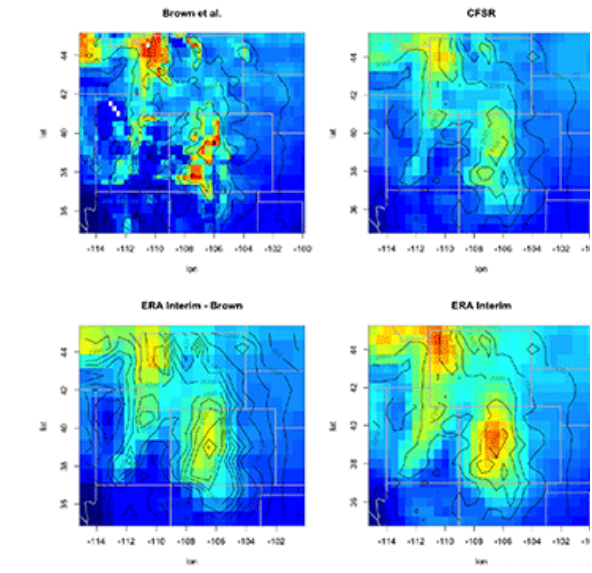
Grand challenges of modeling the Earth System require the interpretation and transformation of geophysical data in many forms. These activities range from mining the Big Data problems associated with remotely sensed observations and the output from large numerical experiments to interpreting the wide range of small but vital historical data sets that document past climate and important geophysical processes. Besides observational data, geophysical models depend on data for initial fields and forcing variables, and typically models generate substantial and complex data objects for interpretation. Part of the challenge of compressing and transforming model data is to preserve scientific value and also make it easy for modelers to use parallel analysis tools. In addition, the discipline of data assimilation combines models and observations to produce predictions, reanalysis products from past weather, and also to diagnose model shortcomings. Thus, to meet the varied needs of our research communities, CISL research takes an interdisciplinary approach where collaboration with scientific teams within and outside NCAR helps to motivate new software tools and analysis methods.

CISL's data-centric view with a focus on high performance computing results in research that integrates different aspects of computational and mathematical science. For example, our research on large data assimilation problems combines algorithms for ensemble representation (e.g., ensemble Kalman filter) with statistical ideas for robustness and stability of the methods. Making regional climate experiments useful for impacts analysis has resulted in combining ideas from fitting statistical distributions with the specific needs for objective basis corrections of model output. The need for spatial statistics for large data sets has spurred approximations to standard Bayesian statistics that are suited to parallel computing. Finally, the research on data compression has involved blending "off the shelf" compression algorithms with the particular requirements and workflows that are encountered in climate model research.

A few highlights that illustrate the breadth of this research are:

- A demonstration of the added value of using carbon monoxide (CO) retrievals from satellite-based instruments (MOPITT) to infer the distribution of CO in the Rocky Mountain region. This is an

January 1980 - May 1997 Mean Transform



This figure illustrates the need for statistics methods to combine geophysical data products of fields. Shown are four different versions of snow water equivalent (SWE) for part of the U.S. Rocky Mountain region and surrounding states (state outlines in gray). For analysis, the SWE values have been transformed with a power transformation and the mean fields for 18 years are shown in these image plots. Despite some common spatial patterns, the data products differ in resolution, smoothness, and their extremes. Besides the need to find a common field to summarize these four products, this example also shows the need to express the uncertainty suggested by the variation among the fields. The difficulty in a statistical solution is compounded by the large number of grid points representing North America and also because SWE follows a skewed, nonGaussian distribution.

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example of the success of NCAR’s data assimilation system (DART) in support of the FRAPPE field campaign.

- Using the NARCCAP regional simulations, a process analysis has drawn a link between more-credible regional models and smaller decreases in the future (2041-2070) for the North American Monsoon. This is an important finding because it increases the value of using the NARCCAP experiments for assessing impacts of climate change.
- The use of wavelet encoders to compress double-precision climate model output gives a striking improvement over naive single-precision truncation. These results demonstrate the value of more-tailored and algorithmic approaches to compressing (i.e., reducing the size) of model output without compromising the information content.
- A statistical approach is able to blend multiple snow water equivalent data products into a single coherent estimate along with measures of uncertainty. This methodology is an example of approximate Bayesian methods applied to a practical problem in assessing snow accumulation for climate modeling and analysis. This work was also noteworthy for resulting from a collaboration between scientists in IMAGe and a SIPARCS student (Colette Smirnoitis). It also leveraged statistical software created in IMAGe for large geophysical data analysis.

Funding for these activities is indicated at the end of each of the more detailed subsections.

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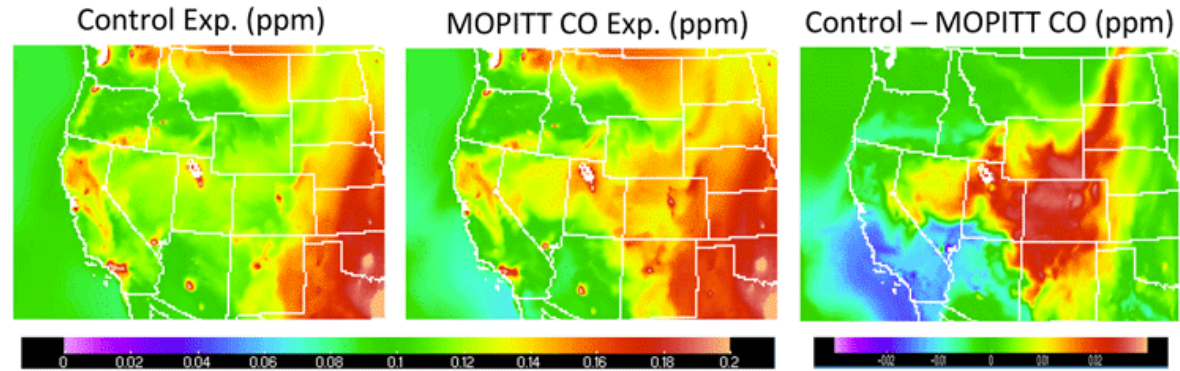
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DATA ASSIMILATION RESEARCH

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 a software facility for ensemble data assimilation called the Data Assimilation Research Testbed (DART). DAReS also provides support to a growing community of NCAR, university, and government laboratory partners who are applying ensemble data assimilation methods.

Impact of Assimilating MOPITT Carbon Monoxide (CO) on the 6-hr CO Forecast for the FRAPPE Study Area after Five Days of Cycling



Concentration of carbon monoxide (CO) in six-hour forecasts produced with the DART/WRF-Chem ensemble data assimilation system for a period during the FRAPPE field experiment. An experiment that assimilates only observations of meteorological variables (left) and one that also assimilates observations of CO from MOPITT (middle) are shown. The differences in concentrations (right) reflect an improved analysis of CO when the MOPITT observations are included and validate the performance of the system.

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.

There is increasing interest in applying data assimilation for the middle and upper atmosphere for space weather applications. DAReS scientists have been collaborating with several groups on data assimilation using the Whole Atmosphere Community Climate Model (WACCM) variant of the Community Atmosphere Model. Tuning of vertical localization of observation impact and adaptive inflation algorithms has been explored with DART. DAReS scientists have also recommended appropriate numerical damping in the WACCM model itself. WACCM forecasts of upper-air observations have improved as a result.

A new observation operator for space weather applications has been implemented in collaboration with Johns Hopkins Applied Physics Laboratory. Slant path observations of total electron content can now be

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assimilated in the TIEGCM and other space weather models like WACCM-X.

Prediction of aerosols in the troposphere is an important area of research for both climate science and air quality predictions. In collaboration with scientists at the Naval Research Laboratory and the University of California at Berkeley, DAREs scientists have been working to improve DART assimilation for aerosols. Improved localization for use with the Navy Aerosol Analysis and Prediction System (NAAPS) and CAM/Chem has helped improve aerosol predictions generated with both systems.

Work continues on improving atmospheric chemistry assimilations in both CAM-Chem and WRF-Chem. DAREs scientists have collaborated with ACOM scientists to improve localization, inflation, and the design of forward operators to assimilate satellite observations of atmospheric trace constituents. The improved systems have been used to generate extended reanalyses with CAM-Chem and are being used for reanalyses of the FRAPPE field experiment period with WRF-Chem.

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HIGH-RESOLUTION RESEARCH DATA FOR CLIMATE CHANGE STUDIES

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

A centerpiece of RISC's activity has been its leadership of the North American Regional Climate Change Assessment Program (NARCCAP). NARCCAP is systematically investigating the uncertainties in regional-scale projections of future climate. It is unique in its balanced design that allows for isolating the influence of individual regional and global models on the resultant climate simulations. The overall goal of NARCCAP is to produce high-resolution (50 km) climate change scenarios using six regional climate models (RCMs) nested within four atmosphere-ocean general circulation models (AOGCMs) forced with the A2 SRES emission scenario, over a domain covering the conterminous U.S., northern Mexico, and most of Canada. The project also includes an evaluation arm whereby the participating RCMs are forced by reanalysis data sets. The resulting regional climate model runs and time slices form the basis for multiple high-resolution climate scenarios that can be used in climate change impacts assessments in the U.S. and Canada. In FY2015, work related to NARCCAP has entailed further application of the data to numerous adaptation contexts (see below).

Further analyses and data products development using NARCCAP

RISC's activities include the development of a number of data products and services to support the users of data from NARCCAP. These will also be useful for future anticipated high-resolution regional climate simulations such as those being developed in North American CORDEX (see below). Seth McGinnis has been collaborating with CISL's VETS group to help guide the development of next-generation data services that will enable users of output from Big Data projects like NARCCAP to access the data they need without downloading large volumes of unwanted data to get it. These new service capabilities include spatial and temporal subsetting, file spanning, aggregation, and format conversion.

Simulation data bias correction

Having identified bias correction as an important need of NARCCAP users, especially for impacts analysis, RISC has been working to bias-correct NARCCAP output using distribution mapping techniques. This work breaks new ground by applying the methods to daily data rather than monthly or seasonal climatologies. Seth McGinnis has developed a novel technique for distribution mapping called Kernel Density Distribution Mapping (KDDM). KDDM makes use of well-established statistical methods to perform distribution mapping using non-parametric estimates of the probability distributions underlying the data sets to be bias-corrected. This technique has been evaluated against existing techniques by use of an oracle analysis, wherein each technique is used to bias-correct synthetic data and the result is compared to a perfect correction, or "oracle." KDDM performs very well according to multiple metrics, and has the best performance on non-idealized data. It is also fast, robust, flexible, and conceptually straightforward. These results have been published in the proceedings volume for the 2014 Climate Informatics Workshop, and plans have been developed to improve on basic KDDM by refining the correction of




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extremes of daily temperature and precipitation.

Evaluation of the North American Monsoon in the NARCCAP simulations

Melissa Bukovsky has led, in collaboration with Dave Gochis in RAL, the evaluation of how well the NARCCAP models reproduce characteristics of the North American Monsoon (Bukovsky et al., 2013, *J. Climate*) and has pursued an investigation of the effect of model errors on the future projections of climate in this area. New findings this year (Bukovsky et al., 2015) include the fact that the least-credible models produce the largest decreases in precipitation, whereas the “best model” produces little change in precipitation (see figure below). This result is particularly noteworthy since strong relationships between biases in current period simulations vs. changes in precipitation in the future are rarely seen.

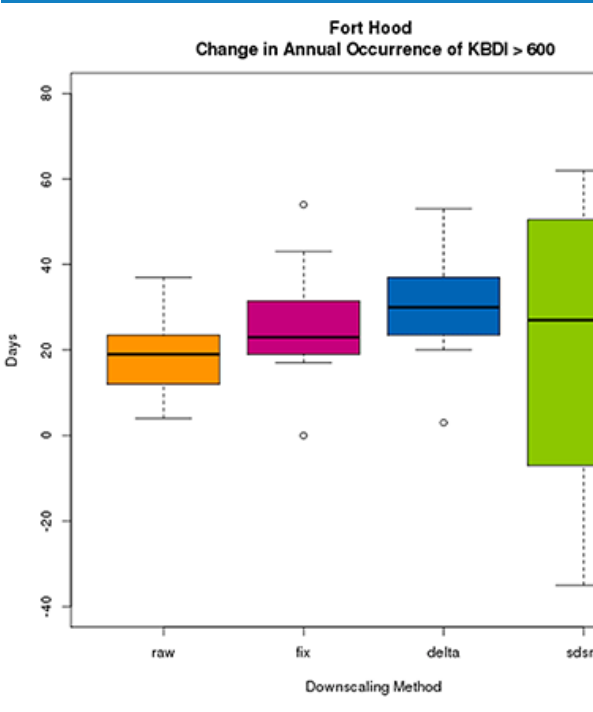
Heat stress

RISC scientists continue to collaborate with scientists from the IAM group in CGD to produce analyses of heat waves based on CESM simulations. The new study (Anderson et al., 2015), part of the BRACE series of papers, finds that considerable reduction in urban heat waves are found when following the RCP4.5 scenario as opposed to RCP8.5. The role of RISC was to apply the KDDM bias correction method to the CESM output (S. McGinnis).

Development and provision of climate information including uncertainty measures for adaptation research

RISC is currently engaged in three different research projects concerning adaptation to climate change at local and regional scales. These projects include one funded from NSF EaSM, “Informing Climate Related Decisions with Earth System Models,” led by RAND; and two funded through the DoD Strategic Environmental Research and Development Program (SERDP): “Decision-Scaling: A Decision Framework for DoD Climate Risk Assessment and Adaptation Planning,” led by U. Massachusetts, and “Understanding Data Needs for Vulnerability Assessment and Decision-making to Manage Vulnerable DoD Installations to Climate Change,” led by PNNL. All three concern decision-making and more specifically risk management under various conditions of uncertainty, including that of climate. All three projects rely to some degree on the NARCCAP simulations in various resource management contexts. The EaSM project specifically considers ecological and water resources in the U.S. East and West, while the two SERDP projects consider a range of resources and climate conditions relevant to U.S. military bases (in the Southeast, mid-Atlantic, Texas, the Front Range of Colorado, and southern California) such as heat stress, flooding, changes in available water resources, and wildfire potential. A Climate Outlook for the mid-Atlantic region has been completed, which is relevant to four of the sites being investigated. It is a challenging area for the development of future climate scenarios, since it is a region of transition between wetter future scenarios to the north and drier scenarios farther south.

An additional aspect of the work in the Decision Scaling SERDP project is comparing the effect of using different downscaling methods to determine changes in impacts. The effect of different downscaling methods on climate impacts has been underexplored in the literature. Rachel McCrary has led the effort to look at the effect of different methods on the determination of future wildfire potential. The Keetch-Byram Drought Index (KBDI), used by the USDA Forestry Service, was calculated for current and future conditions using the 12 NARCCAP simulations as the basic climate information. The four methods investigated included: 1) using the raw output of the regional climate models, 2) using the “delta” approach, 3) using the RCM data corrected via KDDM, and 4) using SDSM, a regression-based method that relates large-scale climate variables from the four GCMs used to drive the NARCCAP RCMs to local-scale daily temperature and precipitation. The figure below shows changes in the number of days with extreme fire danger (KBDI > 600) for Ft.





Hood, Texas. Note that while the medians for the four methods are similar, the SDSM method produces much larger variability. Analysis is underway to determine the causes of the method-based differences.

Development of NA-CORDEX

The Co-ordinated Regional Climate Downscaling Experiment (CORDEX) has been ongoing for several years. North America CORDEX, while in existence for three years, has been slow to advance through production of simulations due to lack of sufficient funding from U.S. funding agencies, yet simulations continue to be performed. (Linda Mearns and William Gutowski of Iowa State are co-Chairs of NA-CORDEX.) In collaboration with Iowa State and the University of Arizona, simulations are being performed for a 150-year time period (1950-2100) over approximately the same domain as that of NARCCAP, with two different regional climate models, at both 50- and 25-km resolutions, using ERA-Interim boundary conditions, and boundary conditions for three different GCMs that span the equilibrium climate sensitivity of the CMIP5 collection of global climate models. Specifically in RISC, Melissa Bukovsky has produced RCM simulations at 25 and 50 km using the Max Planck Institute global model boundary conditions for the RCP 8.5 concentration pathway. This results in a 2 x 2 x 3 matrix of simulations. Other simulations have been produced by other groups, most notably in Canada using the Canadian regional climate model (CRCM). The NA-CORDEX website (na-cordex.org) lists all simulations being performed. Plans have been made to develop an archive of surface variables from all simulations at NCAR next year.

Box plots of change in number of days when the KBDI (see text) exceeds 600 (severe fire danger) at Fort Hood, Texas using four different methods to downscale and/or bias-correct the NARCCAP climate information. The four methods are raw, using NARCCAP output directly (no correction); fix, bias-corrected NARCCAP data using KDDM; delta, adding mean monthly climate changes to daily observed data (using the standard delta method); and SDSM, using a linear regression approach relating large-scale features from driving GCMs to local daily climate.

WCIASP

RISC also maintains and develops the Weather and Climate Impacts Assessment Science Program (WCIASP). WCIASP has three primary thrusts: investigating uncertainty in climate change research, studying extreme weather and climate events and their impacts, and supporting the Climate and Health Workshop series. WCIASP funded projects throughout NCAR, particularly in CGD, RAL, and in IMAGe.

Funding

The Regional Integrated Science Collective (RISC) and Weather and Climate Impacts Assessment Science Program (WCIASP) are primarily supported by NSF Core funding as well as interagency support for NARCCAP and the use of NARCCAP results for adaptation planning from NSF, NOAA, NASA, and DoD.

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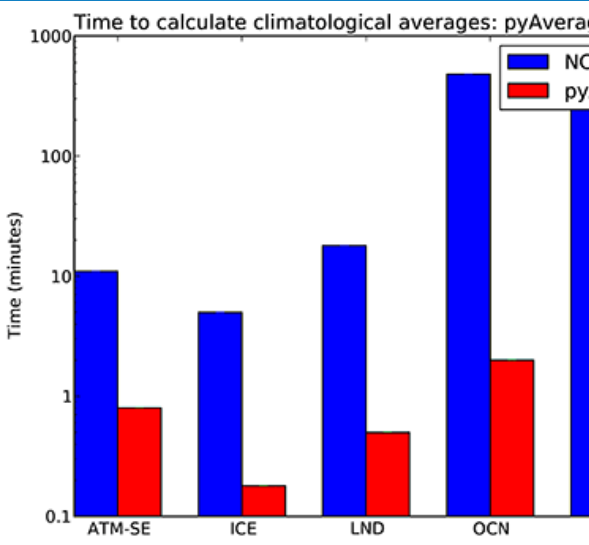
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PARALLEL DATA PROCESSING

The parallel data processing project is critical to the objectives of NCAR for several reasons. While the rate at which it is possible to generate simulation data from the CESM has increased rapidly over the last five years, our ability to analyze it has not due to the serial nature of the post-processing workflow. The impact of a serial post-processing workflow was apparent during the CMIP5 project when the post-processing took as long to perform as the initial simulations. This project will increase the scientific discovery rate by removing post-processing bottlenecks.

In FY2015, members of the Application Scalability and Performance (ASAP) Group in collaboration with NCAR's Climate and Global Dynamics (CGD) Laboratory completed the parallelization of a significant amount of the CESM post-processing workflow including two disk-I/O-intensive calculations and the generation of diagnostic plots. The PyReshaper tool converts time-slice to time-series format, while pyAverager performs a number of climatologically important temporal averages. Both applications are written in Python, use the Message Passing Interface (MPI) for parallelism, and utilize pyNIO (the I/O library from NCL) to access files on disk. Both pyReshaper and pyAverager have been adopted by CGD and are included in future CESM releases. The component-specific diagnostic packages that scientists use to evaluate the fidelity of simulations were redesigned to allow the existing NCL-based scripts to be executed in parallel.

This work on parallelizing the post-processing workflow was supported through NSF Core and NSF Special funds.



This figure compares the previous serial-processing method with a new parallel method. It shows the time to calculate temporal averages using the previous Netcdf Command Operators (NCO) version on a single core of Caldera in blue, while the red bars show pyAverager performing the same tasks while running on 120 cores of Yellowstone.

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SCIENTIFIC DATA COMPRESSION AND VISUALIZING LARGE DATASETS

CISL is exploring a variety of hardware- and software-based approaches for addressing the challenges of storing, visualizing, and analyzing large data sets. CISL is also exploring two interrelated approaches to the challenges of large data sets. The first major software thrust in this area has been research, development, and experimentation with wavelet-based progressive-access data models for structured scientific data sets. Wavelets are the basis for numerous, ubiquitous multimedia compression technologies such as the JPEG 2000 image compression standard. However, unlike the “lossy” compression strategies used in consumer entertainment, our efforts are focused on level-of-detail techniques that offer perfect reconstruction of the original data while allowing the user to make speed/quality tradeoffs when performing interactive work. The second focus is to develop a method for determining how much information can be lost without impacting the results of typical climate analysis. The goals of all this work are to:

- Determine whether, and to what degree, scientific data sets can tolerate information loss.
- Investigate a variety of compression methods and their suitability for geoscience data.
- Develop user tools for data compression and improved, more general, progressive data access.

Exponential growth in transistor density is producing ongoing increases in computer processing power. These increases enable computational scientists to create numerical simulations of physical phenomena at unprecedented scales, thus generating extraordinary amounts of data. Yet while microprocessor performance continues to advance in accordance with Moore’s Law, other computing technologies are improving at much more modest rates. In particular, storage and networking bandwidths have lagged behind. As a result, the challenge of storing, analyzing, managing, and sharing large simulation data sets is becoming ever more problematic. Moreover, large data visualization is a central component in petascale computing and making large and heterogeneous data sets understandable. This is a science frontier specified in CISL’s strategic plan, which specifies these tasks:

- Prepare for petascale and exascale computing.
- Partner with peer institutions and combine efforts to develop and enable visualization of large data.

In FY2015 CISL hosted Samuel Li, a Ph.D. student from the University of Oregon, for a two-month visit to NCAR. Samuel’s thesis work, under Prof. Hank Childs, focuses on a variety of aspects of scientific data compression. While at NCAR Samuel continued efforts begun last year by CISL staff to objectively evaluate the state-of-the-art wavelet encoders, SPIHT and SPECK. Some of the most significant findings include:

- When applied to double-precision data, these encoders are capable of preserving information better than simple truncation to

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single precision – widely used in practice by modelers of all stripes – while achieving compression factors of 6x to 8x.

- The encoders also appear to outperform (in terms of distortion rates) all of the compression strategies applied to climate simulation data evaluated in the 2013 CISL paper by Baker et al.

The promising results of this brief summer internship are expected to lead to a followup of the Baker et al., paper in FY2016, as well as possible integration of the SPECK encoder into CISL’s VAPOR package.

This data compression and visualization research is supported by NSF Core funds, a subaward from the University of California at San Diego, 54067252, and KISTI grant C15012.

Comp.	LMax Evaluation		
	Truncation	SPIHT Rect. Double	SPECK Rect. Double
2to1	2.38E-07	3.35E-08	3.35E-08
3to1		3.36E-08	3.36E-08
4to1		3.48E-08	3.49E-08
6to1		1.16E-07	1.15E-07
8to1		3.58E-07	3.73E-07
Comp.	RMSE Evaluation		
	Truncation	SPIHT Rect. Double	SPECK Rect. Double
2to1	5.26E-08	3.35E-08	3.35E-08
3to1		3.35E-08	3.35E-08
4to1		3.35E-08	3.35E-08
6to1		3.71E-08	3.74E-08
8to1		7.20E-08	7.40E-08

This table compares the LMax and RMSE between original and compressed double-precision data using three different compression methods: truncation to 32 bits, using the SPIHT wavelet encoder, and using the SPECK wavelet encoder. Truncation of double-precision data to single precision is used to save space and is a standard practice among numerical modelers. The results above suggest that more information could be retained using SPIHT or SPECK for the 2:1 compression rate obtained by truncation, or that more aggressive compression with SPIHT or SPECK can be used to retain the same amount of information as truncation.

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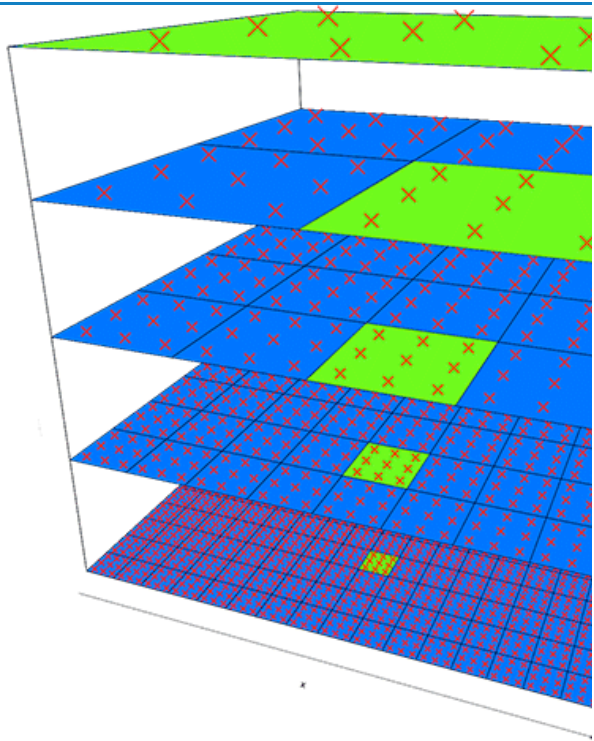
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STATISTICS FOR GEOPHYSICAL DATA AND MODEL EXPERIMENTS

From its unique position within CISL and IMAGE, the Geophysical Statistics Project (GSP) has been a leader in research and training emphasizing the synergy between the geosciences and data science. The mission of GSP is to pursue basic methodological and theoretical statistical research for scientific problems arising in the geosciences and at NCAR. Based on GSP's perspective within CISL it is natural to focus on developing data algorithms and data science tools to harness multi-core and high-performance computing environments to enhance capabilities for analyzing large datasets, and in particular, those involving spatial and spatial-temporal dependence. Further, GSP has a strong interdisciplinary training component supporting graduate students and postdoctoral visiting scientists. These young researchers are immersed in research activities that not only focus their skills as applied statisticians but also expose them to important geophysical applications and innovative computational resources.

GSP also has an active visitor program providing research opportunities for visiting faculty members from across the nation and abroad. One valuable asset is GSP's membership as a node in the NSF-DMS-funded research network named Statistics for the Atmosphere and Ocean Sciences (STAMOS). STAMOS not only helps to fund visits of data scientists to NCAR but also provides a link to key university programs that train students in statistics for geophysical and environmental problems. Visitor programs – as well as the research and training aspects of GSP that emphasize the interaction between statistics and the geosciences – capture the goals 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,




A distributed implementation of multi-resolution approximation for very large spatial data. Conducting spatial statistics for very large data sets, such as satellite data, has been notoriously challenging due to the need to work with matrices that have the same dimensions as the size of the data. We make use of HPC infrastructure and develop statistical models that allow for efficient parallelization to overcome this computational bottleneck. One such method is the multi-resolution approximation, which is based on a hierarchical system of basis functions of increasing spatial resolution. The idea is that finer levels are localized in their use of data and only rely on the parent node for global information. The figure shows an example of a five-level hierarchical structure. The areas highlighted in green show where data located within the grid box on the finest-resolution level (level at the bottom) impact coarser levels. The red crosses indicate the knot locations of the basis functions. At the finest resolution, the knot locations coincide with the data locations, which leads to the attractive feature that the statistical covariance for data within the same grid box is represented exactly and not approximated. This feature is in contrast to other statistical approximations that do not represent the data at its original level. This model specification allows for efficient parallelization by solving each grid box individually but still accounting for dependency at coarser resolutions. We can currently solve systems for over 30 million observations using Yellowstone's Geyser cluster and are working toward solving applications with over 125 million data



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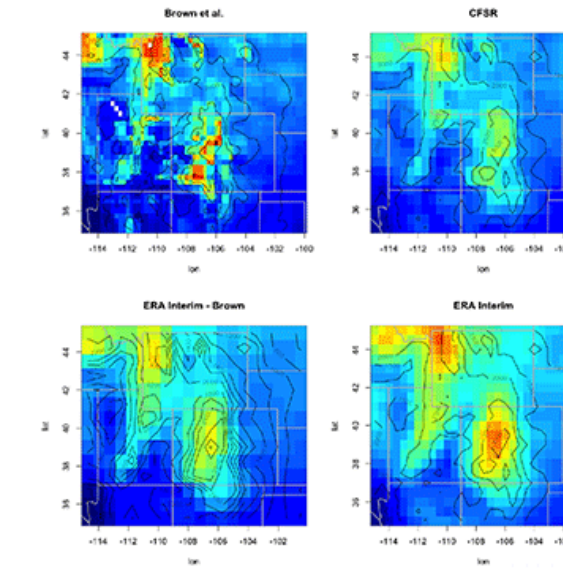
GSP supports CISL’s science frontier of developing innovative statistical design and analysis techniques to improve the efficiency and accuracy of model development and testing.

points such as high-resolution satellite observations of sea surface temperatures.

During FY2015, GSP researchers have been involved in numerous projects including NCAR staff and university collaborators. Some highlights include:

- Developing spatial models for large data sets that lend themselves to parallelization. Spatial data sets derived from remotely sensed measurements are typically too large for standard statistical methods, and this research seeks to find alternative methods to handle these important types of observations. One strategy is to divide up the region of interest recursively and then define specific, multiresolution basis functions that are limited to each of these divisions. (See figure above.) The field of interest is expressed as a sum on these basis functions multiplied by coefficients. A statistical model for the basis coefficients that is similar to a spatial version of the Kalman filter results in a flexible method for representing a spatial process. Moreover, the multiresolution property of the model also means that the computations can be distributed efficiently across many processors. Breakthroughs in the size of data sets that can be tackled have been made with this approach, and the parallel implementation on Yellowstone is a new use of this facility.
- Building software tools to analyze large spatial datasets. This includes LatticeKrig, a contributed package in the R statistical language, that can accelerate spatial analysis by factors of 10 or more using sparse matrix methods. This software was extended to periodic regions and also to inverse problems where the observation is a linear operator applied to the field of interest. This feature is helpful in inverting solar corona measurements to infer 3D features in the solar atmosphere and for combining fields of different resolutions. More broadly, GSP continues to use the LatticeKrig model as a substrate to develop theory and methodology for analyzing spatial and spatial-temporal data (including large datasets, non-stationary covariance functions, and multivariate spatial observations).
- Combining heterogeneous data products. A common data problem in the geosciences is blending several different data products or observations of a physical quantity to produce a single estimate. Even when methods are available to combine fields, they often do not provide measures of uncertainty that reflect disagreement and errors among the individual data products. This research applied a Bayesian hierarchical model to show how data products for snow water equivalent (SWE) measurements could be blended into a coherent single field. The main idea is to create a statistical model that relates each data product, at different resolutions and quality to a single hidden field that represents the geophysical variable. This data layer is combined with a spatial model for the actual SWE field and also some priors that give initial information on statistical parameters. This framework then allows one, via Bayes’ Theorem, to find the distribution of SWE fields that are likely given the collection of data products. One novel feature of this work is to handle large gridded data products, and this was accomplished using the LatticeKrig model for spatial fields.

January 1980 - May 1997 Mean Transfor



This figure illustrates the need for statistics methods to combine geophysical data products of fields. Shown are four different versions of snow water equivalent (SWE) for part of the U.S. Rocky Mountain region and surrounding states (state outlines in gray). For analysis, the SWE values have been transformed with a power transformation and the mean fields for 18 years are shown in these image plots. Despite some common spatial patterns, the data products differ in resolution, smoothness, and their extremes. Besides the need to find a common field to summarize

The GSP project is made possible through NSF Core

funding, as well as grants through NSF’s Division of Mathematical Sciences (DMS1417), and a subaward from the University of Colorado at Boulder, 1551584.

these four products, this example also shows the need to express the uncertainty suggested by the variation among the fields. The difficulty in a statistical solution is compounded by the large number of grid points representing North America and also because SWE follows a skewed, nonGaussian distribution.

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SCALABLE ALGORITHMS FOR MASSIVELY PARALLEL COMPUTERS

NCAR models of the Earth System, the Sun, and the Sun-Earth System motivate CISL's scientific research on algorithms, numerical methods, and computational performance.

A priority in geophysical modeling is to increase resolution because higher resolution can resolve important processes to improve the accuracy of prediction and perhaps uncover unexpected interactions within the physical system.

This goal must be pursued within the context of massively parallel hardware that are the now the norm for high performance computing environments.

Given these two elements, CISL research focuses on areas to increase model resolution through methods that scale to large numbers of processors or coprocessors.

Improvements in simulation speed on these large systems depend on better numerical algorithms and innovative application of computer science.

Moreover, many of these new strategies arise as basic scientific research on idealized problems and are later transferred to the practical requirements of NCAR community models.

Some highlights from 2015 include:

- Steady progress was made on creating a nonhydrostatic and three- dimensional dynamical core (HOMAM) for the NCAR Community Atmosphere Model. Among its significant accomplishments, this new model was able to reproduce gravity wave tests with accuracy that matches standard benchmarks for comparing dynamical cores.
- Radial basis functions were successfully applied to represent the Earth's surface topography as a boundary condition for the electric field in the Earth's atmosphere. This

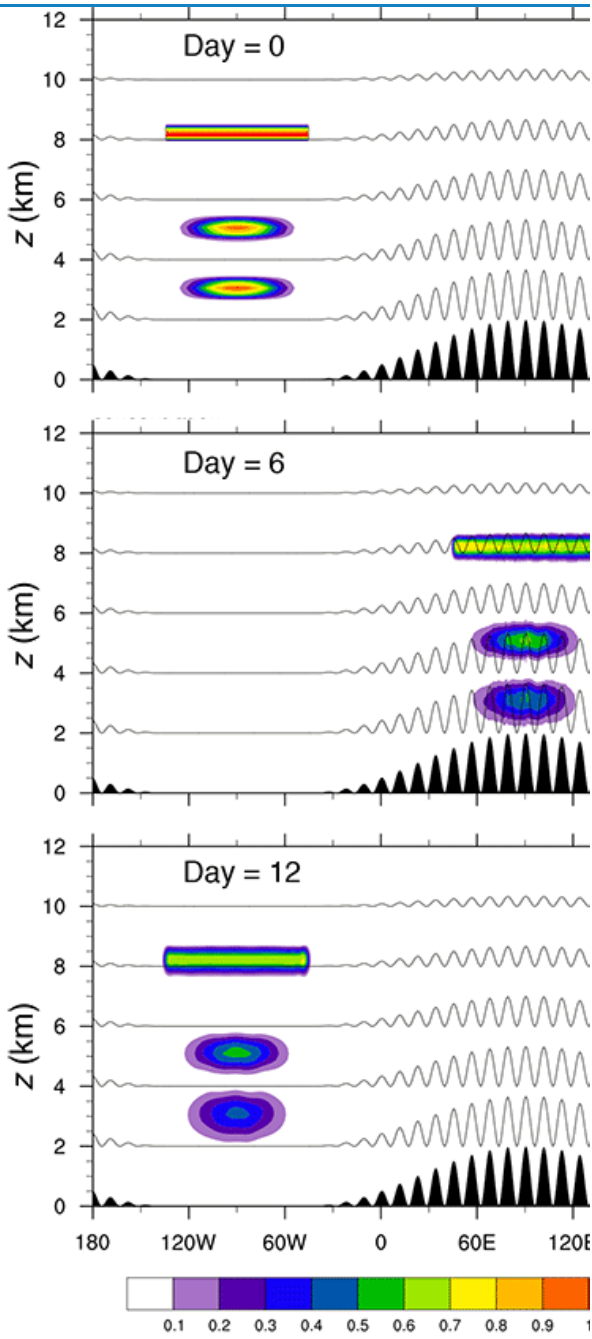


Illustration of the accuracy of simulating three-dimensional atmospheric transport over mountainlike terrain in an idealized global atmosphere. In this case the terrain is a concentric series of idealized mountain ranges expanding out from the equator and 80 degrees east longitude. This figure shows the

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work highlights the application of “meshless” methods for problems that involve irregular boundaries such as coastlines and irregular surface features.

This work is funded as specified in the following individual reports.

Under a separate grant from the NSF, Dr. Natasha Flyer (IMAGe) in collaboration with Dr. Bengt Fornberg (University of Colorado) published the SIAM (Society of Industrial and Applied Mathematics) monograph *A Primer on Radial Basis Functions with Applications to the Geosciences*. This book serves an introduction to numerical

methods that are not constrained to regular grids, and it pioneers their application to numerical models commonly encountered in the Earth System. Besides the numerical accuracy of radial basis techniques, they are also easy to program. Algorithms that use these methods do not require complex coding and so are well suited to parallelization on GPUs and other coprocessors.

vertical cross-section along the equator of a tracer field at three different simulation times (with day 0 being the starting condition). The black-filled sections indicate the physical topography at the surface, and the black lines indicate how the horizontal lines of the numerical grid adapt to this topography. The idealized atmospheric flow is just a constant, solid-body rotation, and the tracer field is represented by the three thin vertically stacked cloud-like patches. These concentrations should circumnavigate the globe and return to their initial positions after 12 days, so a perfect simulation would result in the tracer field returning exactly to its original position and concentrations in that time. Some spreading of the tracer concentrations over space appears, but the modest size of these numerical artifacts and the difficulty of this test case show a state-of-the-art transport computation. The results are computed with the non-hydrostatic formulation of HOMME that is being developed for the next-generation dynamical core of the NCAR atmosphere model.

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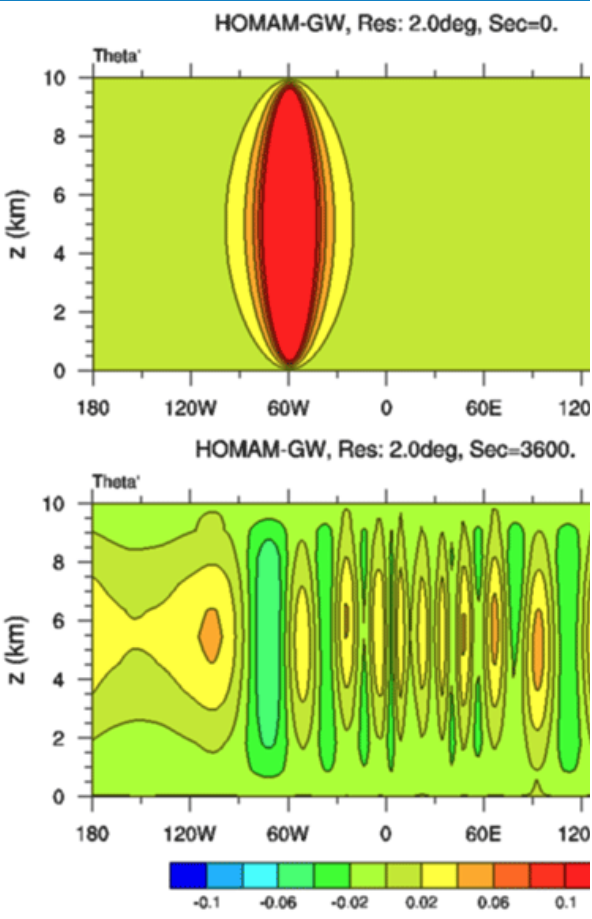
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HIGH ORDER METHOD MODELING ENVIRONMENT

The High-Order Method Modeling Environment (HOMME) is a hydrostatic framework to investigate using high-order element-based methods to build conservative and accurate dynamical cores. Currently, HOMME employs the Spectral Element (SE) and Discontinuous Galerkin (DG) methods on a cubed-sphere tiled with quadrilateral elements. HOMME can be configured to solve the shallow water or the dry/moist primitive equations with explicit time-stepping. The objective of this project is to extend HOMME to a framework capable of providing the atmospheric science community with a new generation of atmospheric general circulation models (AGCMs) for the CESM (Community Earth System Model). Currently the SE version of HOMME is the default dynamical core for NCAR's Community Atmosphere Model (CAM), and HOMME-SE can efficiently scale hundreds of thousands processors on a supercomputer. With the emergence of petascale computing resources, it is now possible to develop high-resolution (cloud-resolving) global models at non-hydrostatic (NH) scales.

In FY2014, a major research focus was to develop a 2D NH model based on DG methods to facilitate testing various time-stepping approaches and the vertical height-based coordinates, which would be applicable to the NH extension of HOMME. The time-split approach, known as the "horizontally explicit and vertically implicit" (HEVI) scheme, was found to be effective on the DG-NH model (Bao et al., 2015; DOI:10.1175/MWR-D-14-00083.1). The maximum stable time step for explicit time discretizations is dictated by the Courant-Friedrichs-Lewy (CFL) stability limit. At a higher resolution (smaller grid spacing), the CFL limit requires extremely smaller time steps, and is not practical for global NH models simulating climate. However, the stringent CFL limit associated with vertical high resolution can be remedied by using a dimension-splitting procedure that treats the vertical component of the equations in an implicit manner and the horizontal components explicitly, and the HEVI scheme does it precisely.

In FY2015, the HOMME framework has been extended to a non-hydrostatic dynamical core named the "High-Order Multiscale Atmospheric Model (HOMAM)." The horizontal aspects of discretization remain the same as that of the current HOMME cubed-sphere grid system, and discontinuous Galerkin (DG) spatial



Simulation of the 3D non-hydrostatic gravity wave propagation (a DCMIP benchmark test) on a reduced planet using the HOMAM dynamical core. This test examines model response to short-time-scale wave motion triggered by a local perturbation, where the initial state is hydrostatically balanced. The upper panel (2D vertical slice) shows the initial potential temperature perturbation, which triggers the evolution of gravity waves as shown in the lower panel after 3600 seconds.

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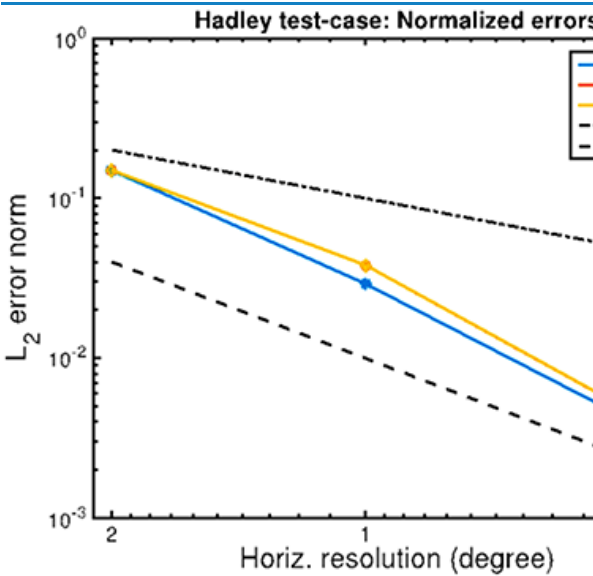
discretization is used. The DG method possesses computationally desirable properties such as local and global conservation, geometric flexibility, high on-processor operations, and minimal communication footprints. The vertical discretization is based on terrain-following z-coordinates as used in the 2D DG-NH model.

Several measures have been taken to extend the HOMME framework in preparation for the NH model implementation. These include restructuring the code, improving the efficiency of the DG algorithms, enhancing the parallel communication, and incorporating various DCMIP (Dynamical Core Model Intercomparison Project) benchmark tests to validate the new 3D NH model formulation. The time-stepping schemes HEVI and HEVE (horizontally explicit and vertically explicit) have been implemented in HOMAM, and their performance has been compared with a fully explicit Runge-Kutta (RK) method.

The figure at right shows the convergence of error norms for different time-stepping schemes as used in HOMAM with a DCMIP benchmark experiment known as the “Hadley test.” This test employs a smooth deformational flow that mimics a Hadley-like meridional circulation, and analytic solution is available at the end of the one-day simulation for comparison. This test is designed to investigate the impact of horizontal-vertical spatial splitting on the accuracy of the scheme. With HEVI and HEVE time integration methods, the HOMAM convergence results show a second-order accuracy, irrespective of a particular time integrator, which is acceptable for a time-splitting model (Nair et al., 2015; DOI:10.1016/j.procs.2015.05.471).

The figure at top shows the HOMAM simulation results with the NH gravity wave test as recommended in the DCMIP test suite. This is an idealized test involving full 3D nonlinear dynamics, where the initial state is hydrostatically balanced. This test examines the response of a model to short-time-scale wave motion triggered by a local perturbation and provides an excellent tool to test model dynamics. For this test, an overlaid potential temperature perturbation triggers the evolution of gravity waves up to a 1-hour period on a reduced (shrunk) planet. The preliminary result with HOMAM is encouraging, and comparable to that of the DCMIP benchmark results produced with established models.

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 HOMME dynamical core. Primary support for HOMME is provided by NSF Core funding. This project was partially funded by the Korean Institute of Atmospheric Prediction Systems of Seoul, South Korea.



Convergence of error for a DCMIP benchmark 3D advection test after one-day simulation with varying vertical and horizontal grid resolutions. HOMAM employs several time-stepping methods including HEVI, HEVE, and fully explicit RK method. The convergence rate shows a second-order accuracy as expected for a time-split model.

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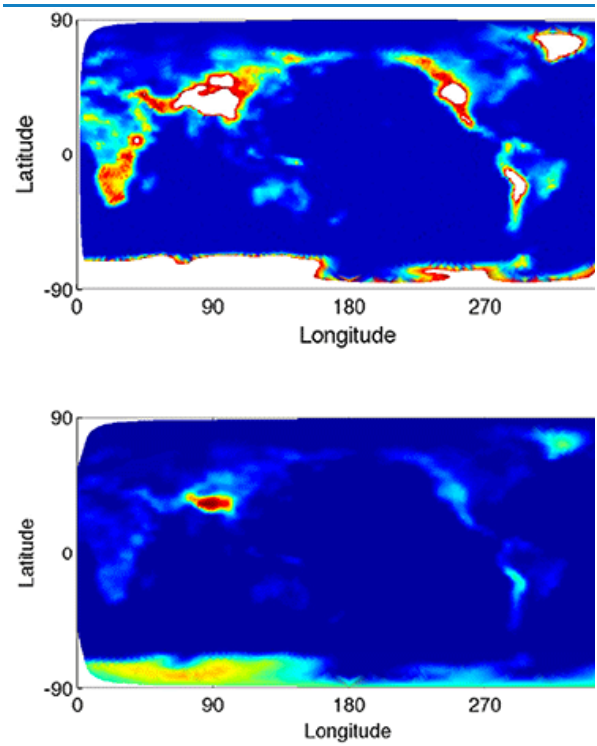
MESHLESS NUMERICAL METHODS FOR GEOPHYSICAL MODELING

While computer architectures have advanced rapidly in recent years, numerical schemes currently used for geoscience modeling have not kept pace with these technological developments. Radial basis functions (RBFs) offer a novel numerical approach for solving partial differential equations to high accuracy. Being a meshless method, RBFs excel in solving problems that require geometric flexibility, local refinement for small features, and with little increase in programming complexity when extended to higher dimensional spaces. In particular, the RBF-generated finite differences (RBF-FD) approach has allowed the RBF method to become computationally cost-effective in terms of scalability, memory, and runtime for solving systems of PDEs. The localized and accurate nature of the RBF-FD method:

- Leads to matrices that are over 99% empty.
- Allows it to scale as  $O(N)$  per time step, with  $N$  being with the total number of nodes.
- Makes it highly suitable for parallelization on accelerator-based computer architectures.

A key advantage of RBFs for geophysical modeling is that they do not depend on any grid, mesh, or coordinate system, but only the Euclidean distance between node locations in any dimensional space. This makes it particularly easy for modelers to incorporate the Earth's topography into physical models. This geometric flexibility is vital, since topography can play a crucial role in applications such as studying global electric currents (GEC) from thunderstorms in the Earth's atmosphere. In fact, this electrical system can be considered the ultimate link between solar, galactic, ionospheric, and magnetospheric processes and processes in the lower atmosphere, cloud system dynamics, and climate evolution.

The figure at right shows two sets of discretizations over the Earth's surface that are used for solving the 3D GEC model with RBF-FD. Note that over the topographical features, the nodes are more irregularly spaced and twice as dense as over the oceans, with no meshes or grids involved. The illustration at top shows the solution for the atmospheric current in kiloVolts (kV) of the GEC RBF-FD model at 1.5 km and 6 km above sea level. Note the topography's strong effect as the



The electric potential (kV) at 1.5 km (top figure) and 6 km (bottom figure) above sea level. In the top figure, the regions in white are the intersection of the 1.5 km constant-height surface with the Earth's topography.



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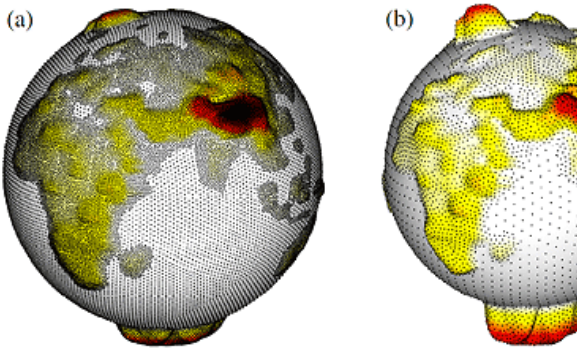
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land areas that modify electrical potential are clearly defined.

The development of the 3D GEC RBF-FD model in FY2015 was made possible by the continual research advancements in meshless numerical methods over the last several fiscal years. In those previous years, modeling was restricted to 2D in regular geometries, such as a rectangle or a sphere. Building on those accomplishments, FY2015 saw the first-ever 3D RBF-FD approach relevant to atmospheric modeling. These advancements were made through the successful collaborations of the IMAGe Computational Mathematics Group working together with HAO and the University of Colorado at Boulder to continue research in the promising area of RBFs for geoscience modeling.

This work advances CISL’s scientific efforts to develop scalable algorithms for atmospheric modeling on massively parallel and accelerator-based computer architectures. This development effort at NCAR is supported by NSF grant DMS-0934317.



Examples of the discretization of the Earth’s topography: (a) 150 km resolution at sea level, (b) 400 km resolution at sea level.

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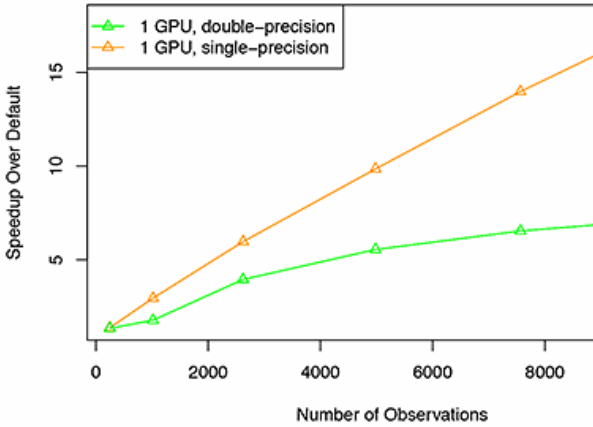
Meeting the grand challenges in simulating the Earth System requires more than just migrating standard algorithms to larger computational platforms. New hardware, new parallel computational approaches, taking advantage of coprocessors, and more efficient algorithms are all needed to reach the resolution and complexity levels necessary to support scientific breakthroughs in modeling. This attention is also required to address the analysis and manipulation of the large data sets now common in the geosciences.

The next three sections describe CISL's efforts to accelerate NCAR software applications on existing as well as future hardware. In the past, application performance improvements came "automatically" – largely from advances in hardware performance. The last decade has seen the gradual end of this regime. Now the emphasis is on acceleration through increased parallelism. CISL research and development in this area has employed the following three strategies.

First, CISL has launched efforts to achieve *acceleration through parallelism* in NCAR's computational models. This means developing tools and techniques for achieving efficiency at higher thread counts and vector length than previously required. The target here is emerging many-core architectures such as Intel's Xeon Phi and NVIDIA's Tesla GPU architectures. One result of this work was the production of a kernel generator for parts of the NCAR atmosphere model has allowed some key components to be optimized. Specifically the micro-physics computations, a significant percentage of the model runtime, has been reduced by half across several Intel Xeon processors.

Second, CISL's acceleration efforts have focused on an *end-to-end workflow approach*. In the past, optimization efforts were focused on the models. However, as computational science has become more data-centric, attention must be given to executing analysis and post processing scripts. To test whether compression of model output degrades its scientific content, a test set of compressed output fields was created in FY2015 for feedback from the modeling community. These results will be evaluated and the compression schemes will be adjusted as needed.

Finally, CISL's numerical experts and computer scientists are working with scientists in other NCAR laboratories to pioneer new numerical schemes and parallel algorithms to achieve *algorithmic acceleration*. Conceptually, algorithmic acceleration means achieving the same numerical accuracy in less time or using fewer cyber-resources. One example of this work is the development of a transport scheme



Speedup using GPUs to complete a standard spatial statistical analysis. This figure reports a timing study for a spatial analysis (i.e., Kriging) that involves fitting a Gaussian process covariance to observations and making a prediction of this surface for locations where the spatial field is not observed. The analysis is done in the R data analysis environment with the fields and RMAGMA packages. Here the times are relative to the fields standard function without using GPU support and are calculated on a laptop. As a reference, the time for the standard function at 10,000 observations is about 2-1/2 minutes. Thus a speedup of over 15 times would shift this standard data analysis time to an interactive activity (about 10 seconds). This difference in the amount of time to wait supports a more discovery-oriented approach, radically changing the dynamic of how data can be modeled and interpreted.

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for the cubed-sphere geometry that has high accuracy but still maintains positive concentrations. Moreover, this method only depends on neighboring elements and so does not degrade the parallelism in the other parts of the numerical procedures.

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EVALUATING MANY-CORE AND ACCELERATOR-BASED ARCHITECTURES

In FY2015, CISL's Application Scalability and Performance (ASAP) group in the Technology Development Division (TDD) has been involved in several collaborations that focus on preparing NCAR applications for future generations of microprocessor architectures. These collaborations include:

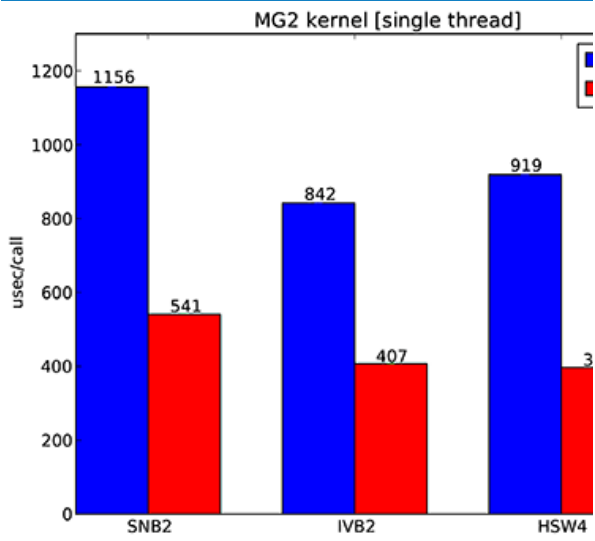
- An Intel Parallel Computing Center (IPCC) focused on Weather and Climate Simulation (IPCC-WACS) funded by Intel in collaboration with the University of Colorado at Boulder (CU Boulder).
- A National Energy Research Scientific Computing Center (NERSC) Exascale Science Application Program (NESAP) in collaboration with NERSC and Cray Inc, the Indian Institute of Science in Bangalore, India, and the University of Wyoming.

These collaborations have enabled advances in application performance and opportunities to help train the next generation of scientists and engineers who will apply these new technologies to challenges of societal importance.

This effort has focused on weather and climate applications, including the Community Earth System Model (CESM), the Weather Research and Forecasting model (WRF), and the Model for Prediction Across Scales (MPAS), three of the most widely used applications in the field. All three are large Fortran-based simulation codes – for instance, CESM is estimated to have about 1.5 million lines of code.

We have developed tools and techniques to streamline the refactoring effort to allow code optimization to keep up with the science-driver model development. In particular, we developed the Fortran kernel generator KGEN that automates the creation of small computational kernels. We have used KGEN to extract in excess of 30 kernels from both multiple CESM component models and MPAS. These kernels have been used to greatly simplify the testing of optimization ideas, as a [collaborative vehicle with compiler and microprocessor vendors](#), and as a benchmark in the [NWSC-2 procurement](#).

CISL has made significant progress optimizing particular sections of CESM and MPAS. The cost of the Morrison Gettelman (MG) microphysics calculations – which represents 10% of The Community Atmosphere Model's total runtime – was cut in half. The reduction in cost for MG microphysics calculations for three generations of Intel Xeon microprocessor are provided in the figure above. Similar reductions in execution time were observed for CAM's random number generator and shortwave radiation module. A dynamical core used within CAM, the High Order Method Modeling Environment (HOMME),



Execution time for the Morrison Gettelman (MG) microphysics kernel, which is part of the Community Atmosphere Model (CAM) using the Intel compiler on three generations of Intel Xeon processors (SNB2 = 2-socket Sandy Bridge node; IVB2 = 2-socket Ivy Bridge node; HSW4 = 4-socket Haswell node). Note that optimization consistently reduced execution time by more than a factor of two. Reducing the cost of the MG microphysics calculations, which consume a total of 3% of all time used on Yellowstone, will increase the amount of science that can be performed on our existing and future supercomputers.

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received additional optimizations that reduced the total cost of HOMME by 20-60% depending on the scientific configuration.

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The IPCC-WACS project is funded by a donation from Intel Corporation. Additional optimization efforts within ASAP are supported by NSF Core funds.


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ACCELERATING DATA ANALYSIS

NSF and other agencies now broadly recognize Big Data as a paramount challenge across science and engineering. Models such as the Community Earth System Model (CESM) have seen dramatic improvements in their performance and in the associated volume of data they produce. At the same time, we have not seen nearly the same progress from our processing, analysis, and visualization tools, which are generally single-threaded and sometimes limited to 32-bit addressing. In addition to emphasizing the hardware cyberinfrastructure (CI) side of the data analysis problem with NWSC resources, CISL is engaged in several activities aimed at exploring the requirements and developing new strategies for the software CI side of the equation.

CISL was heavily involved in the CGD-led process of preparing CMIP5 data for publication into the Earth System Grid for subsequent community use. The existing tools and workflows currently in use are fundamentally serial and seriously inadequate. CISL addressed these deficiencies in collaboration with CGD by developing and releasing several Python-based parallel post-processing tools to the CESM community. A joint project between CGD, IMAGe, and ASAP developed a method to evaluate the use of lossy data compression by analyzing the internal variability of a large ensemble of CESM runs.

We have released compressed climate data to the entire climate community by augmenting the CESM-CAM5 Large Ensemble (CESM-LE) community project with several ensemble members that have been compressed 5-to-1. We are actively soliciting feedback from the climate modeling community as to whether the effects of lossy compression are differentiable from the natural variability of the ensemble.

CMIP5 and data services research and development are supported by NSF Core funds. The new NSF-supported work in model data processing is supported by special award AGS-0856145.

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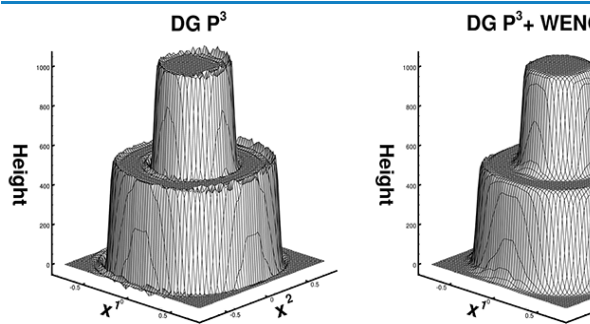
New high-performance computing algorithms are needed to produce increasingly ambitious simulations for the Earth System sciences. Because each doubling of spatial resolution requires a 16-fold increase in computational cost, increases in raw computing power alone will not be sufficient to address the grand-challenge problems we face. To address this issue, CISL is developing new numerical methods, solvers, and time-integration schemes for the algorithms used for Earth System simulations. Another approach is to reduce the computational complexity of the simulation by taking longer time steps or by using fewer grid points. CISL is reporting two highlights in this area for FY2015.

An efficient limiter for spectral-element and discontinuous Galerkin models

Efficient tracer transport schemes with monotonic or positivity-preserving properties are extremely important for climate models. For a practical climate model, hundreds of tracers (chemical species) need to be transported for a very long period of time to study the evolution of these tracers in the atmosphere.

To remove spurious oscillations in the numerical solution and make the solution physically recognizable, a numerical limiter is usually combined with a transport algorithm. The High-Order Method Modeling Environment (HOMME) developed at CISL employs the spectral-element (SE) and discontinuous Galerkin (DG) methods for the spatial discretization. The current default dynamical core in the Community Atmosphere Model (CAM) is based on the SE variant of HOMME (CAM-SE). For atmospheric models based on high-order methods such as SE or DG, the tracer transport is very challenging because efficient limiters are typically unavailable. For this reason the finite-volume based transport schemes are considered for tracer transport in CAM-SE. However, this requires a uniform resolution grid overlaid with the native SE grids, and it leads to complex flux coupling between grid systems.

It is difficult to design limiters for both high-order accuracy and non-oscillatory properties, and the problem is even more challenging for the cubed-sphere geometry. In FY2015, a simple and efficient limiter based on the weighted essentially non-oscillatory (WENO) methodology was developed for DG or SE transport models on the cubed sphere. The uniform high-order accuracy of the resulting scheme is maintained because of the high-order nature of WENO procedures. Unlike the classic WENO limiter, for which the wide halo region may significantly impede parallel efficiency, the new limiter requires only the information from the nearest neighboring elements, without degrading the inherent high-parallel efficiency of the DG or SE scheme. A local bound-preserving (BP) filter can be further coupled in the scheme to guarantee the highly desirable positivity-preserving property for the numerical solution. When combined with the WENO limiter, the DG/SE transport scheme is mass conservative, high-order accurate, non-oscillatory, and positivity preserving for the model based on the cubed-sphere geometry. The new limiter can be implemented in the CAM-SE framework to support climate and atmospheric chemistry



Simulation results with the DG transport scheme for a non-smooth tracer field (step cylinder located on a face of the cubed-sphere), after one revolution along the north-east direction of the cubed-sphere. The left panel shows results without using a limiter and the right panel shows the same but with the WENO limiter. The new WENO limiter successfully removes spurious oscillations and keeps the solution positive-definite.

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applications using the native DG/SE transport scheme.

The figure above shows numerical results for the DG transport on the cubed-sphere using a benchmark solid-body rotation test, where the initial field should return to its original position without incurring any deformation, after a complete revolution (equivalent to a 12-day period around the planet). The initial scalar field is a non-smooth step cylinder with sharp edges. The unlimited solution (left panel) shows spurious oscillations including negative undershoots. The WENO limiter combined with the BP filter completely removes the oscillations (right panel) and preserves the original (initial) shape of the tracer field.

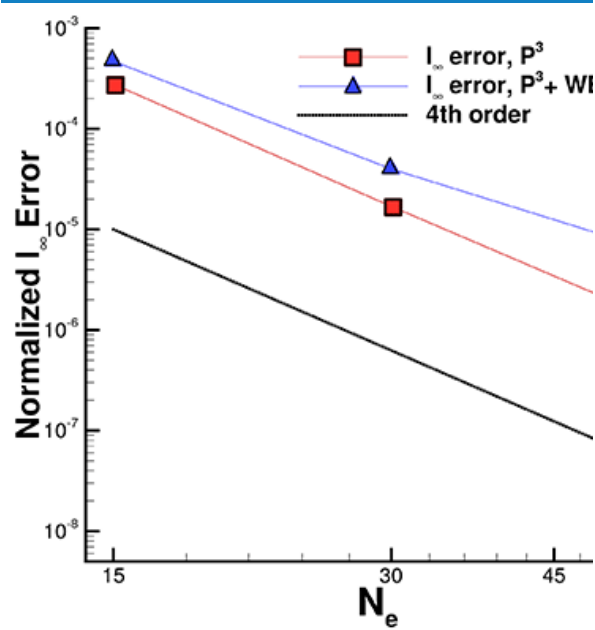
A remarkable feature of the new limiter is its selective application, the limiting operation is only activated when the solution is oscillatory. This not only saves computing time but also maintains high-order accuracy of the smooth solution. The figure at right shows the convergence of the fourth-order DG scheme with and without applying the limiter for a smooth Gaussian tracer field.

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, transport schemes with limiters, new solvers, and new time integration schemes.

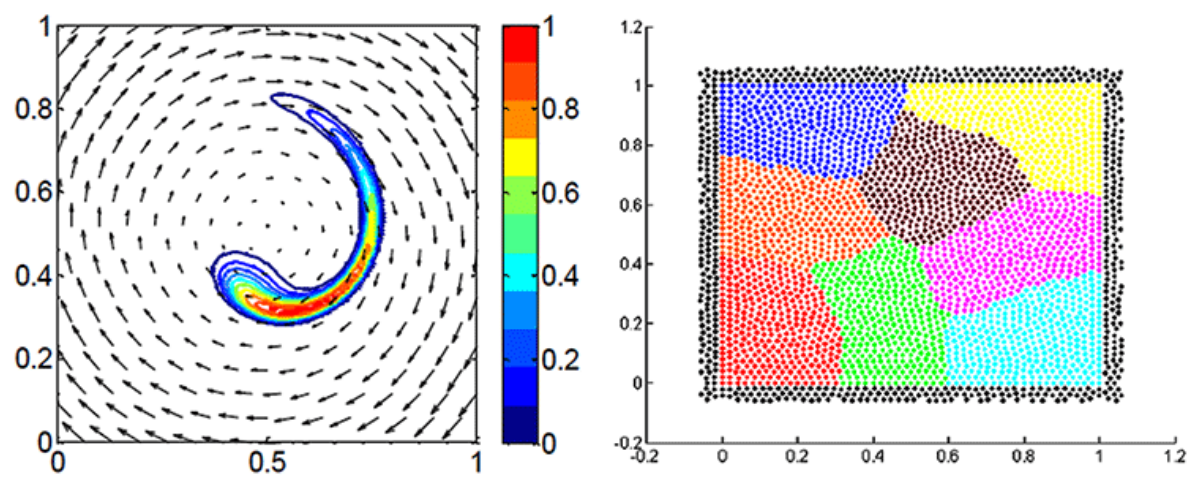
This work is supported by NSF Core funding. In addition, CISL’s RSVP funding was made available to support a graduate student visitor on this project.

Implementing PDE solvers on multi-CPU-GPU systems based on Radial Basis Function - Finite Difference methods

In FY2015 we investigated a multi CPU-GPU framework for PDE solvers based on the radial basis function-finite difference (RBF-FD) method. As a generalized finite differencing scheme, the RBF-FD method functions without the need for underlying meshes to structure nodes. It offers high-order accuracy approximation and scales as  $O(N)$  operations per time step, with  $N$  being with the total number of nodes. Although the meshless nature of RBF-FD with scattered node layout can provide challenges to domain partitioning and communication among processors, the results were highly encouraging. The test case was the transport of a scalar quantity (the amount of a pollutant) in a strong vortex fluid flow. The first figure shows the solution at a point when the scalar quantity is most highly sheared by the flow and a domain partitioning among eight processors for a scattered node layout. (The PDE is solved at each of the nodes using the RBF-FD method.)



Convergence plots of a fourth-order accurate DG transport scheme with (blue) and without (red) the WENO limiter for a smooth tracer field. A limiter is an essential component of the tracer transport model; it keeps the tracer monotonic (positivity preserving) throughout the numerical simulation. The new limiter does not degrade the accuracy of the scheme, conserves the tracer mass, and maintains the tracer free from spurious oscillations.

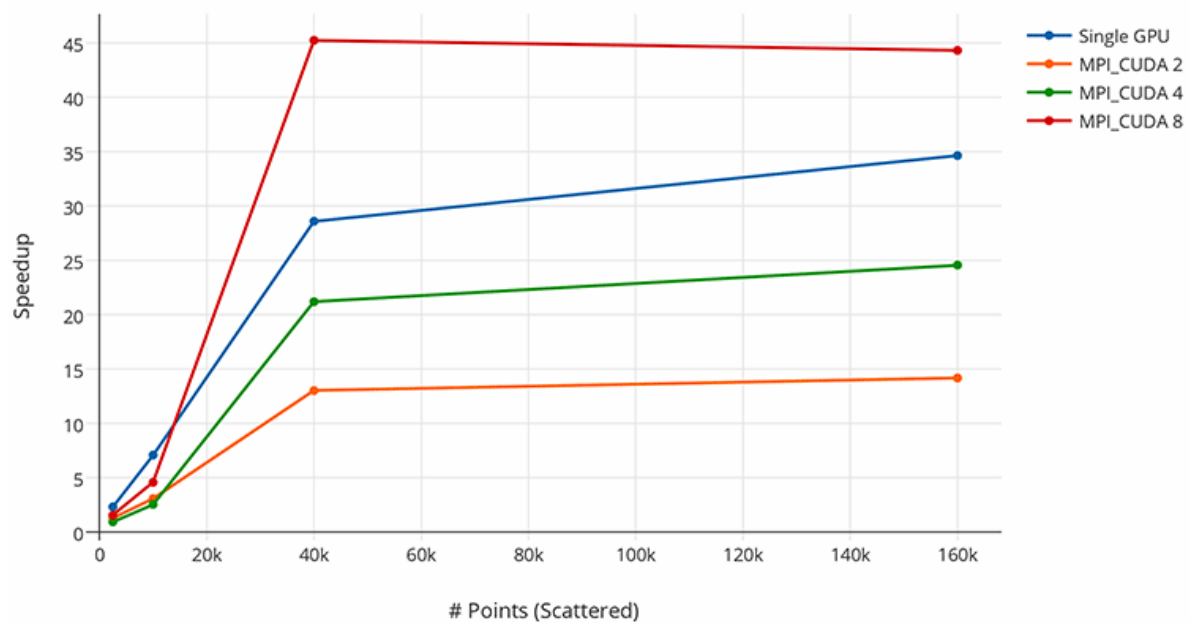


The image on the left shows a solution at a point when the scalar quantity (contour lines represent amount) is most highly sheared by the flow. The image on the right used the METIS software tool to partition a domain for a scattered-node layout among eight processors that will solve the PDE. Each partition is shown in a different color within the black boundary.

The study concluded that:

- On a single GPU, the RBF-FD method could produce a 35-times speedup over a serial code on a single CPU.
- On multi-CPU-GPU architectures, there is a general bottleneck in communication, with only a 15-times speedup using two CPUs and two GPUs and a 25-times speedup using four CPUs and four GPUs. Only until eight CPUs and eight GPUs are used does the achieved performance gain for the computation overcome the communication costs, with a 45-times speedup. This is demonstrated in the figure below.

Speedup over Serial Code (Caldera)



Speedup over the serial RBF-FD code (on one CPU) for transport of a scalar quantity in a strongly sheared flow with regard to one GPU and multiple CPU/GPU platforms. The notation MPI\_CUDA n uses n CPUs and n GPUs (e.g., MPI\_CUDA 4 uses 4 CPUs and 4 GPUs). The runs were performed on

the distributed-memory Caldera cluster.

This work advances CISL’s scientific efforts to develop algorithms for computationally accelerating applications of NCAR-wide science. This development effort at NCAR is supported by NSF grant DMS-0934317.

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CISL EDUCATION, OUTREACH, AND TRAINING

CISL’s education programs integrate research and education and teach the technical skills that students and faculty need to make effective use of advanced cyberinfrastructure. These programs also promote diversity, enhance CISL’s culture of teaching and mentorship, and stimulate collaborations with the university community. These objectives are accomplished through internship, visitor, workshop, and training programs.

A supercomputing laboratory in a national research center is a unique place to help integrate research and education between disciplines. CISL focuses on the computational and atmospheric sciences, and has a math institute dedicated to education and advancing research using applied mathematics and statistics. CISL’s educational efforts are designed to complement and supplement programs at universities and other centers.

CISL manages two principal training thrusts: one for HPC systems and another for CISL-developed data analysis and visualization tools. NCAR and CISL also provide cyberinfrastructure resources and user support for community workshops, tutorials, and summer schools in the atmospheric and related sciences.

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

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INTEGRATING RESEARCH AND EDUCATION

As a supercomputing laboratory embedded in a national center focused on the atmospheric and related sciences, CISL provides resources to integrate research and education between the disciplines of the computational and atmospheric sciences. This unique interdisciplinary focus enables CISL’s educational efforts to complement and supplement related programs at universities and other centers.

CISL’s inter-supporting programs that foster the integration of research and education include:

- The Summer Internships in Parallel Computational Science (SIParCS) program offers graduate and undergraduate students significant hands-on opportunities in computational science, applied mathematics, and geostatistics to help build a workforce that can exploit petascale computers. CISL budgets for approximately 10–12 SIParCS interns each year.
- The Theme-of-the-Year (TOY) is held in IMAGe as a series of year-long programs, each focused on a specific aspect of mathematics applied to the geosciences; it is designed to advance research, education, and collaboration between the mathematics and geosciences communities. The TOY program establishes collaborations around potentially rewarding research activities and encourages contributions from talented young investigators in a variety of disciplines.
- The Research and Supercomputing Visitor Program (RSVP) facilitates prolonged engagement and collaboration between our staff, the university community, and researchers at peer centers around the world, and offers special travel support for training classes and workshops to faculty and students from minority-serving and EPSCoR-state institutions.

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 backgrounds in computational science, applied mathematics, computer science, or the computational geosciences. The 11-week internships provide opportunities for exceptional students to gain practical experience with a wide variety of parallel computational science problems by working with the HPC systems and applications related to NCAR’s Earth System science mission. The ultimate goal of SIParCS is to address shortages of trained scientists and engineers capable of using and maintaining these high-end systems to achieve the goals of 21st-century computational geoscience research. SIParCS supports NCAR’s and Cisl’s core missions in education and directly contributes to Cisl’s strategic imperative to integrate research and education. Cisl is teaching the mathematical and computational science concepts and skills that students will need to make effective use of advanced cyberinfrastructure.



The SIParCS class of 2015 included 17 interns, plus one early-career visitor, Qian Zhang, who recently received her Ph.D. and was affiliated with the program. Pictured here are, left to right: Delilah Feng, Shreya Mittapalli, Mundabi Srivatsa, Whitney Nelson, Negin Sobhani, Vinay Ramakrishnaiah, Ian Bragg, Qian Zhang, Dongliang Chu, Sam Elliot, Collette Smirniotis, Gaston Seneza, Adnan Haider, Lee Richardson, Jenish Koirala, Albert Yao, Kyle Marcus, and Tuan Ta. SIParCS is an 11-week summer program run by Cisl that provides undergraduate and graduate students with an opportunity work on research projects in the computational sciences that span computer science, applied mathematics, statistics, visualization, and software engineering.

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The 2015 class of the SIParCS program was the second-largest in its nine-year history, with 17 students participating. It was also the most diverse, with three interns from Minority-Serving Institutions (MSIs), five female interns, and eight interns from seven different EPSCoR states. EPSCoR states are defined as those determined by the government to be underserved by federal research and education funding, and are thus eligible to receive funds to advance their research infrastructure through the Experimental Program to Stimulate Competitive Research (EPSCoR).

Also varied were the types of projects students undertook with their mentors: they ranged from a team of four undergraduate students designing and building an end-to-end, cloud-based workflow for collecting, storing, and displaying real-time weather data on a website using low-cost Raspberry-Pi processors, to interns porting, benchmarking, and analyzing the performance of the WRF weather model. Others worked with graphics processing units (GPUs) to do raycasting of volumetric data (computing a 2D image from a 3D data set), simulate atmospheric equations, assimilate data into forecast models, or solve geostatistics problems, while others focused on enhancing the performance of climate models and climate data analysis workflows. Still others used high-performance tools to shed light on real-world geostatistics problems, such as understanding future changes in Rocky Mountain snowpack in response to projected climate change.

During the summer, SIParCS students had an opportunity for enrichment activities such as a technical writing seminar, high performance computing (HPC) training classes, and a field trip to the NCAR-Wyoming Supercomputing Center (NWSC) to see the Yellowstone supercomputer. At the end of the summer program, the interns presented their research results in NCAR’s main seminar room from 29–31 July.

The FY2015 SIParCS program was made possible by NSF Core funding.



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## IMAGE THEME OF THE YEAR

IMAGe's Theme Of the Year (TOY) is a series of activities that explore the opportunity to enrich both applied mathematics and the geosciences through a common scientific topic. TOY is designed to advance research and education between the mathematical and geosciences communities; it uses targeted projects for building interdisciplinary communities. The topics are selected by the IMAGe external advisory panel and coordinated by one or more visiting co-directors. The yearly TOY programs support CISL's education imperative to integrate research and education, sparking collaborations between the mathematics community and Earth System scientists.



Dr. Glen Romine, a project scientist with a joint appointment between NCAR's MMM and CISL laboratories makes a point about numerical weather forecasting during the tutorial part of the Frontiers in Ensemble Data Assimilation workshop. Glen is also a member of the NCAR team testing a real-time ensemble forecasting system for forecasting storms. These ensemble forecasts are an operational and practical use of the DART assimilation software presented in this tutorial.

For 2015 the TOY focused on data assimilation through two events: STATMOS Summer School in Data Assimilation (18-21 May 2015) and Frontiers in Ensemble Data Assimilation for Geoscience Applications (3-7 August 2015). Data assimilation (DA) refers to a class of methods that link physical and probability models with the goal of inference or prediction for often complex, nonlinear dynamical systems. In

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applied mathematics this area is referred to as inverse problems or Bayesian hierarchical models. Applications are many and include geophysical sciences, engineering, and computational sciences.

Perhaps the most visible application at NCAR is weather forecasting where a physical model for the atmosphere is updated by observations to give a better estimate of the atmospheric state. Typically, neither the model or the observations on their own are adequate for forecasting. However, their combination through DA often gives an improved estimate of the atmosphere.

One hurdle for entry into DA applications and research is the difficulty of creating software to work with large and realistic geophysical models. The Data Assimilation Research Testbed (DART) is a software environment developed and supported in CISL to provide a tool for DA research. It has been very successful in allowing graduate students, university faculty, and other scientific groups to apply DA in novel ways without the substantial investment of engineering a new software system. One of the TOY goals was to offer tutorials for students to learn how to use DART.

Both the school and workshop provided a mathematical/statistical introduction to a variety of data assimilation techniques, talks on current research, and also a DART tutorial. Presenting DART in a lab setting allowed students to get hands-on experience using this software with Matlab-based analysis tools to study results. The school in May was partly sponsored by the NSF-DMS Research Network for Statistical Methods for Atmospheric and Oceanic Sciences (STATMOS). This research group is comprised mainly of statistical and data scientists and the activity reached a group that is not well engaged in DA. Thus, the goal of this school was to stimulate more interest in DA research within a mathematical community.

The workshop in August also included more technical material on new directions for DA and featured 13 presentations by scientists from national research labs, NCAR, and U.S. and international universities.

For the coming year, a TOY is planned on the analysis of climate extremes including the probability models that can represent rare events. Philippe Naveau, LSCE-CNRS, France, will co-direct this theme and will be visiting NCAR for a year on a sabbatical leave. The elements of this TOY will focus on bringing some key visitors that represent the areas of climate, statistics, probability, and machine learning. Besides organizing an independent workshop at NCAR to synthesize ideas, this program will also partner in the organization of three other international conferences. Of particular interest is involving statisticians more closely in the attribution of extreme weather events through participation in the International Detection and Attribution Group, held annually at NCAR.

Outreach activities of the Theme of the Year are supported by NSF Core funding, and the STATMOS summer school was partly sponsored by the NSF-DMS Research Network for Statistical Methods for Atmospheric and Oceanic Sciences.

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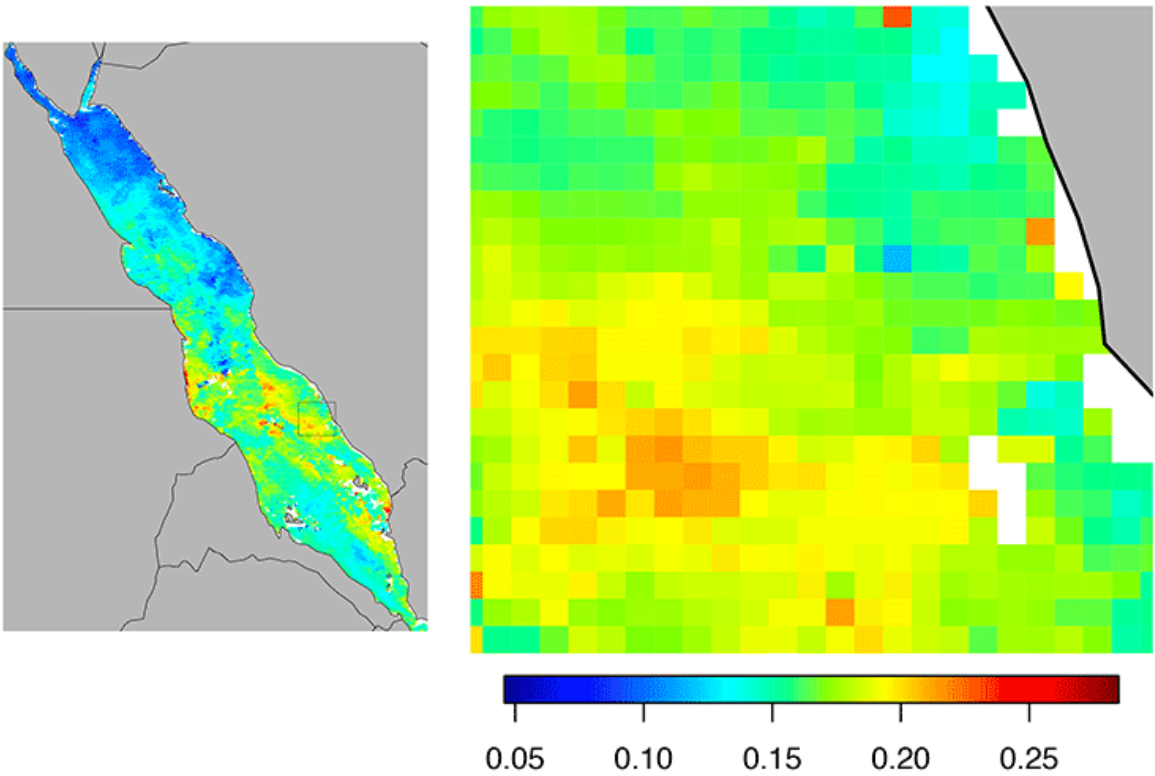
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RESEARCH AND SUPERCOMPUTING VISITOR PROGRAM

The Research and Supercomputing Visitor Program (RSVP) is designed to bring university faculty, researchers, and students to NCAR to foster collaboration with CISL staff and to provide training opportunities for underrepresented groups. The program pays for travel and living expenses for stays of up to three months.



Remotely sensed aerosol optical thickness for Fall 2014 over the Red Sea (image at right shows detail of box in image at left). The goal is to separate a smooth spatial signal from this retrieved data product. The aerosol (fine particles) concentration is important for determining how much radiation reaches the surface and what absorbed by the atmosphere. These data are used by Dr. Joseph Guinness as an example of geophysical, spatial observations on a regular grid but having an irregular boundary. The challenge is to exploit the grid structure for fast computation but also to adjust the boundaries to avoid artifacts that are common if edge effects are ignored. Dr. Guinness's approach for handling boundaries is also valuable for the multi-resolution spatial techniques developed in IMAGe.

These extended visits help establish stronger relationships that lead to long-term collaborations.

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For many visitors, this program represents a unique opportunity to interact with Cisl and NCAR scientists and staff on topics ranging from high-performance computing and Earth System modeling to applied mathematics and statistics.



Joseph Guinness, Assistant professor in the Department of Statistics, North Carolina State University was an RSVP visiting scientist collaborating with Cisl staff on the statistical compression of climate model output and also on the analysis of large spatial data sets. During his stay he also spoke as part of the IMAGE triple crown, an afternoon symposium on statistics and the geosciences.

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This program supports Cisl’s education imperatives of integrating research and education and broadening participation by being a key component that integrates Cisl’s education, outreach, and training efforts.

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RSVP has sponsored graduate students, junior faculty, senior faculty, and scientist visitors from around the U.S. and the world.

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Visitors in FY2015 included applied mathematicians to work with staff on numerical methods for geophysical models (e.g., new dynamical cores) and also graduate students in statistics to expand their mathematical research by including more focused methods for large geophysical data sets.

Also in FY2015, RSVP partially funded eight EPSCoR students to attend NCL workshops at NCAR.

In addition, Cisl used some RSVP funds to attract students from minority-serving and EPSCoR-state institutions to participate in the SEA Conference and Scalable Profiler Workshop.

This program is made possible through NSF Core funding.



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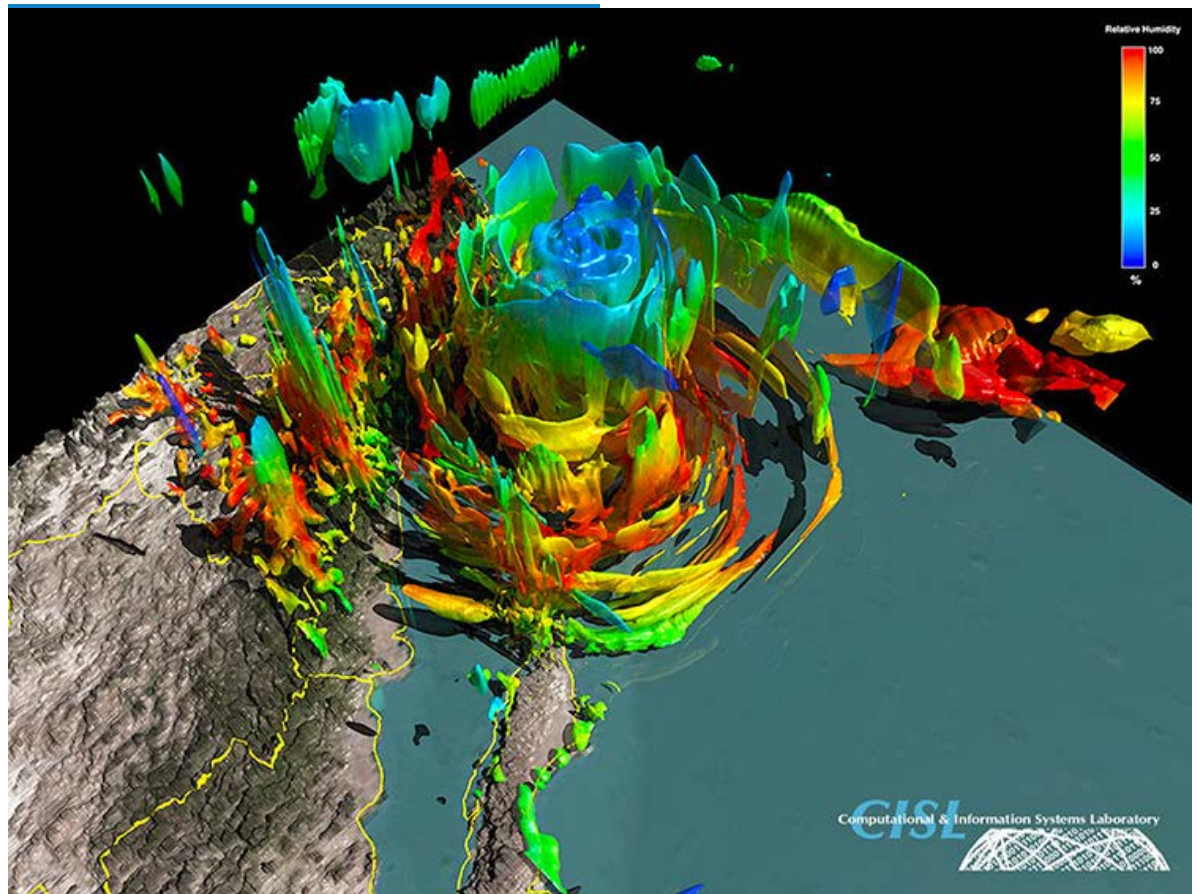
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## VISUALIZATION LABORATORY OUTREACH

CISL's Scientific Visualization Services Group (SVSG) operates the VisLab, a visual computing center that is used to conduct many of CISL's education, outreach, and collaboration efforts. The 1,000-square-foot facility supports video conferencing technologies, data analysis and visualization, and theater-style presentations in a widescreen, high-resolution, 3D format. The facility is equipped with a collaborative touch-screen interface, a high-definition 3D 1920×1080-resolution active stereo projector, and a 12×7-foot screen. This system displays imagery and presentation materials simultaneously from multiple sources including user laptops, digital media systems, and high-definition video conferencing platforms.



Hurricane Odile swept across the Baja California Peninsula in September 2014 leaving behind widespread damage, flooding, and power outages. It reached category 4 intensity before weakening as it tracked along the length of the peninsula. VisLab staff produced this visualization from data generated by Hurricane Weather Research Forecast (HWRF), an advanced hurricane prediction system developed by NOAA. VisLab visualizations such as this are regularly used for demos, presentations, and on social media to help inform, educate, and share information about NCAR research and collaborations.

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The VisLab serves as an important resource for CISL’s education and outreach efforts, fulfilling the strategic action item for CISL to tell NCAR’s story to the world. VisLab activities serve hundreds of staff and visitors each year and include support for advanced collaboration environments that foster geographically distributed research and communication. The VisLab operates a sizable outreach program that provides 3D presentations to a wide range of student, governmental, and scientific visitors. The VisLab’s implementation and support of collaborative technologies help enhance communication while minimizing the need for travel by geographically distributed teams collaborating on cross-institutional projects. The VisLab is also routinely used as an important presentation venue by UCAR staff for general meetings, conferences, and classes.

In FY2015 the VisLab continued serving as a venue for demos to many high-level visitors and as a meeting space for conferences and classes to help engage a broad and diverse community, increasing awareness and understanding of science, high-performance computing (HPC), and environmental issues. The Scientific Visualization Services Group (SVSG) supported approximately 160 meetings and demos in the CISL VisLab to over 2,100 users including Congressional staffers, NSF officials, corporate and research representatives, university students, and international visitors from Mexico, China, Barbados, Iran, and Panama, to name a few. Collaborative technologies and tools for video, web, and telephone conferences were used to host over 30 HPC and NCL training classes and webinars, connect remote participants at NCAR campuses and at domestic and international institutions, and provide AV and editing support for online access to class recordings. SVSG partnered with the UCAR Center for Science Education to provide 3D demos to hundreds of K-12 visitors, helping to educate and inspire young students about the Earth sciences, scientific research, and HPC.

Additionally, SVSG continued to develop scientific visualizations to help communicate NCAR research and to provide engaging and educational material for presentations and publication on social media. Visualizations published this fiscal year have been viewed on YouTube over 115,000 times and have been seen in at least 190 countries.

This project is supported by NSF Core funds with supplemental funding provided by NCAR’s Research Application Laboratory (RAL).



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WORKFORCE TRAINING AND DEVELOPMENT

CISL provides training opportunities for researchers in the atmospheric and related sciences to help them effectively use NCAR’s petascale high-performance cyberinfrastructure. CISL delivers educational content synchronously through workshops and training classes, and asynchronously through Internet-based content such as webinars, recorded lectures, and online documentation.

CISL’s education imperative for workforce training and development is supported primarily by NSF Core funding, with supplemental funding supplied by other sources as noted in the following reports.

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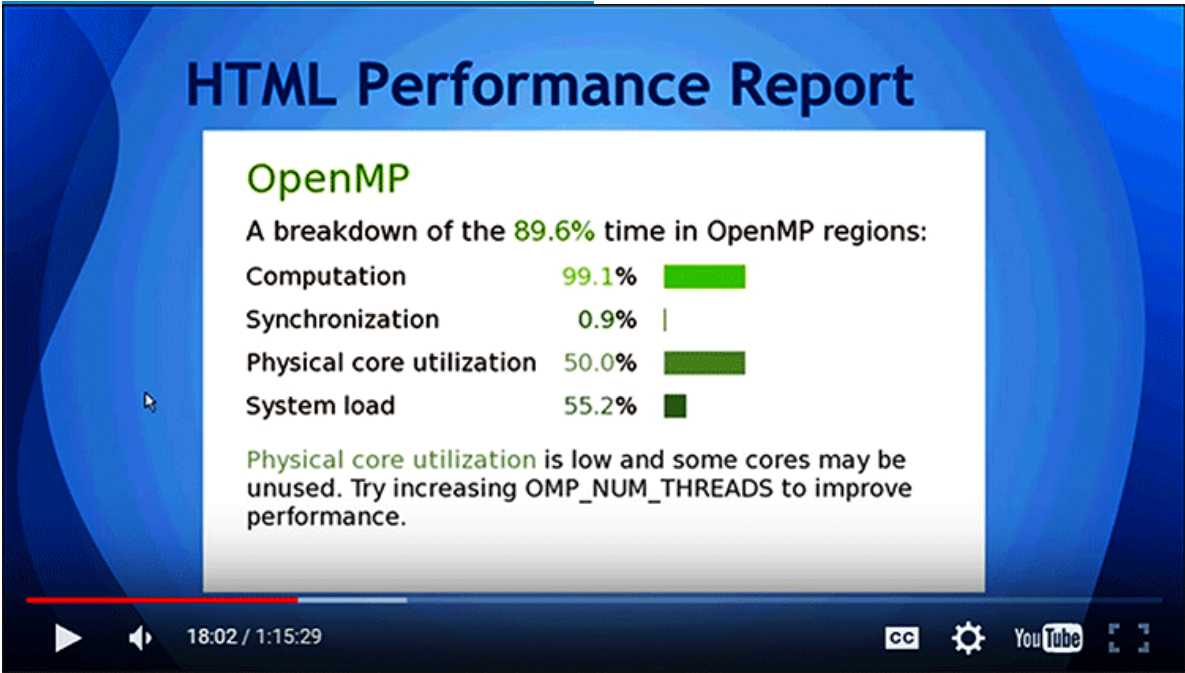
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TRAINING USERS AND INTERNS IN COMPUTING AT NCAR

The timely training and other learning opportunities that CISL provides help prepare researchers to answer questions in the atmospheric and related sciences using high-performance cyberinfrastructure. CISL delivers this content synchronously through workshops, webinars, and training classes, and asynchronously through its website.



This image from the training course “Optimizing Performance: Finding Hotspots and Bottlenecks” shows a report summarizing code performance. CISL training typically includes hands-on activities and demonstrations in addition to lectures, slides, and video presentations. Many courses and webcasts are recorded and published on the CISL website and CISL’s YouTube channel.

CISL instructors provided training classes in high-performance computing to more than 400 local and national HPC users. CSG and USS personnel presented the following courses and seminars in FY2015: Introduction to Yellowstone; Using the Globally Accessible Data Environment (GLADE) File Spaces; Optimizing Performance: Finding Hotspots and Bottlenecks; Modern Fortran; and three Yellowstone User Seminars. CSG also organized training events taught by outside experts, including Object-Oriented Fortran and Coarrays; Introduction to Performance Tuning and Optimization; and Allinea Performance Tools Overview. USS also supported Yellowstone users with authentication tokens for climate modeling classes at the University of California, Davis, and the University of Washington.


In addition to the regular curriculum, CSG personnel coordinated the 2015 UCAR Software Engineering Assembly conference, which included five days of talks and tutorials on high-performance computing; Python in scientific computing; debugging and profiling HPC codes; user environment tracking and

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problem detection; software deployment; monitoring resource usage; dynamic data structures; testing scientific codes; using the KGEN Fortran Kernel Generator; Software Carpentry; Data Carpentry; and data analysis and visualization. CSG staff also supported NCAR training events that were delivered by others, including Weather Research and Forecasting (WRF) model workshops; Community Earth System Model (CESM) workshops; and the IMAGe-taught High Performance Computing for Spatial Statistics workshop at the University of Michigan.

The NCAR Command Language (NCL) team taught three workshops in Boulder in addition to others at the University of Nebraska-Lincoln and the Institute of Meteorological Science of Jilin Province, China. Nearly 120 students attended the workshops. NCL workshop content also was produced as a series of 12 recorded webinars for students who are unable to attend in person.

CISL has also served as a satellite site for select events in the XSEDE HPC Monthly Workshop Series. CISL further leverages its participation in the national XSEDE cyberinfrastructure to expand the training opportunities available to users by cross-posting XSEDE training opportunities on CISL’s website and in the CISL Daily Bulletin.

CISL’s user and intern training is supported by NSF Core funding.

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TRAINING IN GEOSCIENTIFIC TOOLS

Staff in CISE and CGD have collaborated for 15 years to provide a series of training workshops for the NCAR Command Language (NCL) – a free, interpreted language designed specifically for geoscientific data analysis and visualization. NCL workshops are 3-1/2 days in length with morning lectures and intensive hands-on labs in the afternoons. In the last 2-1/2 years we've provided the NCL workshop lectures in a series of free webinars to reach a large base of users who are unable to travel to attend workshops. Given the growing popularity of Python, we have recently expanded our training to include related Python tools. CISE staff also provide hands-on and remote (e.g., webcast) training for the CISE-developed VAPOR package.

The NCL and VAPOR hands-on labs are targeted toward students' specific needs by encouraging students to use their own datasets for analysis and visualization rather than using canned datasets and examples. The instructors work with students individually during the labs, and by the end of the workshop most students have developed nearly complete NCL programs or VAPOR "sessions" that produce meaningful results from their data. A core NCAR value is partnership with the university community.

We proactively reach out to U.S. university students by offering at least one fully or partially funded NCL workshop at a U.S. university each year, and by covering some of the travel expenses for qualified students from EPSCoR universities and minority-serving institutions (MSIs) to attend workshops. (EPSCoR universities are located in states that are deemed to be underserved by federal research and education funding. The goal of the Experimental Program to Stimulate Competitive Research – EPSCoR – is to balance national research and education support by strengthening it in these states.) These workshops and webinars advance CISE's strategic education imperative to provide workforce training and development.



This photo was taken during the VAPOR tutorial at the annual WRF Users Workshop, held at NCAR in June 2015. CISE staff members provide a two-hour hands-on tutorial at the workshop each year. About 30 students attended this year.



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This photo was taken at the June 2015 NCL Workshop in Boulder, Colorado. Attendees included graduate students from seven universities (six of these were students from EPSCoR states whose attendance was supported by CISL funds), a SIParCS intern, staff from NOAA and Pacific Northwest National Laboratory, four NCAR employees, and a scientist from the Government of Alberta. Their research interests included land surface modeling, marine weather, air pollution modeling, carbon cycling in permafrost soils, monsoon climate over Africa and Asia, and biogenic and anthropogenic emissions of volatile organic compounds.

At end-FY2015, a total of 79 NCL workshops have been taught to 1,276 students at universities and research centers worldwide. Five workshops were taught in FY2015 to 117 students at the Institute of Meteorological Science of Jilin Province in China, the University of Nebraska-Lincoln (UNL), and three local workshops in Boulder. We finished recording the NCL workshop material in a series of 9 additional webinars, making a total of 19 webinars available to students unable to attend the workshops in person. We held the first training course for PyNIO at the SEA Conference, and have been accepted to teach an 8-hour course on PyNIO and related Python tools at the Annual AMS meeting in January 2016. CISL fully funded the UNL workshop, and partially funded eight EPSCoR students to attend workshops at NCAR. Similarly, VAPOR tutorials were given to atmospheric science researchers at the Korean Supercomputing Conference in Seoul, as well as the annual WRF workshop held at NCAR in Boulder.

The VAPOR website was given a long-needed overhaul this year, with a particular emphasis on improving E&O to the VAPOR user communities, providing, for example, numerous new tutorials accessible from YouTube.

The VAPOR tutorial at the Korean Supercomputing Conference was funded by the Korea Institute for Science and Information Technology. All other VAPOR tutorials and the NCL workshops were supported by NSF Core funds.

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SUPPORT FOR COMMUNITY WORKSHOPS, TUTORIALS, AND SUMMER SCHOOLS

CISL hosts community workshops, tutorials, and summer schools on strategic topics designed to advance science, develop collaborations, and inform strategies for the future. This past year, CISL hosted a broad range of these events across numerous topics. Examples described here are the Multi-core V Workshop hosted by the Technology Development Division (TDD) and five data science conferences hosted by the Institute for Mathematics Applied to the Geosciences (IMAGE).

Multi-core V Workshop

The purpose of the Fifth Multi-core Workshop was to provide a forum for open discussion to better understand the application of new high performance computing technologies for the next generation of weather, climate, and Earth System models. The new generation of high performance computer architectures has diverse heterogeneous architectures that present significant challenges to the community working on these models. The workshop was held September 16 and 17 at the NCAR Mesa Laboratory, and included 39 U.S. and international attendees.



Multi-core V brought to NCAR experts in many-core processor programming applied to geophysical fluid flow problems. Participants came from multiple laboratories, agencies, companies, and nations. Seven students and postdocs also participated.

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The workshop’s primary goals were to:

1. Provide a forum for presenting experiences and lessons learned from the development of weather and climate models on these platforms.
2. Create a community of developers who can work together to develop the software standards needed for these platforms.
3. Exchange information about programming techniques, code parallelization and optimization, and I/O strategies on these platforms.
4. Provide input to standards committees on what the community would like to see in programming models for the applications.
5. Exchange ideas on the issues surrounding the scalability of these codes on future platforms.

At Multi-core V, there were 19 talks arranged in five sessions focusing on thematic areas such as: overviews and strategies, tools and techniques, and climate, weather, and ocean models. Multi-core V was hosted using NSF core funds.

**IMAGe summer conferences focus on Big Data for research**

In FY2015, CISL’s Institute for Mathematics Applied to Geosciences (IMAGe) offered a variety of conferences designed to help Earth science researchers cope with the ever-increasing challenges of “Big Data.” These conferences support the research communities’ need to extract scientific knowledge from the petabytes of data being produced by today’s instruments and computers.

In May, the IMAGe-STATMOS Summer School in Data Assimilation was part of a series designed to help train the next generation of researchers working in data-rich disciplines. It brought together graduate students, early-career scientists, and senior scientists in environmental statistics and related fields to explore contemporary topics in applied environmental data modeling. During their four days at the workshop, participants received an introduction to data assimilation methods and their applications, as well as hands-on training in the use of IMAGe’s Data Assimilation Research Testbed (DART).

In June, IMAGe presented a week-long Data Analytics Bootcamp for High School Students, an opportunity for 10 Boulder high school sophomores and juniors to learn about being a data scientist. Demand for data scientists continues to increase as the Big Data era produces data in varieties and volumes far exceeding anything scientists and engineers have ever had to manage before. The bootcamp’s curriculum was an engaging hands-on experience for the students as they performed exercises using authentic data to analyze and solve real-life problems.

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Each pair of students at the Data Analytics Bootcamp received guidance from one expert during the workshop exercises. The support staff shown in this photo includes, from left to right, Colette Smirniotis, Dorit Hammerling, Lee Richardson, and Nathan Lenssen. The 10-minute exercise being conducted here followed five minutes of instruction in a new concept. This format was designed to sustain student interest during the intensive training and ensure that each participant had immediate, supported practice applying their new skills.

IMAGE hosted three more conferences in July, August, and September to continue developing researchers’ skills in Environmental Data Analytics, Ensemble Data Assimilation, and Climate Data Informatics.

*Data analytics* is the discipline of interpreting data to discover useful information and patterns with the goal of answering specific questions, gaining scientific insight, or making more effective decisions. Data analytics uses methods and algorithms drawn from statistics and computer science to help researchers explore the ever-increasing volume of data that supports science, engineering, medicine, commerce, and many other aspects of society. For NCAR researchers, effective data analytics reveals more scientific information from both observations and numerical simulations, and it often produces graphics to communicate results visually. In July, IMAGE hosted the Second Annual Graduate Workshop on Environmental Data Analytics was part of an ongoing series designed to prepare the next generation of researchers and practitioners to work within and contribute to the data-rich era. Each workshop brings together researchers from graduate students to senior scientists in environmental statistics and related fields to explore contemporary topics in applied environmental data modeling. This second annual workshop offered hands-on computing and modeling tutorials, presentations from graduate student participants, and invited talks from early-career and established leaders in environmental data modeling. Tutorials and invited talks addressed useful ideas and tools that are directly applicable to student participants’ current and future research. Seven of the 29 participants came from EPSCOR states.

*Data assimilation* refers to methods that combine data from observations and the output of numerical models to provide improved estimates and better prediction of real systems. An *ensemble* assimilation uses a sample of states of the system where the variation among the ensemble members quantifies the uncertainty in the state. A familiar application of data assimilation in the geosciences is weather forecasting, where a large set of weather observations are combined with the output of a numerical weather model to make forecasts. At NCAR, data assimilation is also used to improve climate models and check physical models against observations. In August, the IMAGE workshop Frontiers in Ensemble Data Assimilation for Geoscience Applications focused on (1) ensemble data assimilation for atmosphere,



ocean, land, and coupled Earth System models, and (2) hybrid ensemble variational assimilation techniques. Participants explored current techniques and applications of data assimilation in the geosciences. Indicating the international appeal of ensemble data assimilation, 13 of the 27 participants came from non-U.S. universities. Two participants came from EPSCOR states.

*Data informatics* is a discipline for examining large data sets to find patterns and structure that can help in understanding the relationship between different variables or to make predictions. Climate data informatics broadly refers to any research combining climate science with approaches from statistics, machine learning, and data mining. Conferences between researchers from all of these areas stimulate the discussion of new ideas, foster new collaborations, grow the climate informatics community, and accelerate discovery across disciplinary boundaries. In September, the Fifth International Workshop on Climate Informatics emphasized communication among all the various fields, with a strong emphasis on brainstorming during the breakout sessions and panel discussions. Most of the 86 participants came from U.S. research universities, with 13 from international universities, 10 from corporations, and 10 from other research laboratories. This workshop series was co-founded by Claire Monteleoni (George Washington University) and Gavin Schmidt (NASA Goddard Institute for Space Studies) under a multi-year NSF grant, and a variety of other sponsors help fund the series. An extra full day was added on the Saturday after this workshop for NCAR’s first data science “hackathon,” where participants were given a challenge problem in climate informatics. Small teams were formed to implement machine-learning and data-mining algorithms using the python programming language. The event, referred to more formally as a Rapid Analysis and Model Prototyping (RAMP) had 28 participants, and encouraged them to test different analytics solutions for a problem, then deliver a prototype as an initial outcome. The event trained novice data scientists in hands-on analytics, introduced a complex, real-world scientific problem, then benchmarked different solutions. The focus was on collaboration and efficient exploration.



The participants in the Fifth International Workshop on Climate Informatics interact during the “Knowledge discovery in climate science” presentation by Imme Ebert-Uphoff of Colorado State University. The workshop’s poster session and reception on the first night featured more than 40 posters. Also on the program were two panel discussions, “Deep Learning for Climate Science” and “Encoding climate knowledge into climate learning,” that were designed to generate new ideas across research disciplines.

These IMAGE workshops were supported by NSF Core funding, except as noted above.

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OUTREACH ACTIVITIES

Outreach is a gateway activity: it is the conduit through which other goals are reached. Examples include integrating education and research, broadening participation, and workforce development. Enhancing these activities offers opportunities to better connect with our user community, students, and future employees at all levels. In general, the goals for enhancing our outreach programs include:

- Reach a larger and broader audience.
- Develop our message to be more impactful and compelling.
- Communicate our accomplishments and the benefits of working in CISL more effectively.

CISL’s outreach program supports CISL’s education imperative for outreach: to actively attract qualified candidates, particularly those from diverse backgrounds. This work fulfills CISL’s strategic action item to expand outreach activities at conferences that enable CISL to effectively interact with our user community, students, and potential employees. Conference outreach also contributes to CISL’s educational imperatives for workforce training and development, and for broadening participation.

These efforts are supported by NSF Core funds, with supplemental funding supplied by other sources as appropriate.

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NWSC Visitor Center Exhibits

A key goal of the NWSC facility project was to broaden its impact through an active public visitor program. The primary element of that program was a planned NWSC visitor exhibit to explain the science goals of NCAR and the University of Wyoming, as well as the technology employed at the NWSC to realize these goals. The NCAR-Wyoming partnership’s NWSC education and outreach strategic goals are derived from an understanding of the national and regional challenges of STEM education and are designed to leverage the unique strengths of the founding NWSC partners. In October 2012, the NWSC opened its doors to the public, and inaugurated its Educational Visitor Center.



A student group concludes a visit at the NWSC, where they learned about supercomputing, science, and how research and technology benefits society. Experiences like this help students explore STEM disciplines and consider careers in science and high-tech fields.

Cisl OSG staff, in collaboration with advisors from the UCAR Center for Science Education, the University of Wyoming (UW), and the Laramie County Public Library, worked to create a visitor experience at the NWSC that would engage and educate audiences of all ages and backgrounds in NCAR’s and UW’s science, the facility’s state-of-the-art green design, and the capabilities of the supercomputers it houses. The educational goal of the exhibit was to explain how the NWSC’s research and science mission benefit people and society while providing visitors with a fun and memorable experience.

In total, the content includes 16 professionally produced video segments, three short animated films, two touchscreen interactive games, two kinesthetic interactive elements, multiple question-and-answer displays, and science and technical content and accompanying vivid “story-telling” imagery for the six focus-area themes. This year, a new animation that describes the infrastructure of the NWSC was added to the exhibits.

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The NWSC visitor center has exceeded initial estimates for community interest, total visitors, organized group tours, and school group visits. Since opening in October 2012, the visitor center has hosted more than 7,000 visitors, which is about 11% of the population of Cheyenne, Wyoming, where the NWSC is located. In FY2015, nearly 30 school groups and more than 550 students visited the NWSC. In addition, the center has received 32 non-school groups. Currently, relatively few American students pursue studies in the fields of science, technology, engineering, and mathematics (STEM), and STEM education for both students and teachers has become a national priority. The NWSC exhibit has served as the nexus for regional STEM events tackling this problem, hosting groups like the Boys and Girls Clubs of Douglas, Wyoming, school field trips, and summer activity groups.

In short, the NWSC Visitor Center has yielded rich opportunities for outreach and education about NCAR science, scientific computing, mathematics, and engineering. The STEM disciplines come to life at the NWSC, where visitors can explore interdisciplinary yet related topics like extreme weather, climate change, energy, water resources, supercomputing, facility design, energy efficient technologies, and human health.

The NWSC visitor center is intended for self-guided tours for individuals and groups of all ages and backgrounds, and it can also be used for presentations and special events. The visitor center consists of a theater for watching a video overview; two science displays, each with two sides having a different science focus area; a young scientist display that includes a tornado simulator and an interactive computer speed demonstration; and a supercomputer display at which visitors can see inside the supercomputer and interact with an exhibit that connects the concepts of electrical power with computing power through a hand-crank “generator.” A key educational goal of the visitor center was to include content that would convey elements of computational thinking. These include interactive activities that explain the concept of speedup in parallel computing and identify other kinds of parallel systems in everyday life. To engage diverse audiences, the videos in the exhibits also include Spanish-language subtitles.

The NWSC visitor center was financed using NWSC construction funds from the NSF and the University of Wyoming, and it is maintained using NSF Core funds.

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## NWSC EDUCATION AND OUTREACH

The Wyoming-NCAR partnership's NWSC education and outreach strategic goals are derived from an understanding of the national and regional challenges of STEM education and are designed to leverage the unique strengths of the founding NWSC partners. NWSC's high-level strategic EOT goals are to:

- Integrate university research with K-16 education.
- Build cyberinfrastructure and computational science capacity in Wyoming, regional EPSCoR states, and Front Range institutions.
- Train the next generation of computational scientists.
- Complement and enhance programs at community colleges to prepare students for careers in related technical fields.

- Broaden participation by enhancing the capabilities of community colleges to train students in technical fields that better prepare them for careers in HPC-related technical fields.
- Broaden diversity by engaging minority-serving institutions, particularly regional tribal colleges and historically black colleges and universities.
- Build strong foundations and foster innovation to improve K-12 computational thinking, mathematics, and computational geosciences.
- Engage and inform the public about NWSC science through informal education.

In FY2015, CISE's Outreach Services Group collaborated with the University of Wyoming and UCAR's Center for Science Education (SciEd) to materially advance each of these goals. For example, CISE's Outreach Services Group supported K-12 STEM enrichment by participating in the Wyoming State Science Fair for the fifth consecutive year. This summer, as part of the Boys and Girls Clubs of Douglas, Wyoming's "Brain Gain" summer activities, nearly 70 members participated in hands-on activities to learn about extreme weather and related topics at the NWSC. In the past year, the NWSC has hosted over 30 school groups and nearly 400 other groups, including adult professional organizations, military, and industry groups, and received a total of over 7,000 visitors since opening in 2012. In FY2015, the NWSC has hosted 28 school groups, 32 adult professional organizations, and a total of 1,736 visitors.

CISE's contributions to the Wyoming-NCAR partnership's NWSC education and outreach strategic goals are supported by NSF Core funding.



Students explore the inner workings of the NWSC and its systems through an interactive display in the visitor center. The material covers electrical, cooling, and networking systems that enable the supercomputer to run and support NCAR's science mission. Students gain important hands-on exposure to multiple facets of science and technology through the exhibits at the NWSC.

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OUTREACH AT REGIONAL, NATIONAL, AND INTERNATIONAL LEVELS

CISL's outreach program supports CISL's education imperative for outreach: to actively attract qualified candidates, particularly those from diverse backgrounds. This work fulfills CISL's strategic action item to expand outreach activities at conferences that enable CISL to effectively interact with our user community, students, and potential employees. Conference outreach also contributes to CISL's educational imperatives for workforce training and development, and for broadening participation.

CISL deploys exhibit booths for a variety of scientific and technical conferences where CISL staff demonstrates supercomputing capabilities, scientific visualization, and NCAR research in science, computational science, computing technology, and applied mathematics and statistics for the geosciences. CISL also invites scientists and researchers, to present their current findings in the CISL exhibit booth. At the height of its conference outreach program, CISL staff provided demonstrations and presentations at many conferences each year, including Supercomputing, the American Meteorological Society, the American Geophysical Union, Richard Tapia ACM Richard Tapia Celebration of Diversity in Computing (biennially), and the ADMI Computer Science Symposium and others. CISL also hosts and provides planning and logistics support for mission-appropriate conferences and workshops.

CISL's outreach activities at SC14 in New Orleans included a series of presentations, a stop on the Intel technology tour, and supported a scavenger hunt for students attending the international supercomputing conference. The presentations in CISL's booth included science and computing talks about CESM, aerodynamics and wind energy simulations on Yellowstone, and GPU applications in data assimilation. Other topics included HPC education, a demonstration of VAPOR for Big Data applications, and a status update on the procurement of NCAR's next supercomputer.

Another key part of what happens at SC is the technical conversations and private meetings with vendors, some requiring specific non-disclosure agreements, that provide information about future HPC developments. These meetings allow CISL staff to get a sense of the future technology landscape, and are critical for operational planning and procurements.

CISL again staffed a table at the Supercomputing Student Job Fair, talking to students and job seekers about educational, internship, and employment opportunities at NCAR and UCAR. The Student Job Fair event was open to all students and postdocs participating in the SC14 Conference.

As part of its diversity program, CISL conducts outreach in mission-appropriate diversity-oriented venues, such as the Association of Computer/Information Sciences and Engineering Departments at Minority Institutions (ADMI) Symposium on Computing at Minority Institutions and the Rocky Mountain Advanced



CISL's Raghu Raj Prasanna Kumar and Kristin Mooney engage with students and postdocs during the SC14 Student-Postdoc Job and Opportunity Fair held 19 November 2014 in New Orleans, Louisiana.



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Computing Consortium ([RMACC](#)). CISL staff described NCAR research careers, encouraged faculty members to nominate students for NCAR programs, and distributed printed information about internship opportunities and professional development programs including SOARS and SIParCS.

CISL supported the March 2015 Wyoming State Science Fair at the University of Wyoming in Laramie. CISL and UCAR Spark supplied three volunteers as judges, presented four awards for top junior and senior computational and Earth System science projects, presented atmospheric science demonstrations, and exhibited information about the NWSC facility in Cheyenne. CISL's outreach efforts are part of the NWSC partnership with the State, University, and business community of Wyoming. CISL encourages students to embark on careers in computational science and engineering, and our efforts at this venue demonstrate our long-term commitments to outreach, workforce development, and broadening participation in the sciences.

CISL's Outreach Group developed and maintains the public visitor area at NWSC. This [education exhibit in Wyoming](#) informs K-12 students and the public how high performance computing supports and advances scientific research and discoveries. This past year, CISL's student visitor support strategy included providing a docent at NWSC as well as adding science talks and interactive demonstrations of parallelism using a Raspberry Pi power wall. CISL collaborates in this effort with staff at the University of Wyoming, the Laramie County Library System, and UCAR Education and Outreach efforts.



In July 2015, a Computer Science Summer Camp of fifth- through eighth-grade students from the Sweetwater County School District visited the NWSC. The program is organized by Carla Hester-Croft, a faculty member at Western Wyoming Community College. The students traveled four hours each way to visit the supercomputing facility in Cheyenne.

The NWSC Education and Outreach Strategic Plan, which was written in a collaboration between directors of CISL and the University of Wyoming, calls for NWSC education efforts to support diversity and in particular to serve tribal colleges and community colleges throughout the intermountain west. Over the past two years a relationship has developed between CISL and Salish-Kootenai College (SKC), a tribal college in Montana, and Front Range Community College (FRCC), Laramie County through the SIParCS externship program. At SKC, this technology outreach has spawned "Tech Tuesdays" an open laboratory environment where Native American students work with technology provided by CISL to advance their understanding of information technology. At FRCC, CISL externship efforts have resulted in Raspberry Pi-based HPC concepts being incorporated into an IT course at that Community College.

CISL provided mentors for UCAR's Significant Opportunities in Atmospheric Research and Science (SOARS) program every year since its inception. This past year CISL's Outreach Services Group has worked strategically with the new NCAR Diversity, Education and Outreach Director, Carolyn Brinkworth, and other E&O programs at NCAR to become more integrated with other internship programs. CISL's

SIParCS program collaborates with SOARS in outreach activities. CISL has established a reciprocal arrangement with other internship programs at NCAR for training, coordinating social events, and referring candidates between the programs.

These efforts are supported by NSF Core funds, with supplemental funding supplied by other sources as appropriate.

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BROADER IMPACTS

CISL engages in a spectrum of activities designed to broaden the laboratory’s impact through outreach, collaboration, and community engagement, and through capacity building at regional, national, and international scales. These activities have two main thrusts. First, CISL does outreach and provides training and education opportunities aimed at broadening participation and encouraging the development of the trained and diverse workforce necessary to continue advancing the scientific use of high performance computing resources. Second, CISL encourages collaboration and exchanges of information and expertise for developing shared cyberinfrastructure and standards that will advance high-performance computing, not only in the atmospheric and related sciences, but also in the general HPC community.

Clear examples of how CISL’s education efforts broaden the laboratory’s impact on the U.S. STEM workforce arise yearly from CISL’s internship program SIParCS and IMAGE’s Theme of the Year (TOY) interdisciplinary education series. Numerous interns and early-career scientists have redirected their career plans in response to their positive research experiences in CISL. Students often come to CISL for a specific SIParCS or TOY session, return as postdoc collaborators, take jobs as university faculty, then send their students here to enrich their development. This process keeps refreshing our workforce with new talent, it reinvigorates others at the universities, and it is a healthy model for a national center.


This work is supported by NSF Core funding.

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DIVERSITY-FOCUSED ACTIVITIES

CISL provides significant opportunities for students and recent graduates from diverse backgrounds to hone their skills in mathematical and computational science concepts. CISL also lowers barriers for students and staff from underrepresented groups and underfunded states through participation at diversity-oriented conferences, staffing a full-time Diversity Specialist, providing student travel support to attend training courses and conferences, and offering diversity-focused internships and externships.

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DIVERSITY-FOCUSED OUTREACH

CISL performs diversity-focused outreach to encourage students to pursue careers in computational science and to inform them about internship and training opportunities offered by CISL, UCAR, and NCAR. CISL actively performs diversity outreach focused on the computational sciences at regional and national events such as the IEEE Supercomputing and the American Geophysical Union conferences.

For example, for the third year in a row, CISL has participated in the Association of Computer/Information Sciences and Engineering Departments at Minority Institutions (ADMI) Symposium on Computing at Minority Institutions. This year the Symposium was held on the campus of Georgia Tech University in Atlanta, Georgia on 19-21 March 2015. ADMI was founded in August 1989, with the mission of exploring and providing remedies to the educational issues in computer/information science and computer engineering that confront minority institutions of higher education. The 2015 ADMI Symposium highlighted undergraduate and graduate research with particular interest on innovations in the computing field. An important facet of the symposium is the opportunity to explore collaborations between major research institutions, industry, and minority institutions. Faculty and students present research papers, discuss poster presentations, and explore graduate school options.



CISL staff reviewed student posters at the 2015 ADMI Symposium in Atlanta. These outreach activities to underrepresented groups encourage students to pursue careers in computational science, and at NCAR and CISL.

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This year the CISL representatives at the ADMI Symposium did outreach to the attendees on behalf of the NCAR-UCAR-Wyoming partnership by distributing information about NCAR/UCAR/University of Wyoming internships, graduate research, and other educational and career opportunities. CISL staff also gave a keynote speech, "Using low cost clusters to teach high-performance computing," and judged ADMI's student poster competition.

Several of the student projects in the poster competition had a geosciences or low-cost computing connection. For instance, one student poster dealt with the issues surrounding the origins and adaptation efforts related to flood risk in the Mississippi delta region, another with remote sensing of ice shelves in the Antarctic, and a third was a robotics project designed to help hospitalized children.

These and other similar activities were funded by NSF core travel funds.

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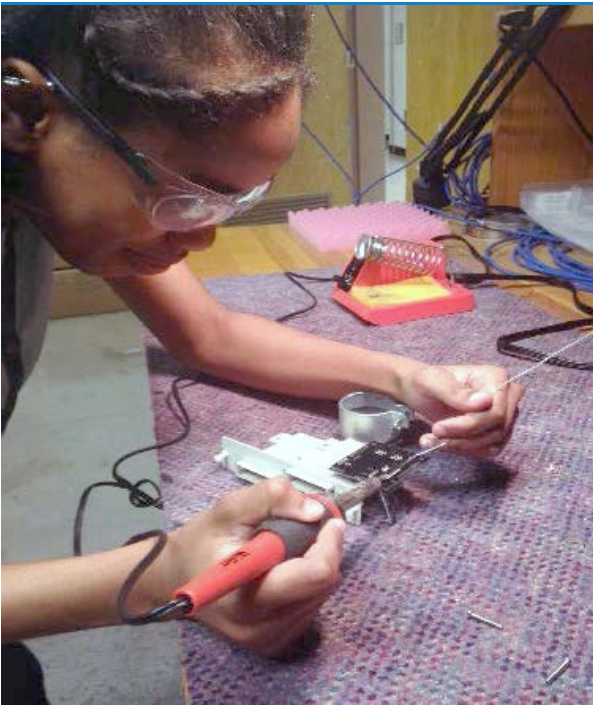
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DIVERSITY-FOCUSED INTEGRATION OF RESEARCH AND EDUCATION

As part of its diversity strategy, CISL provides hands-on integrated research and education experiences to students from diverse backgrounds.

One important way this is done is through the SIParCS program. For its second year offering SIParCS externship projects, CISL attracted a team of three students from MSIs and one non-traditional student. This year's project was again based on low-cost Raspberry Pi computers, a technology that lowers the barrier to access HPC technologies for students from under-served colleges and universities.

The team worked to build an end-to-end weather information system, including weather sensors, a data cloud, a MySQL database server/client system and webserver with web interface for displaying the data – all based on the Raspberry Pi system. This system, named Pi-in-the-Sky, brought students together from Jacksonville State University, Claflin College, Hampton University, and Philander Smith College.



A SIParCS extern solders a Raspberry Pi-based WeatherPi sensor.

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The 11-week project was funded with NSF core funds.

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TRAINING PROGRAMS FOR BROADENING PARTICIPATION

CISL is actively working to broaden diversity among technical and scientific research communities related to the computational geosciences. CISL uses its Research and Supercomputing Visitor Program ([RSVP](#)) funds to bring students from Minority Serving Institutions (MSIs), as well as under-served EPSCoR-state universities to attend CISL training events, such as [NCL Workshops](#) and the annual UCAR Software Engineering Assembly ([SEA](#)) Conference.



Undergraduate and graduate students shared their career interests and educational experiences with NCAR scientists, engineers, and other SEA attendees during a conference luncheon. Carolyn Brinkworth, NCAR Director of Diversity, Education, and Outreach, is standing at left.

For example, in 2015 CISL, in partnership with NCAR's Advanced Study Program, supported undergraduate and graduate students attending the SEA conference. This technical meeting is a community event that promotes professional development, advocates effective, up-to-date software engineering practices, and fosters collaborations both internally and with our peer institutions. The conference also provides a forum for discussions on aspects of software engineering that support scientific disciplines.

This year, travel support enabled 12 students from 11 institutions – both MSIs and universities in EPSCoR states – to participate in the conference. EPSCoR universities are located in states that are deemed to be underserved by federal research and education funding, so the National Science Foundation increases support for research and education in these states to improve its funding balance across the U.S. These 12 students met and made connections with engineers, researchers, and other professionals during the conference's presentations, tutorials, social events, meals, and at the CISL-sponsored luncheon with NCAR staff. CISL staff also introduced the students to the many internship opportunities throughout

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UCAR, with the goal of attracting these motivated young scientists and engineers to begin their careers at NCAR or UCAR.

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The 2015 SEA Conference on Python in Scientific Computing convened at UCAR’s Foothills Laboratory campus in Boulder, Colorado on 13 April and ran for five full days. Funding was supplied through NSF Core funds provisioned in CISL’s RSVP and NCAR’s Advanced Studies Program (ASP).

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## CISL LEADERSHIP IN CYBERINFRASTRUCTURE

CISL participates in a broad portfolio of activities intended to further the advancement of computing, data storage, and networking technology and the improvement of regional, national, and international cyberinfrastructure. These activities are consistent with NCAR's leadership role as a national Federally Funded Research and Development Center (FFRDC), and are supported by NSF Core funding.

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REGIONAL CI ENGAGEMENT

CISL has a strong presence in regional cyberinfrastructure (CI) development, including both the high-performance computing (HPC) and networking communities. Working with regional entities broadens NCAR's impact by fostering the maturation of regional CI, leverages unique regional resources and partnerships to tackle regional problems, and is a natural and mutually beneficial component of a national center's role.

Contributions to metropolitan and regional networks

CISL's [Network Engineering and Telecommunications Section](#) (NETS) is a recognized leader and participant in many regional networking projects that are tightly integrated with national networks. NETS provides a vital service to NCAR's research communities by linking scientists to supercomputing resources and each other. These activities are essential for the effective use of UCAR/NCAR scientific resources, and they foster the overall advancement of scientific inquiry.

CISL's involvement with regional networking consortia includes the Front Range GigaPoP (FRGP), the Bi-State Optical Network (BiSON), Western Regional Network (WRN), Boulder Point-Of-Presence (BPOP), Boulder Research and Administration Network (BRAN), the City of Boulder CG4 inter-building cabling, and the National Regional Networks Consortium named The Quilt. These collaborations and networks are all designed to provide NCAR/UCAR and other institutions in the region with robust regional and wide-area data pathways.

On behalf of UCAR, CISL continues to lead and participate in these important metropolitan, regional, and national networking initiatives. The tangible benefits of such participation include economical, diverse, high-performance networking for UCAR and its member universities. However, the intangible benefits are at least as important: participating in these initiatives reinforces UCAR's public mission of providing services to its members while simultaneously fostering cooperative ventures, collaborations, and relationships among these institutions. As a leading participant in such community alliances, NETS contributes to strengthening UCAR's value as an institution and helps UCAR fulfill its leadership and outreach obligations for NSF funding.

Commitment to HPC partnerships

CISL is actively engaged with regional HPC partnerships. These activities allow CISL to gain hands-on experience in collaborating with campus IT staff through the processes of CI acquisition, deployment, and resource federation.

Wyoming-NCAR Alliance and regional campus partnerships

Perhaps CISL's most important regional partnership is the Wyoming-NCAR Alliance (WNA), which governs the joint activities of NCAR and the State and University of Wyoming related to the NWSC facility, the Yellowstone environment, and NWSC's Education, Outreach, and Training activities. Through this partnership, CISL collaborates with Wyoming to enhance their campus HPC capabilities and extend Wyoming's research partnerships with other EPSCoR states. CISL has also supported several University of Wyoming-focused STEM education activities and proposals including a recently funded NSF ITEST proposal related to robotics and computer gaming.

In FY2015, CISL is completing its collaboration with the University of Colorado at Boulder and the University of Colorado at Denver on a Major Research Instrumentation (MRI) project that brought Janus,

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a 184-TFLOPS Intel-based Dell supercomputer to the CU Boulder campus. NCAR controls a 9.8% portion of this system and used more than 4.1 million core-hours across 15 allocated projects. Access to Janus’ computing resources were used to support a number of new startup research projects, thus serving as an important staging area for scientists preparing for the Yellowstone supercomputer.

In collaboration with the Colorado School of Mines (CSM), the Mesa Lab Computing Facility continued to host CSM’s IBM supercomputer named “BlueM” through FY2015. CISL collaborated with CSM on a computational science research project related to this novel hybrid computing system that combines IBM’s iDataPlex and Blue Gene/Q platforms.

In an effort to extend CISL’s engagement with other regional high-performance computing facilities, on 6 February 2015, a team of engineers visited NREL’s computer center and discussed HPC system administration challenges and best practices.

**Intel Parallel Computing Center for Weather and Climate Simulation**

CISL and the University of Colorado at Boulder continued their collaboration on an Intel award for the Intel Parallel Computing Center for Weather and Climate Simulation (IPCC-WACS). This collaborative center promotes the discovery of new methods for optimizing the performance of weather and climate models on Intel Xeon and Xeon Phi hardware and accelerates the adoption of these optimizations in key weather and climate community models. Additional details of this work are discussed in the section [Optimizing model performance on NCAR supercomputers](#).

**Rocky Mountain Advanced Computing Consortium**

CISL continued its participation in the activities of the Rocky Mountain Advanced Computing Consortium (RMACC), a consortium of regional HPC organizations including Colorado State University, the University of Colorado, Colorado School of Mines, the University of Wyoming, NCAR, the Department of Energy’s National Renewable Energy Laboratory, and NOAA’s Boulder Earth System Research Laboratory and research and educational organizations from Colorado, Idaho, Montana, New Mexico, Utah, and Wyoming. RMACC representatives meet monthly to discuss and organize joint training, education, and outreach activities. They also consider other collaborative measures to benefit the regional development of HPC.

In August 2015, RMACC organized and hosted the fifth annual RMACC Symposium, which attracted hundreds of registered participants to a series of lectures, tutorials, and affinity group discussions at the CU Boulder campus. CISL representatives gave presentation and led discussions on “HPC Debugging Techniques.” Three CISL interns won prizes in the Symposium’s poster competition.

**Rocky Mountain Cyberinfrastructure Mentoring and Outreach Alliance**

CISL was awarded an NSF Collaborative Research CC\*IIE Region Proposal titled the “Rocky Mountain Cyberinfrastructure Mentoring and Outreach Alliance (RMCMA).” Colorado State University (CSU), the Idaho Regional Optical Network (IRON), the University Corporation for Atmospheric Research (UCAR), the University of Colorado at Boulder (UCB), and the University of Utah (UU) have a long and fruitful history of collaboration, leadership, and innovation in regional and state networking, cyberinfrastructure (CI), and high performance computing (HPC) technology and infrastructure operations. These partners are leveraging their expertise and organizational structures to lead and manage an outreach effort to better inform, educate, and drive adoption and expansion of advanced networking and CI technologies to small colleges and universities in the western region of the United States, specifically those in the states of Colorado, New Mexico, Idaho, Utah, and Wyoming.

During the two-year award term, the project team will conduct four regional workshops for smaller institutions focused on High Performance Networking (HPN) as an enabler of scientific discovery through computational modeling and simulation, data-driven analysis, collaboration, and community building. Two workshops have been held. The first, in January 2015 at Arizona State University, focused on small school CIOs and strategically positioning HPN and HPC at their universities. The second was held in conjunction with the RMACC Symposium in August 2015 at the University of Colorado at Boulder. This workshop focused on HPN and HPC for engineers from small schools.

The team will make site visits and consult with smaller institutions in the region to mentor, educate, and

support proposal development and campus investment for research infrastructure and related funding opportunities. Engineering support is being provided to smaller institutions on the approaches and benefits of HPN performance measurement, performance troubleshooting and optimization, use of Science DMZs, enhanced information security protection, IPv6, and network interactions with HPC data nodes. Finally, strategies for preparing and submitting CI-related proposals are being addressed for administrators and faculty leaders, and many proposals from the community were submitted and awarded in the recent round of NSF CC\*DNI (Data Networking and Infrastructure) awards. The outcome of this proposal will benefit many students and faculty in the geographically challenged Intermountain region and enhance the deployment, utilization, and access of advanced CI. UCAR has also collaborated through the RCMOA grant, with the other five regional awardees in The Quilt including presentations on the effort at Internet2, NSF PI, and Quilt Meetings.

UCAR also submitted and was awarded a supplement to the RCMOA grant. This proposal is a partnership between UCAR, the Department of Energy’s Energy Sciences Network (ESnet), and the Keystone Initiative for Network Based Education and Research (KINBER). Five women will receive funding to participate in the 2015 Supercomputing Conference (SC15) while gaining valuable hands-on training in building one of the world’s premier IT networks.

The five awardees will join the volunteer workforce that puts together a dedicated high-performance research network known as SCinet. It comes to life for the duration of the Supercomputing Conference (SC) each year, and is critical to the conference’s information and communication flow. The network is among the fastest and most advanced in the world, often referred to as “the fastest network connecting the fastest computers” by SC organizers. The new initiative is known as “Women in IT Networking at SC” – WINS for short – and it is an effort to expand the diversity of SCinet volunteer staff and provide professional development opportunities to highly qualified women in the field of networking.

**Purpose and funding**

These efforts advance Cisl’s strategic computing imperatives in hardware cyberinfrastructure, software cyberinfrastructure, and facilities. Further, this work also addresses Cisl’s education imperative to broaden participation. Cisl’s work in this area is supported by NSF Core funding, NSF MRI grant CNS-0821794, and UCAR non-federal funds.

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NATIONAL CI ENGAGEMENT

CISL has a strong presence in national CI development, including both the HPC and networking communities. Working with national entities broadens NCAR's impact by fostering the maturation of national HPC CI, leverages national resources and partnerships to tackle national problems, and is a natural and mutually beneficial component of a national center's role.

XSEDE Federation contributions

Building on its participation in the TeraGrid as a Resource Provider since 2007, CISL continues to be engaged as an active member of the NSF's Extreme Science and Engineering Discovery Environment (XSEDE) Federation and Service Provider (SP) Forum as a Level 2 Service Provider. NCAR supports XSEDE cyberinfrastructure by integrating the networking, data transfer, and science gateway services at the NCAR-Wyoming Supercomputing Center (NWSC) with XSEDE resources. Although NCAR does not provide allocable resources to XSEDE, NCAR provides a dedicated 10-Gbps networking link to XSEDEnet, with which NCAR provides high-performance access to the 16-petabyte central file system at NWSC to users having both NCAR and XSEDE source and destination accounts.

In FY2015, CISL became the first site outside of XSEDE to leverage the XSEDE Resource Allocation Service (XNAS), an XSEDE-hosted service that is now supporting the submission and review of CISL allocation requests. CISL also continued to use the open-source release of the XD Metrics on Demand (XDMoD), developed by the University of Buffalo through the XSEDE program, a web-based application for querying and reporting on supercomputing job and user statistics.

This past year, CISL worked on two science gateway assignments from XSEDE's Extended Collaborative Support Service. The first, the Asteroseismic Modeling Portal (AMP), provides a web-based service that allows scientists to derive the properties of Sun-like stars from observations of their pulsation frequencies. The second project, Web-based Simulation Library of Astrophysical galaxy cluster Mergers (WebSLAM), provides a science gateway to existing simulations of galaxy cluster mergers. In both projects, CISL's expertise in science gateways is applied to XSEDE's broader science mission, thus enhancing future science gateway skills and capabilities.

NCAR is also active in coordinating training, education, and outreach goals with other XSEDE SPs, including participating as a satellite site for several training workshops. CISL staff also contributed as part of the program committee for the XSEDE '15 annual conference in St. Louis, and several CISL staff attended. XSEDE is funded through a five-year grant from the NSF Advanced Cyberinfrastructure division.

Contributions to national networks

CISL is a recognized leader and participant in a number of national networking projects that are tightly integrated with regional networks. Active participation helps guide and set strategic direction for these national organizations, which helps ensure that UCAR and NCAR have access to the national network connectivity and services required to carry out their missions.

CISL's involvement with national networking consortia includes Internet2 (I2), NOAA's science network NWave, and the Department of Energy (DOE) Energy Science Network (ESnet). These are the United States' premier networks in research and education. On behalf of UCAR, CISL/NETS maintains high-speed connectivity to these national networks to ensure the required connectivity between researchers that enables collaboration and access to local and remote computing, data, and instruments.




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UCAR is a collaborator on the recently funded Pacific Research Platform. A series of ultra-high-speed fiber-optic cables will weave a cluster of West Coast university laboratories and supercomputer centers into a network called the Pacific Research Platform as part of a five-year \$5 million dollar grant from the National Science Foundation. The network is meant to keep pace with the vast acceleration of data collection in fields such as physics, astronomy, and genetics. It will not be directly connected to the Internet, but will make it possible to move data at speeds tens or hundreds of times faster than is typical now: 10 to 100 gigabits per second among 10 University of California campuses and 10 other universities and research institutions in several states.

CISL has continued its strong engagement with NSF’s EarthCube initiative. CISL staff served on the Architectural Advisory Panel for the SDSC-led EarthCube Conceptual Design Award, a steering committee responsible for forming the EarthCube Council on Data Facilities (CDF). CISL’s service included working to form a draft charter.

**ACM/IEEE Supercomputing conference participation**

CISL is also an active participant in the ACM SIGARCH and IEEE Computer Society Supercomputing conferences, which attract thousands of HPC experts from government, academia, and industry every year. CISL staff members serve each year on the infrastructure committee, present technical papers, and operate an NCAR exhibit booth on the conference floor.

CISL is also active each year at the Supercomputing Student Job Fair, which is an opportunity to reach a broad population of students in computational science, engineering, and other job candidates seeking careers in high performance computing and networking. CISL also participates in the design, implementation, and operation of SCinet.

In FY2015, NETS manager Marla Meehl served as Principal Investigator of the Women in IT Networking at SC (WINS) program to increase diversity in the national network engineering field. The WINS program helps train and mentor women faculty and staff from institutions across the U.S to enhance their use of advanced technologies and the national scientific infrastructure. SCinet is the fastest and most innovative computer network in the world, delivering more than 1.6 terabits (or trillion binary digits) per second of network bandwidth to attendees of SC15, allowing them to demonstrate the latest research in high-performance computing – from genomic analyses to multi-gigabit simulations. The SC15 conference will be held in early FY2016.

Marla Meehl is also the co-chair for the Internet2 Gender Diversity Initiative, which has been charged by Internet2 to create and implement a program that provides support for emerging information technology women professionals to attend Internet2 technical conferences, thereby supporting their entry into the information technology field and the Internet2 community.

CISL staff members serve on a number of advisory panels, including the Science Gateways Institute, the Petascale External Advisory Committee of the NSF Blue Waters Project, and the Technical Evaluation Panel of the Department of Defense HPC Modernization Office.

**Purpose and funding**

These efforts advance CISL’s strategic computing imperatives in hardware cyberinfrastructure, software cyberinfrastructure, and facilities. With the exception of CISL’s participation in XSEDE, CISL’s national leadership activities are funded by NSF Core funds.

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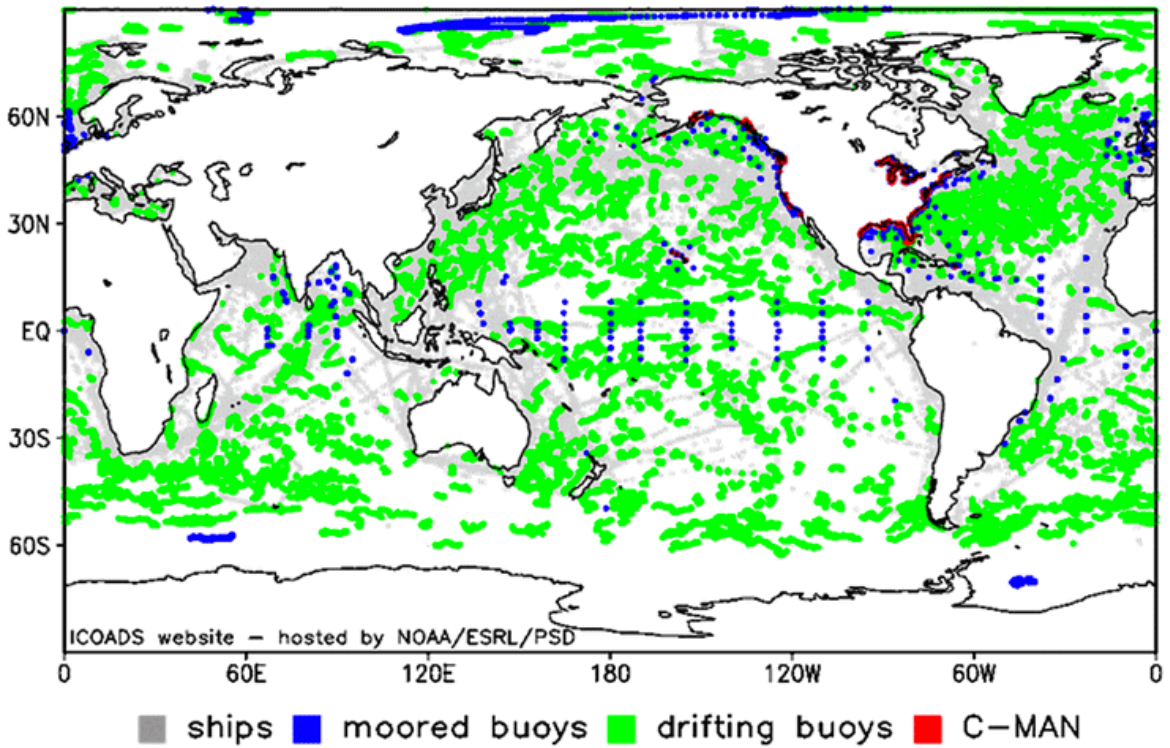
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INTERNATIONAL IMPACTS

CISE is highly visible on the international front and engages with international climate and weather organizations, programs, peer supercomputing centers and laboratories, and international projects. Our international impact spans data services and exchanges, analysis and visualization tools, computational support, strategic advisory functions, training, capacity building, and participation in international conferences.



Global distribution of marine surface measurements for September 2015 in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). ICOADS collects and distributes environmental observations from merchant and research ships, moored and drifting buoys, and coastal stations. In collaboration with NOAA partners at the National Center for Environmental Information (NCEI) Asheville and Earth Systems Research Laboratory, NCAR processes data and adds them to ICOADS on a monthly basis. The data are openly shared with the international community, and program guidance and assistance are given by the ICOADS Steering Committee (ISC). The ISC has co-chairs from the US and UK, and representatives from the US, UK, and Germany.

CISE contributes to developing the World Meteorological Organization (WMO) Information System (WIS). Under the auspices of the United Nations, the WMO is designing, developing, and deploying WIS as a next-generation globally federated information system for weather, climate, hydrology, oceanography,

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and many other disciplines. CISL plays a strong role in the management and technical direction of WIS and has contributed ideas, strategies, and services developed through our work with CDP, ESG, and ACADIS. CISL staff have served on several WIS committees, recently including the Expert Team on WIS Centres (ET-WISC), the Task Team of Data Centres (TT-DC), and the Task Team on WIS Centre Audit Certification (TT-CAC).

At the request of the U.S. National Weather Service (NWS), CISL attended the WMO WIS Centre Audit for NWS. CISL data collections are now being harvested by GISC-Washington into WIS as part of production operations. CISL also shares data management and science discipline-specific information through membership and active participation on the Ocean Observations Panel for Climate (OOPC), which is sponsored by the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the World Climate Research Programme (WCRP).

There are several noteworthy formal international data exchange agreements associated with the development of the NCAR Research Data Archive (RDA). ECMWF and JMA routinely share data under longstanding Memoranda Of Understanding with NCAR. These reanalyses and operational model outputs add to the RDA and are important because they are not readily available anywhere else in the U.S. CISL reciprocates by preparing observational datasets and delivering them to support future reanalysis efforts. Overall, the RDA is an internationally recognized source for over 10 reanalysis collections, all at the highest resolutions available, as in the SPARC Reanalysis Intercomparison Project (S-RIP) that is coordinated by the World Climate Research Programme (WCRP) group named Stratosphere-troposphere Processes And their Role in Climate (SPARC).

CISL is very active internationally in the area of data services. The RDA is an extremely valuable international scientific data resource, providing important collections to the global community and making EU collections available to U.S. scientific communities. CISL's Science Gateway Framework (SGF) federates with the global Earth System Grid Federation (ESGF), sharing catalogs and security protocols making CCSM, CESM, WCRP/CMIP5, and other data collections accessible via the ESGF environment. Similarly, CISL is a primary partner in the ACADIS effort. CISL provides the SGF-based ACADIS Gateway that offers data management support for NSF-sponsored Arctic research including Arctic Observing Network (AON) data for the International Polar Year (IPY). CISL also provides computing and data management support for the Antarctic Mesoscale Prediction System (AMPS), an experimental, real-time numerical weather prediction capability that supports the United States Antarctic Program, Antarctic science, and international Antarctic efforts. Finally, CISL staff have contributed to the development of the UK's National Environment Research Council (NERC) Big Data program.

CISL's analysis and visualization tools (e.g., NCL, PyNGL, and VAPOR) are widely used in centers and universities around the world. Three quarters of the VAPOR user base, for example, are outside of the U.S. Development of VAPOR has been funded, in part, by the Korean Institute for Science and Technology Information(KISTI). In FY2015 CISL hosted visitors from KISTI, as well as Germany's DKRZ, and collaborated to add numerous new features to the VAPOR package. NCL is used in 114 different countries, and CISL has conducted NCL data analysis training workshops in Australia, Turkey, Germany, Korea, and Switzerland.

CISL continues to participate in international collaborations designed to grapple with the challenges of emerging exascale technologies. The NCAR/CU Intel Parallel Computing Center for Weather and Climate Simulation includes a collaboration with the Indian Institute of Science focused on improving the scalability of CESM's radiation code. The G8 Exascale Climate Science (ECS) project, completed this year, was a collaboration between CISL's Technology Development Division and computer scientists and climate experts from Inria (France), the University of Illinois at Urbana Champaign (USA), the German Research School for Simulation Sciences (Germany), Tokyo Institute of Technology (Japan), University of Tennessee at Knoxville (USA), University of Tsukuba (Japan), Victoria University (Canada), and Barcelona Supercomputing Center (Spain). Over three years, this collaboration studied various aspects of the exascale climate modeling challenge, including application scalability, node performance, and system resilience. The project uses CESM as one of the target applications, and relied heavily on NCAR staff for technical support of the project.

CISL participates in International Standards (ISO) activities to contribute to the development of the

Fortran programming language, with a CISL staff member serving as chair of the U.S. Fortran Committee. This participation allows programmers at NCAR to track and influence Fortran's development. With NCAR science at the forefront of ever-larger numbers of processors, program resilience in the face of processor failures is becoming a critical limitation, and NCAR is a part of the evolution of strategies for treating this limitation. NCAR is planning to host the joint meeting of the international and U.S. Fortran committees in 2016.



CISL supports the ISO's U.S. Fortran Committee.

CISL hosts and organizes the popular international Computing in Atmospheric Sciences (iCAS) workshop every other year in Europe, with the most recent event taking place in September 2015. iCAS is a forum where scientists, industry experts, and computing professionals from around the world can attend and discuss challenges and new approaches to advance climate and weather research. Finally, CISL staff members collaborate with many more foreign institutions and serve on various international committees and advisory panels, including the German Climate Computing Center (DKRZ) Advisory Committee.

These efforts advance CISL's strategic computing frontier in center virtualization and strategic computing imperatives in software cyberinfrastructure and data curation. Further, this work also addresses CISL's science imperative for scientific excellence and CISL's imperative to broaden participation. This work is supported by NSF Core funding that is augmented by registration fees and sponsor donations.

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INTERACTIONS WITH INDUSTRY

CISL maintains close contacts with High Performance Computing (HPC), networking, and related vendors as a way of providing information to vendors regarding the computational requirements of the Earth System sciences and to track technology. To this end, CISL has up-to-date nondisclosure agreements (NDAs) with HPC-related vendors that allow CISL to keep abreast of the latest technical developments and plans in this fast-moving industrial space. CISL also routinely receives loaner equipment and new software products from vendors for evaluation and testing under these agreements.

CISL has a robust set of ongoing collaborations that are focused on the effective use of current and future microprocessor architectures for NCAR applications. These collaborations take the form of a regularly scheduled HPC-related workshop and regularly scheduled teleconferences on code optimization. The MultiCore 5 Workshop held in September 2015 included vendor presentations from Intel and NVIDIA and provided a venue to discuss issues important to the weather, climate, and Earth System modeling communities.

CISL maintains an active collaboration with both Intel and Cray to optimize code for both the Intel Xeon and Xeon Phi technologies. The [Intel collaboration](#) involves regular weekly teleconferences consisting of participants from NCAR, Intel, NREL, and NERSC. This working group has explored a wide range of issues associated with the Xeon and Xeon Phi, including the efficiency of the Intel vectorization compiler, coding structures that may inhibit vectorization, and effectiveness of performance profiling tools. The Cray collaboration involves bi-weekly teleconferences that focus on identifying a number of issues in NCAR applications, the Cray compiler, and the OpenMP 4.0 standard that either negatively impact application performance or programmer productivity.

This collaborative work with industry is supported by NSF Core funds, as well as resource allocations and gifted funds from industrial partners. In addition, NETS activities are supported by UCAR Communications Pool indirect funding.

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CISL PARTICIPATION IN THE HPC COMMUNITY

As part of its leadership role in the High Performance Computing (HPC) community, CISL organizes, hosts, or participates in several large-scale conferences. Through this participation, CISL fosters the interchange of ideas, technical information, best practices, and research findings. In addition to participation in relevant conferences when topics and CISL interests intersect, CISL regularly engages the HPC community via the following conferences:


- SC conferences:** CISL is a longtime participant in the IEEE and ACM-sponsored Supercomputing (SC) conference series, the premier HPC event in the United States. CISL staff members participate on organizing and event committees, organize Birds of a Feather sessions, operate an NCAR exhibit booth on the conference floor, routinely submit technical papers to this conference, and participate in the design, implementation, and operation of SCinet. CISL also participates in the SC Student Job Fair, a prime venue for meeting employee candidates from a variety of backgrounds who are interested in careers in HPC and related scientific fields.
- XSEDE Annual Conference:** CISL participates in the XSEDE program's annual conference by attending, presenting papers, and participating on committees where appropriate.
- iCAS conference:** To foster international dialogue by peer centers, CISL hosts the popular International Computing in Atmospheric Sciences (iCAS) conference every two years under NSF sponsorship, with the most recent event taking place in September 2015. CAS brings together international colleagues to discuss information technology advances and the transformative infrastructure that allows scientists to investigate atmospheric research as part of understanding the Earth System.
- RMACC HPC Symposium:** As a member of the Rocky Mountain Advanced Computing Consortium (RMACC), CISL engages with students and researchers from other HPC providers in the region by attending, participating in the conference organization, and presenting posters and invited talks. The fifth annual RMACC Symposium in August 2015 attracted hundreds of registered participants to a series of lectures, tutorials, and affinity group discussions at the CU Boulder campus. CISL representatives gave presentation and led discussions on "HPC Debugging Techniques," and three CISL-sponsored students won prizes in the Symposium's poster competition.
- SEA Conference:** Members of CISL's CSG currently hold several committee positions, including chair, for UCAR's Software Engineering Assembly (SEA). With FY2015 marking its fourth year, SEA's annual conference has evolved from a primarily local event into a widely attended scientific computing event with roughly half its speakers and half its 160 attendees from outside of UCAR. This year, CISL's RSVP program and NCAR's Advanced Study Program provided travel support for 16 speakers and 12 students from minority-serving institutions and institutions from EPSCoR states.

This work is supported by NSF Core funding and augmented by registration fees and sponsor donations.



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DIRECTOR'S MESSAGE



It is my pleasure to present to you the Earth Observing Laboratory annual report for Fiscal Year (FY) 2015. It has been another successful year for EOL that is reflected in the high quality of service the Laboratory has provided to the atmospheric observational science community. In addition, EOL scientific and engineering staff, postdocs, students and visitors have contributed to advancing the observational-data-based physical discovery and developments of a next generation of observational systems and data services to be placed in service of the observational science community in the years to come.

In the past year, EOL supported a number of field campaigns and investigator teams by providing our end-to-end service that extends from the field program planning and guidance through the operation of facilities and instruments in the field to data services in the course of a field campaign and afterwards. In FY 2015, EOL-deployed instrumentation to five NSF-approved field campaigns, four of which fell into the small/simple category (CSET, Nor'Easter, WINTER, MASCRAD), and one that was considered a

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complex/large project (PECAN). EOL also supported one cost recovery project for NASA (IceBridge 2015), one cost recovery project for NOAA (SHOUT), and three NSF-approved instrumentation tests on the NSF/NCAR aircraft (ARISTO, HCR Test, SABIRPod). These campaigns ranged from a few days to over four months long, and put to use a variety of the NSF LAOF that EOL manages to support critical scientific work. EOL’s work on these campaigns entailed direct support of more than 90 principal investigators from over 100 institutions. More than 180 students (undergraduate, graduate and postdoctoral – were directly involved in these field campaigns as well. The PECAN campaign stands out in this group for EOL not only in terms of the number of investigators, mobile platforms and the overall complexity of nighttime operations but also in terms of the EOL co-leadership of the science team.

The end-to-end service that EOL provides to our scientific community includes not only the deployment of instrumentation to the field but also data processing, quality control, and archival and stewardship of field project data. As of the end of FY 2015, EOL has issued over 400 Digital Object Identifiers (DOIs) for archived datasets as well as for EOL platforms and facilities for use by the scientific community for citation. The use of such DOIs will improve metric tracking as well as provide scientific data attribution. Our data management staff has also identified over 400 field projects supported by EOL or its predecessor ATD (Atmospheric Technology Division). The up-to-date list can be found at <https://www.eol.ucar.edu/all-field-projects-and-deployments>.

In conjunction with support of field campaigns, we have continued to provide help to the investigators to implement targeted and tailored outreach activities via education and public engagement. In FY 2015 EOL supported two educational deployments, BaseCamp II and CABL, and engaged the public and media during the PECAN and WINTER field campaigns, among other activities.

Finally, I would like to highlight some of highly innovative instrumentation developments in EOL. Our highest new instrumentation development priority continues to be the Airborne Phased Array Radar (APAR), a unique C-band airborne phased array radar with dual-Doppler and dual-polarimetric capabilities designed for a large fuselage aircraft such as the NSF/NCAR C-130. In FY 2015, the APAR team continued work on the basic elements of the APAR antenna and initiated work on the APAR Master Project Management Plan (MP2). In addition to APAR, teams of EOL scientists and engineers having been busy with advancing the state of our ongoing developments, including the HIAPER Cloud Radar (HCR), the Water Vapor Differential Absorption Lidar (WV DIAL), Laser Air Motion System (LAMS) and the Advanced Vertical Profiling System (AVAPS).

As in the past years, this annual report is organized around the Imperatives and Frontiers of the EOL Strategic Plan. I invite you to enter the following pages and read more about the Laboratory’s remarkable activities and accomplishments in FY 2015.

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EXECUTIVE SUMMARY

The ability to make observations of the atmosphere, Earth System, and Sun is fundamental to achieving the science goals of NSF, NCAR, and our scientific community. When established, NCAR was charged with providing for the community of atmospheric scientists observing facilities and services that are too large and expensive to be operated by a single university group and are thus best managed and operated centrally. A significant portion of this charge to NCAR now rests with the Earth Observing Laboratory (EOL), which defines its mission to be:

***To develop and deploy observing facilities and provide data services needed to advance scientific understanding of the Earth System.***

EOL’s activities are framed in the context of our mission statement, and are further encapsulated in our “Four Ds”: Deployment, Development, Data Services and Discovery. This annual report describes the efforts we undertook in Fiscal Year (FY) 2015 to carry out the objectives described in our Strategic Plan.

Deployment

The NSF-funded Lower Atmosphere Observing Facilities (LAOF) that EOL manages include research aircraft, ground-based and airborne remote sensing systems, vertical profiling systems, in situ sensing systems, and a number of individual instruments that can be deployed in conjunction with these larger systems. EOL works continuously to maintain and improve these NSF LAOF with which we are entrusted, and to ensure their safe and reliable operation for deployment. Several of these activities are described in 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.”*

Deployments of those LAOF are encompassed in our Imperative II: *“Support observing needs of research programs at a level that serves NSF, university, and NCAR program needs.”* In FY 2015, EOL-deployed instrumentation to five NSF-approved field campaigns, four of which fell into the small/simple category (CSET, Nor’Easter, WINTER, MASCRAD), and one that was considered a complex/large project (PECAN). EOL also supported one cost recovery project for NASA (IceBridge 2015), one cost recovery project for NOAA (SHOUT), and three NSF-approved instrumentation tests on the NSF/NCAR aircraft (ARISTO, HCR Test, SABIRPod). These campaigns ranged from a few days to over four months long, and put to use a variety of the NSF LAOF that EOL manages to support critical scientific work. EOL’s work on these campaigns entailed direct support of more than 90 principal investigators from over 100 institutions. More than 180 students – undergraduate, graduate and postdoctoral – were directly involved in these field campaigns as well. EOL’s deployments of the NSF LAOF in FY 2015 are described in the Imperative II section of this report.

Development

EOL’s Strategic Plan Imperative III incorporates most of our Development activities: *“Anticipate future needs resulting from changing priorities, aging equipment or emerging opportunities, and develop new technology (instrumentation, software, and infrastructure) to meet those needs.”* In FY 2015 EOL conducted work on several high priority developments: CentNet, the 449 MHz modular wind profiler, the Water Vapor Differential Absorption Lidar (WV DIAL), and the Airborne Phased Array Radar (APAR).

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Other, longer-term and emerging EOL development efforts are contained in our Frontiers, which focus on promising opportunities or developing needs in the atmospheric science community that EOL could address. In FY 2015, EOL addressed some of our Frontiers by conducting the successful maiden voyage of the airborne HIAPER Cloud Radar (HCR); making progress on the LROSE software suite; continuing work on the Laser Air Motion Sensor (LAMS); moving ahead with a new environmental chamber for instrumentation calibration; and furthering our sensor investigations for CentNet.

**Data Services**

The end-to-end service that EOL provides to our scientific community includes data processing, quality control, and archival for field project data, and these facets of that service are expressed in our Imperative IV: *"Provide comprehensive data services, open access, and long-term stewardship of data."* This includes further development of the Field Catalog into version 2.4; enhancements to operating software for instrumentation; increased data stewardship activities; and collaboration with NCAR's Computational Information Systems Laboratory (CISL) for improved data access.

**Discovery**

Activities under EOL's Imperative V, to *"Attract and inspire new generations of scientists, engineers and the general public to atmospheric science, conveying the excitement and intrinsic value of observational research,"* show our commitment to promoting curiosity about atmosphere and Earth sciences and to inspiring the next generation of observational scientists and engineers. In FY 2015, EOL conducted education and outreach activities for two field campaigns, and continued two internship programs: the Summer Undergraduate Program for Engineering Research (SUPER), and our Technical Internship Program (TIP II). EOL scientists were also Principal Investigators on a large field deployment (PECAN) and we conducted a workshop to discuss various approaches to field operations with attendees from a range of US and international agencies and entities.

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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***

State-of-the-art, accurate observations and measurements of the atmosphere and other parts of the Earth system continue to be the driver for scientific discovery and impetus for advances in geosciences. Such observations are also critical inputs for the robust performance and continued development of weather, climate, and chemistry models. Therefore, our first Imperative is the maintenance of NSF-funded Lower Atmosphere Observing Facilities (LAOF) for research in atmospheric science, with emphasis on systems that are beyond the capabilities of most universities or smaller groups.

In this endeavor, EOL conducts countless day-to-day efforts to preserve and consistently improve the NSF LAOF resources that are entrusted to NCAR, and to maintain readiness for a vigorous deployment schedule (see Imperative II). In the run-up to each field campaign, all instruments undergo exhaustive testing by EOL engineers and technicians to ensure optimal campaign performance. After the field phase commences, it often becomes necessary to make adjustments or upgrades to overcome difficult or unforeseen environmental conditions in order to meet scientific objectives. Then, upon completion of the field phase, calibrations, repairs and reconditioning are often required to maintain instrumentation readiness state for the next activity. The activities described below are a sampling of these efforts for FY 2015.

IMPROVEMENTS TO THE ADVANCED VERTICAL ATMOSPHERIC PROFILING SYSTEM (AVAPS) FOR THE NSF/NCAR GV

In FY 2015, EOL modified the large dropsonde design for AVAPS to allow for integration of additional or alternate sensors, thus expanding possible sensors for and quantities measured by dropsondes. This was accomplished by adding flexible interface circuitry into the mini-dropsonde circuit board and firmware, which will enable testing of a small infrared sensor that measures sea-surface temperature. We also created a test electronics board, combining an accelerometer and GPS receiver, which will enable us to capture data to test the ability of the accelerometer to improve other motion measurements such as vertical velocity.

These enhancements to the AVAPS dropsonde systems will provide EOL's user community with new dropsonde measurement capabilities. If successful, combining an accelerometer and GPS receiver could provide unprecedented vertical velocity measurements with dropsondes.

ENHANCEMENT OF THE 449 MHZ MODULAR WIND PROFILER

The Plains Elevated Convection at Night (PECAN) field campaign benefited from work conducted in FY 2015 to harden the 449 MHz modular wind profiler. The EOL-developed high power amplifier (HPA) for the profiler was used for the first time during PECAN and provided about 5 kW of peak power. We also enhanced the wind-finding algorithms available in real time: now, in addition

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to the Full Correlation Analysis (FCA) technique, the Slope-at-zero-lag (SZL) technique is available for real-time wind calculations. Previously this technique was only used as a post-processing option. Finally, the system sensitivity and measurements at near range were improved with changes to the radar receiver components. This work and the deployment of the modular wind profiler to PECAN have yielded a more reliable field system with better efficiency and reliability. Pre-project setup and operation were smoother than prior projects, and we experienced little trouble changing between radar modes. Because of its ability to measure higher than the previous 915-MHz wind profilers, this system contributed to PECAN science with excellent observations of bores and waves and associated vertical air motion.



The 7-panel 449 MHz wind profiler system.

**AIRBORNE INSTRUMENTATION PERFORMANCE AND DATA ANALYSIS**

EOL also made improvements to airborne instrumentation during FY 2015 in order to improve the measurements they collect. The Three-View Cloud Particle Imager (3V-CPI) and the Small Ice Detector, version 2 (SID-2H) both underwent flight testing in FY 2014. Following that, 3V-CPI instrument performance and data analysis was conducted in FY 2015 through comparisons with more traditional optical array probes was completed, while improvements to the signal detection by SID-2H due to electronics upgrades were evaluated.

For 3V-CPI, we now have comparison data in several types of cloud systems, with the most recent comparisons done in warm cloud (no ice phase) during CSET. A review of 3V-CPI’s performance during CSET indicated good agreement with other instruments in non-precipitating clouds but revealed some possible effects that we believe are due to the splashing of raindrops in the 3V-CPI tube. These effects will be further investigated in FY 2016.

We also evaluated the addition of a circuit to record the triggering signal to the SID-II, which should allow for improved operations in the future, by improving the characterization of the effects of dead time on the instrument. The modified instrument underwent testing in ARISTO and evaluation of the tests will follow in FY 2016.

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IMPERATIVE II

Support observing needs of research programs at a level that serves NSF, university and NCAR program needs

Field program planning and implementation is a critical community service, and EOL’s efforts under our Imperative II are part of NCAR’s Strategic Imperative to provide observational facilities that meet the science community’s needs. EOL employs and trains project staff, assists principal investigators (PIs) with project planning and preparation, supports observing programs by operating facilities and instruments, and preserves quality of collected data for decades in support of research and field programs worldwide. EOL enables science for each campaign’s PIs through this support, and, when we are a science lead or participant, directly engages in that science. EOL provided field program planning and implementation for five NSF-funded, one NASA-funded and one NOAA-funded research campaigns, as well as three NSF-approved instrumentation tests. These were:

- MASCRAD (small)
- Nor'Easter (small)
- WINTER (small)
- PECAN (large)
- CSET (small)
- IceBridge 2015 (small, NASA-funded)
- SHOUT (large, NOAA-funded)
- ARISTO (instrumentation test)
- HCR Test (instrumentation test)
- SabirPod (instrumentation test)

In FY 2015, EOL’s work on these campaigns entailed direct support of more than 90 principal investigators from over 100 institutions. More than 180 students – undergraduate, graduate and postdoctoral – were directly involved in these field campaigns as well.

MASCRAD

The Accurate Characterization of Winter Precipitation using Multi-Angle Snowflake Camera, Visual Hull, Advanced Scattering Methods and Polarimetric Radar project, or MASCRAD, was conducted in winter 2014/2015. The project, which took advantage of the FRONT radar network and one GAUS system, collected dual polarization data when snow was forecast to occur at the location of the Multi-Angle Snowflake Camera (MASC). EOL collected 134.5 hours of excellent radar data during 10 distinct snow events between 14 December 2014 and 27 February 2015, and launched radiosondes during all snow events. The principal goal of MASCRAD was to establish a novel approach to characterization of winter precipitation and modeling of associated polarimetric radar observables, with a longer-term goal to significantly improve the radar-based quantitative precipitation estimation in stronger, more hazardous, winter events.

NOR'EASTER

The NSF/NCAR GV with the HIAPER Cloud Radar aboard flew on February 2, 2015 along the upper East Coast for Nor'Easter project. This one-day campaign was aimed at studying a northeast snowstorm, which is usually associated with significant disruption of nationwide transportation, particularly the air transportation system. This was HCR’s maiden scientific campaign voyage, and it collected high-resolution radar data of a Nor’easter winter storm flying repeated flight tracks from North Carolina to Maine and back.

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The single research flight provided a unique scientific opportunity to obtain the data necessary to investigate the relationship between elevated convection, generating cells aloft, precipitation streamers generated by the cells, and banded precipitation. The project resulted in the collection of a spectacular dataset that according to the PI, Bob Rauber (University of Illinois at Urbana-Champaign) “revealed circulations in the storm that none of us could have anticipated, and for which we will have a lot of work to do to provide solid scientific explanation and interpretation.” The data analysis from Nor’Easter also helped EOL further assess the performance of the HIAPER Cloud Radar and better prepare for the CSET campaign.

WINTER

The Wintertime Investigation of Transport, Emissions, and Reactivity (WINTER) project was conducted in January/February 2015, and used the NSF/NCAR C-130 with a full complement of in-situ and remote-sensing instrumentation to focus on wintertime emissions and chemical processes in the northeastern United States. Based at NASA Langley Research Center in Hampton, VA, WINTER had a total of 13 research flights, flying 96 research hours in the eastern U.S. and documenting pollution and air chemistry in a variety of areas. Missions were flown to sample air around large metropolitan areas such as New York City, Baltimore and Washington D.C., Pittsburgh, and Atlanta. Other regions of interest were the Ohio River Valley and central Appalachia, where energy production is significant, along with areas offshore to study outflow and long-lived pollutants. Some of these areas were sampled at different times so that day and night only, along with day-into-night and night-into-day transitions could be studied, and approximately half of the project was done on night operations to meet these objectives. Overall, the PI team was very happy with the dataset collected and they and deemed WINTER to be a success.

PECAN

The Plains Elevated Convection at Night (PECAN) campaign was a multi-agency project designed to advance the understanding of continental, nocturnal, warm-season precipitation. Conducted during May-June 2015 and using the EOL-managed S-Pol radar, mobile and fixed sounding units (including the 449 MHz profiler), WV DIAL, and a GPS Advanced Upper-Air Sounding (GAUS) system (along with a large number of other airborne and ground-based platforms provided by other entities), PECAN focused on nocturnal elevated convection, including mesoscale convective systems (MCSs), over the southern Great Plains. One of the PECAN scientific leads was EOL Scientist Tammy Weckwerth.



S-Pol operations at PECAN

There were more than 300 U.S. and international participants in the project, including principal investigators, young scientists, technicians, engineers, aircrews, operations support staff, and a large number of graduate and undergraduate students. The main ground observing facilities included nearly two dozen mobile radars, lidars, sounding systems, and mesonet vehicles; seven fixed ground-based stations with radar, profiler, and sounding capabilities; and three research aircraft including the University of Wyoming King Air, the NOAA P-3, and the NASA DC-8. The ground armada logged ~5000 miles or more per vehicle during the 45-day campaign and more than 1200 soundings were launched from both mobile and fixed sites.

PECAN collected a rich and varied set of data on a variety of phenomena, including mesoscale convective systems (MCS), convection initiation (CI), low-level jets (LLJ), and bores that develop on nocturnal stable layers (Bore). These features were sampled in coordinated missions by in-situ and remote sensors from the ground and aircraft to help form a much better understanding of the forcing for nocturnal convection across the high plains. The exceptional datasets from PECAN will help improve the prediction of nocturnal convection, mesoscale convective systems (MCS), and hazardous weather posing significant risks for public safety.

CSET

The Cloud System Evolution in the Trades project, conducted in July/August 2015, aimed to describe and



explain the evolution of boundary layer aerosol, cloud, and thermodynamic structures along trajectories within the north-Pacific trade winds. CSET also marked the first extended scientific deployment of HCR and the first joint HCR/HSRL deployment on the NSF/NCAR GV. CSET was also the first time that the HIAPER Cloud Radar (HCR) performed extensive low-level sampling over water in a tropical environment. Other instruments deployed to the campaign included AVAPS and several HAIS instruments.



The view from the NSF/NCAR GV during CSET operations.

During the campaign, these instruments were able to sample cloud structure of shallow, low-level stratocumulous clouds in the Pacific, examining the same airmass multiple times. Among all instruments, terabytes of data have been created, and the resulting unprecedented dataset will enable the studies of cloud, precipitation, and aerosol fields in stratocumulus and fair-weather cumulus regimes within the subtropical easterlies between California and Hawaii. A total of 13 NSF/NCAR GV missions were conducted in CSET.

Furthermore, the HCR real-time data display deployed in CSET enabled scientists onboard the NSF/NCAR GV to make real-time decisions and EOL staff to monitor the health of the HCR system in order to make necessary adjustments. The images of HCR data were transmitted to Boulder and were available for PIs in both Seattle and Sacramento via the EOL data catalog. The combined HCR and HSRL data will allow PIs and EOL scientists to further classify the microphysical properties in these clouds, and HCR data will be carefully examined with other in situ measurements. The potential of the dual-wavelength retrieval of microphysical properties was presented at the 37th AMS Conference on Radar Meteorology, held 14 – 18 September 2015 in Norman, OK.

ICEBRIDGE 2015

Starting in September 2015, the NSF/NCAR GV again participated in one of the NASA IceBridge missions over the Antarctic, which is one of the largest airborne surveys of Earth’s polar ice. IceBridge is conducted over both the Arctic and Antarctic and is critical for ensuring a continuous set of polar observations since NASA’s Ice, Cloud, and Land Elevation Satellite (ICESat) ceased collecting science data in 2009. The replacement satellite, ICESat-2, will not be launched until 2016. The 2015 IceBridge campaign was staged from Punta Arenas, Chile and involved several overflights of the Antarctic ice sheet.

SHOUT

EOL supported the NOAA-led Sensing Hazards with Operational Unmanned Technology (SHOUT) science program beginning in August 2015, with the automated dropsonde system (AVAPS) on the NASA Global Hawk (GH). Similar to previous hurricane campaigns, the dropsonde system was a key instrument of the GH payload. For the first few weeks of the campaign, the GH was based out of NASA Wallops Flight Facility in Virginia where it flew three science missions into Hurricanes Erika and Fred. Operations were moved by NOAA midway through the project to NASA’s Armstrong Research Facility at Edwards Air Force Base in southern California to pursue eastern Pacific hurricanes. EOL provided the support of engineers and one technician during the program for dropsonde flight operations, instrument preparation, and post-flight maintenance along with general troubleshooting and repairing of the instrument. This was the first SHOUT field deployment; at least one more campaign is anticipated to achieve the goal of evaluating how the additional data from the GH flights can impact weather forecasts for hurricanes or other significant weather impacts, such as atmospheric rivers during the winter months in the Pacific.

ARISTO



The first annual Airborne Research Instrumentation Testing Opportunity (ARISTO) project began in late FY 2015 on the NSF/NCAR C-130. The purpose of the ARISTO program is to provide regular flight test opportunities for newly developed or highly modified instruments as part of their development effort. The program was created in response to a critical need, expressed by the NSF community, for regularly scheduled flight-testing programs to be able to not only test instrumentation, but also data systems, inlets and software well ahead of a field campaign in order to maintain cutting-edge and vibrant airborne research. In FY 2015, five research flights were flown over Colorado, Kansas, Nebraska, Wyoming, Oklahoma, Utah, and New Mexico; each flight focused on a different objective, including clouds, aerosols, wind maneuvers, radiometer calibrations, and chemistry. Twenty-one instruments were flown and 13 PIs and 8 students were involved for the effort, representing 8 institutions, including 5 universities. The data collected through ARISTO was a great opportunity for testing.

HCR TEST



HCR installed in its pod on the NSF/NCAR GV.

The HCR Test Flight Program was conducted in early FY 2015. The 12 hours of flight tests focused on performing a set of flight maneuvers to provide HCR an opportunity to verify the functionality of the newly implemented capabilities: an Active Pressurization System (APS) and automatic shutoff control, and a real-time B-scan display. The program also allowed the HCR team to further verify its standard calibration procedure, pointing accuracy, and address the deficiencies identified during the IDEAS-IV campaign. Additionally, this program provided a testing opportunity for other instruments participating in the CSET project and

key objectives for instrumentation such as LAMS, HARP and SID-2 were also accomplished. The HCR Test Flight program consisted of short flights from the RAF base at the Rocky Mountain Metro Airport in Broomfield, CO.

SABIRPOD

Scientists and engineers from EOL tested a Special Airborne Mission Installation and Response (SABIR) arm for use in air sampling; the arm can be door mounted on a C-130, allowing the aircraft to maintain essential cargo capabilities. A modified airborne research pod was flown on the NSF/NCAR C-130 using

the SABIR arm installation. Inlets for air sampling were installed on the pod and connected to air quality instrumentation for condensation nuclei, ozone, carbon monoxide, methane, carbon dioxide, and water vapor. The purpose of the tests was to determine if contamination of engine exhaust or cabin air could be detected at arm location. No measurable contamination was found; however, we determined that the pod could not be operated with the wheels down, which suggests that more testing may be required on the LC-130 platforms before use in air sampling.

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## 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.***

The NSF LAOF maintained and deployed by EOL are of vital importance to the community’s scientific interests, and these systems continue to be in high demand. However, community priorities and technological opportunities also call for ongoing development to ensure that EOL’s observing systems and support matches evolving community needs. There is also a constant, ongoing process of acquiring new capabilities, and retiring and replacing those that become outdated. In addition to such evolutions, it is necessary to plan for the replacement or end-of-life of systems that become obsolete or too costly to maintain. Thus, Imperative III calls upon EOL’s scientific and engineering leadership and expertise for a healthy development effort, and for the retention and training of staff who can conduct that research and development. It also requires the development of life-cycle and end-of-life plans for major facilities, instruments and software (see Imperative IV for more information on data services and software developments).

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The shift toward an emphasis on studies that contribute to the support of climate process study research, on both local and global scales, can be well served by new or developing EOL facilities such as the planned CentNet sensor array. The attendant shift in the use of observing facilities features increased aircraft use in collection of global-scale observations, longer-term deployment of observing systems and sensors, repeated observations to cover seasons and broader areas, networks that provide a larger number of measuring stations, and development of reliable, easily deployable sensors.

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Our development efforts in FY 2015 included continued work on the prototyping of CentNet; deployment and incremental improvements to the 449 MHz wind profiler system; further development of the Water Vapor Differential Absorption Lidar; work on the Airborne Phased Array Radar; improvements to the Airborne Vertical Atmosphere Profiling System for HIAPER; the Laser Air Motion Sensor; and the Lidar Radar Open Software Environment (LROSE). Plans for other, emerging developments are discussed in our Frontiers.

### SURFACE EXCHANGE: CENTNET

CentNet’s large deployable sensor network is expected to facilitate research in the biogeosciences, hydrology, and urban meteorology. CentNet is designed to address a range of research topics including understanding turbulent flow over complex terrain, predicting convective initialization, and characterizing the exchange of trace gases within a vegetative canopy. The integration of new capabilities in FY 2015 improved not only CentNet’s design, but also sensors and capabilities available as part of the Integrated Surface Flux Facility (ISFS).

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In FY 2015, EOL worked to develop and optimize a smart-sensor interface for CentNet for the Hukseflux NR01 net radiometer, to develop a suitable deployment stand for the radiometers, and to improve the design of the in-house soil temperature probe, which currently fails in water-saturated soil. We successfully modified the Hukseflux integrated net radiometer to be a smart sensor with integrated calibration and data handling. It performed well in long-term outdoor testing over 4 months using a new

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commercial tripod. A new version of our soil temperature profile probe was designed and 3 months of testing in the ground yielded good success; this probe would help us overcome past failures in high-moisture soil.

CentNet capabilities were used in FY 2015 for the Characterizing the Atmospheric Boundary Layer (CABL) educational deployment. Eight data systems supported two complete surface energy balance stations and an additional 12 sonic anemometers over 4 months. That a project of this complexity could be carried out as an educational deployment is due in part to the use of CentNet's integrated sensors and their reliability.

## TROPOSPHERIC WIND PROFILING: 449 MHZ WIND PROFILER

EOL made progress on the 449 MHz wind profiler by fielding the new high-power amplifier (HPA) as part of the PECAN deployment. While the spaced-antenna technique used by this profiler has great advantages for enabling a broader research application, a stronger signal is needed to obtain high-quality measurements. The new HPA produces 5 kW of peak power, enabling higher measurements than those possible with previous LAOF wind profilers. In addition, activities to harden the 449 MHz modular wind profiler prior to its use in PECAN led to better efficiency and reliability.



The 449 MHz wind profiler at DEEPWAVE.

We also continue to seek partnerships to enhance and increase the speed of our progress on this development, and visited potential collaborators in India during FY 2015 to further such discussions.

## TROPOSPHERIC WATER VAPOR PROFILING: WV DIAL

EOL continued its partnership with Montana State University (MSU) in FY 2015, to upgrade the prototype water vapor differential absorption lidar (WV DIAL) for field deployment, in order to profile water vapor and aerosols in the lower troposphere. This eye-safe, low-cost WV DIAL profiler will fill a national long-term observing facility gap and greatly benefit studies of micro- and mesoscale meteorology, water cycle, carbon cycle and, generally, biosphere-hydrosphere-atmosphere interaction research at weather and climate variability time scales. EOL's long-term plan is to construct up to 10 units that could be deployed as a network for obtaining continuous-in-time vertical profiles of water vapor and temperature.

In FY 2015, EOL added an etalon filter to significantly reduce the background solar radiation and improve daytime performance of the instrument. EOL successfully test deployed WV DIAL in PECAN and routinely obtained WV data up to 6 km altitude. We also began to develop a hardened container for the instrument, which in turn will help enable its longer term unattended operation. EOL is well on its way to offering enhanced, high-resolution, accurate and continuous measurements of water vapor to the meteorological and climate research and forecasting communities.

## NEXT-GENERATION AIRBORNE DOPPLER RADAR: APAR

During FY 2015, EOL continued to seek partnerships for a state-of-the-art, flat panel, electrical scanning Airborne Phased Array Radar (APAR) to be mounted on the NSF/NCAR C-130 fuselage as a next generation airborne Doppler radar and a successor to the ELectra DOppler RADar (ELDORA). We visited and/or conducted conference calls with potential university and industry collaborators, and presentations were made to outline the APAR project. The APAR Advisory Panel (AAP) was formed, and the first face-to-face meeting was conducted in March 2015. The panel, which consists of 10 individuals with expertise in scientific and engineering disciplines that directly relate to APAR, is tasked with providing guidance and advice to the EOL team throughout this multi-year development. As part of the meeting, EOL briefed the AAP on the preliminary design for the advanced phased array radar system, which in return considered the technical feasibility of this major R&D effort. Discussions centered around the need to demonstrate capability in order to attract funding, the challenges associated with the lengthy development period, the

necessity for a working prototype, the involvement of outside contractors for significant portions of the development, and the desire to involve young scientists and engineers in the effort.



In April 2015, the APAR Project Team was given the opportunity to brief staff members from the U.S. Senate Appropriations Committee, who are responsible for both NSF and NOAA budget preparations and negotiations in the U.S. Congress. This presentation was made as part of a larger UCAR/NCAR visit. EOL presented an overview of the project, including information about the prototype transmitter/receiver module and the C-band antenna panel. The guests also visited EOL/RAF and were given tours of the NSF/NCAR GV and C-130 aircraft. The proposed placement of the APAR faces on the C-130 was described during a tour of the aircraft. EOL continues to seek external funding support and partnerships for the APAR development.

Also in FY 2015 EOL evaluated two prototype printed circuit boards that form the "Brick" Line Replaceable Unit (LRU); 56 such LRUs would be needed for a single APAR panel. The testing and redesign of the PCBs will continue in FY 2016. While implementing dual-polarization on APAR will be technologically difficult, the polarimetric capability of APAR would enable unprecedented microphysical study utilizing this airborne radar. Phased-array technology applications will also help advance science in several areas related to mesoscale meteorology, mixed-phase clouds in the polar regions and climate process studies related to clouds in general.

### LASER AIR MOTION SENSOR (LAMS)



As described in to [Cooper et al. \(2014\)](#), LAMS measures the true airspeed with an uncertainty of less than  $0.1 \text{ m s}^{-1}$  and so reduces uncertainty in the measured component of the wind along the longitudinal axis. The expected pitot pressure calculated from the LAMS airspeed provided a basis for calibrating the measurements of dynamic and static pressure, reducing the uncertainty in these measurements to less than 0.3 hPa. These improved measurements of pressure, combined with high-resolution GPS altitude measurements, can be used to determine the offset and

uncertainty in temperature measurements. Once tested, LAMS can provide improved four-dimensional wind and turbulence data on either NSF/NCAR aircraft and should be available on a routine basis. The utility of LAMS for routine three-dimensional turbulence measurements was tested during the FY 2015 - FY 2016 ARISTO program. Furthermore, the calibration testing that has been done with LAMS on the NSF/NCAR GV was applied to the NSF/NCAR C-130 during ARISTO, which we expect will improve the precision of its measurements. ARISTO data will be further analyzed in FY 2016.

### LROSE

In conjunction with the development of new remote sensors, EOL is leading a community effort to develop the next general radar and lidar analysis software suite. This suite adopts an open software framework to encourage and enable community contribution in developing next-generation software, and is an effective way for software sharing. LROSE will replace the suite of legacy radar and lidar software that is mostly maintained by EOL.



For LROSE in FY 2015, EOL improved the general graphic display to be used for HCR, HSRL, and WV DIAL, and improved data ingest routines into CfRadial, a standard data format for exchange of lidar and radar data in the community. Improved CfRadial ingest routines were updated to the RADX open source library available on the EOL website. We included a common B-scan display for HCR, HSRL, and WV DIAL as well, and this display was successfully deployed in PECAN and CSET. EOL also successfully fixed bugs for NEXRAD-Level II, NOAA TDR, SIGMET, and Solo3, and submitted a proposal in collaboration with the University of Hawaii (UH) to one of the NSF cross-cutting solicitations (NSF 14-520, Software Infrastructure for Sustained Innovation - SSE & SSI (SI2 - SSE&SSI)).

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IMPERATIVE IV

*Provide comprehensive data services, open access, and long-term stewardship of data*

NSF policy requires data set preservation and availability to users pursuing research questions apart from those that justified the original project, and NSF requires that grant proposals include comprehensive data management plans. Additionally, one of NSF’s core expectations in the NSF - UCAR Cooperative Agreement focuses on data issues, specifically calling for NCAR to “serve as stewards of high quality scientific data on behalf of the community through maintenance, enhancement and curation.” For EOL, this charge is a joint effort between the three EOL research platform Facilities (ISF, RAF, and RSF) and the Computing, Data and Software Facility (CDS). Whereas the first three Facilities are responsible for data acquisition from our sensors, instruments and facilities, CDS is responsible for developing and maintaining EOL’s data and metadata services, collaborative tools, and software engineering, all of which are integral to EOL Imperative IV.

Data sets collected and preserved by EOL have value that extends far beyond immediate project-team use. Modern data-access mechanisms increase the importance and utility of data set preservation, and improve data access by the scientific community. Leveraging these mechanisms, EOL has enlarged the scope of its data services to include service provision from mission planning stages, to data collection and quality control and long-term archives. EOL also provides stewardship for a select set of data not collected by its observational facilities. These efforts directly feed into NCAR’s Strategic Plan Imperative to develop and provide state-of-the-art data services that meet the needs of NSF, NCAR, and the science community.

DATA MANAGEMENT AND STEWARDSHIP

The EOL Metadata Database and Cyberinfrastructure (EMDAC) long-term archive relies on NCAR’s Computational Information Systems Laboratory (CISL) hardware, but certain project datasets are hosted on EOL servers. In FY 2015, EOL began the process of consolidating our project archive holdings - currently over 4 million files scattered over thousands of cartridges on the CISL High Performance Storage System (HPSS) - so that it will be easier and faster to create a copy for disaster recovery and create an off-site backup. EOL is coordinating this effort with CISL and working closely with the CISL Research Data Archive (RDA). For EMDAC, moving more recent datasets to CISL-hosted hardware greatly improved access times, provided a disaster recovery and off-site backup, and will allow EOL to better serve the community in the future.

EOL also worked to complete its inventory of legacy projects in FY 2015. As of the end of FY 2015, over 400 field projects have been identified in which EOL or predecessor divisions have participated (see the up-to-date list: <https://www.eol.ucar.edu/all-field-projects-and-deployments>). As additional project documentation and information were found, these project web pages have been updated, and as legacy project datasets were recovered from older media, processed, and uploaded to EMDAC, EOL staff created Master Lists of datasets facilitate data

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access. EOL also enhanced its automated access to preliminary datasets in the field and continued to migrate data tracking tools to the new metadata database.

In FY 2015, we established a Digital Object Identifier (DOI) Implementation Team and that group successfully finished a lab-wide plan for implementing DOIs for a subset of the Lower Atmosphere Observing Facilities and datasets collected during EOL-managed NSF-funded field campaigns. The goal of this process is to publish archived datasets based on an internationally accepted standard that uses a persistent identifier. Each DOI provides a globally unique, web compatible, alphanumeric string that allows access to dataset metadata and the digital data themselves. Integral to the functioning of this persistent identifier is the associated citation summary web page maintained by the data set publisher. Starting with the CONTRAST field campaign that was carried out in early calendar year 2014, and continuing with every field project for which EOL generates data, every final dataset that is entered into the EOL EMDAC data archive will be assigned a DOI after an internal metadata review and before public release. By the end of FY 2015, EOL had issued over 400 DOIs for archived datasets as well as for EOL platforms and Facilities for use by the scientific community for citation. The use of such DOIs will improve metric tracking as well as provide scientific data attribution.

Finally, EOL staff participated in the new NCAR-wide Data Stewardship Engineering Team (DSET) and Data Assimilation (DA) initiatives in FY 2015. The DSET goal is to provide easier access to data holdings within NCAR and UCP to a wide range of users and the group is specifically tasked with coming up with a strategic vision of an “integrated front door” for data discovery and access across the organization that will better serve the community. Taking a user-focused approach, DSET will investigate how to simplify data discovery and share metadata within the organization to improve the efficiency of access, improve the quality of the user experience, and reduce the costs associated with operating data services. The DSET effort is also responsive to external policy developments, including federal mandates, NSF requirements, and new journal policies related to scientific data. NCAR’s Data Assimilation effort has the goal of developing new data assimilation tools and to work on the characterization and quality control of observational data for assimilation needs. Both of these initiatives will extend through FY 2016 for EOL.

FIELD CATALOG

EOL worked to complete the redevelopment of the Field Catalog to version 2.4 in FY 2015. This included better simulation of flight operations for dry runs, incorporation of Web Mapping Service (WMS) into Catalog Maps, merging of the Mission Coordinator and Catalog Maps tool functionality, and the integration of OpenLayers and OpenStreetMaps technology to facilitate mobile device and low-bandwidth access to the Computing Data and Software (CDS) Facility’s mapping products.

During FY 2015, EOL provided field catalog support for the WINTER, the High Altitude Ice Crystals - High Ice Water Content Project (HAIC-HIWC 2015), PECAN, CSET, and Tropical Cyclone Intensity (TCI) campaigns, as well as the O2/N2 Ratio and CO2 Airborne Southern Ocean Study (ORCAS) Dry Run. Much of the Field Catalog development during FY 2015 was directed at supporting PECAN, which had a large number of mobile ground-based and airborne instrument platforms and needed real-time tracking and deployment mapping of all the instrument platforms. EOL successfully obtained real-time data from each platform and plotted that data in Catalog Maps for real-time display and playback, and developed a Mission Planner tool for the instrument coordinators to map expected deployment locations, track current locations, and communicate instructions and status via text messaging with each mobile instrument



Legacy data archives in EOL.

team. EOL also worked with the National Severe Storms Laboratory (NSSL) to incorporate an interactive site map that included Google street view and satellite imagery. Real-time tracking of mobile project assets was critical for the success of a complex field program like PECAN with many moving parts. Mapping continues to grow in importance for real-time decision making as well as for situational awareness and monitoring. The playback capability within the Field Catalog and Catalog Maps software is also a very important tool for researchers that is not often available from other sources.

EOL also developed software in FY 2015 to improve Catalog Maps functionality for users; automatically email special reports/Operations plans to all project participants; improve viewing, paging, and printing of pdf reports ; implement resource tracking so that EOL staff could update expendable resource spreadsheets and automatically update plots in the Field Catalog; and provide a simple method for emailing flight plan waypoints that would automatically generate flight plan kml files for the Catalog Maps and Mission Coordinator Displays as well as email the EOL project manager and pilots.

SOFTWARE ENHANCEMENTS FOR CORE INSTRUMENTATION

EOL made significant software enhancements for core instrumentation in FY 2015. For example:

- A comprehensive web-based data viewer (<http://datavis.eol.ucar.edu/>) was developed, providing quick-look browsing and visualization of EOL data holdings. Core functionality in software and firmware subsystems were completed for the APAR prototype Transmit-Receive Module, resulting in a flexible and structured Field Programmable Gate Array (FPGA) code base, which will efficiently support testing and characterizing this cutting-edge radar component.
- The HCR real-time software matured significantly, allowing the instrument to reliably collect unprecedented new cloud measurements during several field programs.
- A new signal processor, based on the EOL SD3C FPGA technology, was developed for S-Pol. This modern processor was successfully validated during the PECAN field program and will soon replace the legacy system.
- New visualization of MTP data in the Aeros package was prototyped, and a refactor of the track plot solved performance and maintenance problems. Merging of the Nimbus processor with the NIDAS syncserver is reaching completion, which will greatly streamline operation and workflows for the aircraft field missions. For MTP, integration with the RAF Nimbus processor has begun, the data flow diagram for the top level loop has been created, and a netCDF file format has designed.
- Collaboration with EOL scientists, NOAA AOC, and NOAA HRD led to corrections and improvements in the Aspen quality control algorithms and user interface.

These software enhancements and remote instrument control for EOL platforms will enhance instrument capabilities, lower maintenance burdens, improve reliability and increase data quality. For example, the GV AVAPS dropsonde system was completely operated from a ground terminal (via the Remote Instrument Control link) for the CSET field campaign. This freed up valuable cabin space on the aircraft, while providing a more productive working environment for the instrument operator. Improvements to the 449 MHz profiler, including the addition of oversampling and a refactored control interface, enhanced the scientific productivity and reliability of this instrument. Extensive improvements to the S-Pol software, including server upgrades, improved monitoring, Modbus integration and interface changes, allowed this system to perform very productively during the PECAN program. Software developments also lead to significant stability improvements for the HSRL, the addition of real-time image generation on the GV, and an ongoing migration to a 64-bit operating system.

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IMPERATIVE V

*Attract and inspire new generations of scientists, engineers and the general public to atmospheric science*

The promotion of atmospheric science is crucial to inspire the development of the next generation of observational scientists and engineers, and is an institutional charge that is important to EOL. EOL's commitment to both continuing and expanding the Laboratory's portfolio of education and outreach (E&O) contributions is reflected in EOL's Strategic Plan Imperative V. This Imperative aligns with NCAR's goal to attract a diverse group of university students and early career scientists and engineers, and to provide exciting educational and professional opportunities. The EOL-managed LAOF, EOL's mission and the Lab's E&O activities and visitor programs offer excellent and unique opportunities for education and training for undergraduate and graduate students interested in observational meteorology, and the integration of traditional engineering fields with areas of science. These opportunities can also motivate students to pursue careers in observational meteorology. EOL also strives to educate the public on the value of observational atmospheric science, through demonstrations of direct atmospheric measurements combined with explanations of what scientists learn from such observations.

Students pursuing education in science, technology, engineering and mathematics (STEM) can be motivated to seek careers in observational meteorology through exposure to NSF LAOF, and EOL outreach activities. EOL can also help the public understand better the value of observational atmospheric science by demonstrating direct measurements of the atmosphere and explaining what scientists learn from these observations. The mechanisms EOL provides to support and inspire undergraduates and graduates, high school students, teachers, and faculty will ensure the field of atmospheric science remains vibrant well into the future.

In FY 2015 EOL conducted education and outreach activities for two field campaigns; participated in an educational field deployment; and conducted another successful year of EOL's Summer Undergraduate Program for Engineering Research (SUPER) and Technical Internship Program opportunities.

PUBLIC ENGAGEMENT AND E&O FOR FIELD CAMPAIGNS

EOL staff worked closely with the PIs of PECAN and WINTER on dedicated education and outreach efforts during each field campaign to increase the understanding of and public appreciation for observational research in the atmospheric sciences and its relevance to society.

PECAN

PECAN was a multi-agency, multi-facility campaign that involved a significant number of organizations, who subsequently conducted their own education and outreach efforts. EOL education and public outreach (EPO) efforts for PECAN included the provision of 15 pages of online content on the [PECAN website](#) that summarized the various participating observing facilities and how radars work. EOL outreach efforts also entailed a tour of the University of Wyoming King Air for 30 high school students who were participating in the Upward Bound Program; meeting with a troop of seven Girl Scouts Daisies who earned their Meteorology and Weather Awareness badges through the visit; offering a PECAN Teacher Workshop to ten middle and high school science teachers; a tour of the mobile facilities for 16 freshman and sophomore high school students who were participating in the Fort Hays State University Energy Camp; and, lastly, holding an open house at one of the PECAN Integrated Sounding Array (PISA)

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sites. In addition to these interactions, EOL worked with UCAR Communications to increase media interest, which resulted in at least 34 unique articles about PECAN research.

## WINTER

EOL's educational activities for WINTER were hampered due to severe winter weather conditions in the area. Nevertheless, the school visits during WINTER were the EPO highlight. With an emphasis on engaging colleges and university students, five of the eight schools visited were higher education institutions, and the remaining three were K-12 schools, engaging a total of 1179 students and staff during 15 presentations. Website and social media metrics demonstrated a significant online success with the materials provided. WINTER received modest media coverage, with eight unique articles, including one from the Associated Press.

## EDUCATIONAL DEPLOYMENTS FOR EOL LAOF

EOL continues support for deployment of observing facilities for education through NSF's Deployment Pool. On average, four to six educational deployments are approved by NSF per year, involving primarily the Center for Severe Weather Research's Doppler on Wheels (DOW) platforms.

In FY 2015, the NSF Deployment Pool supported 12 educational deployments. Two of those - the Boundary Structure Experiments with Central Minnesota Profiling II (BaSE CaMP II), and the Characterizing the Atmospheric Boundary Layer (CABL) project - involved EOL-managed Lower Atmosphere Observing Facilities.

BaSE CaMP II exposed students at Saint Cloud State University in Minnesota to the Mobile Integrated Sounding System from 18 October to 18 November 2014. About 80 students benefited from this hands-on exercise. The CABL educational deployment leveraged multiple outreach opportunities closer to home by providing scientific opportunities to high school, undergraduate, and graduate students along Colorado's Front Range. Several EOL facilities were deployed as part of CABL, including 12 sonic anemometers and 6 temperature/relative humidity probes mounted on the Boulder Atmospheric Observatory (BAO), 40 mobile GPS Advanced Upper-air Soundings (MGAUS), and the deployment of two Integrated Surface Flux stations: one at the BAO and one in the vicinity of Erie High School.

## INTERNSHIPS

In FY 2015, EOL once again offered undergraduate engineering students with interest in the atmospheric sciences an opportunity to participate in the EOL Summer Undergraduate Program in Engineering Research (SUPER) Internship. SUPER provides hands-on experience with atmospheric observing systems to students by teaming them with lead engineers. SUPER focuses on engineering problems directed at scientific advancement and EOL typically receives resumes from mechanical, electrical and computer, aerospace, optical, environmental, chemical, and industrial engineering students.

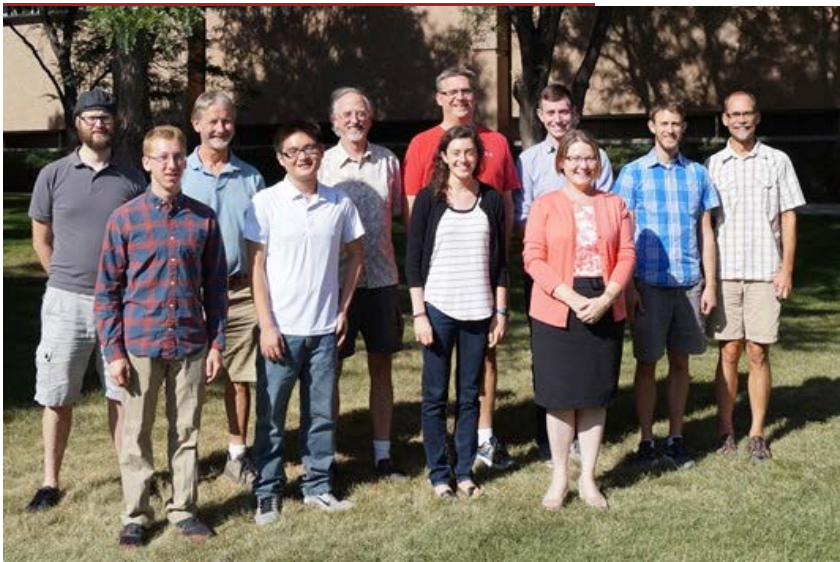
EOL hosted four SUPER interns in FY 2015:

- Scott Hally worked with engineer John Sobtzak on automating ISF's power amplifier test bench, which involved writing LabView code/programs that interface with the RF test equipment (signal generators, RF power meters, spectrum analyzers, vector signal analyzers, digital multimeters) over their GPIB interface ports.
- Hien Nguyen was mentored by software engineer Gordon Maclean while working on a project to enhance the NCharts data display application at EOL. NCharts is a python and javascript web application which uses Django, JQuery and HighCharts for near real-time display of NetCDF time series from a variety of EOL observing platforms.
- Lucas Reed explored a solar/energy-harvesting Lithium/multi-chemistry battery charging system for the ISFS Wisard and TRH sensors while working with engineer John Militzer. Lucas' work involved circuit design, layout, fabrication and testing.
- Katie McMenamin worked on characterizing the electronics response time of the fast-2D boards used by RAF's PMS-2D probes. These probes are used on the NSF/NCAR aircraft to characterize cloud particle size distributions. Katie was mentored by project scientist Matt Hayman for her work.



In addition to SUPER, EOL also hosted two students under our Technical Internship Program (TIP) during FY 2015. This program is designed to bring students from non-scientific disciplines to EOL and expose them to the types of science support careers available at NCAR.

- Susana Guilford was mentored by technician Jonathan Emmett for tasks for the HIAPER Cloud Radar, conducting mostly electronics work.
- Zakary Starr worked with systems administrator Mike Paxton to provide helpdesk and other computer support to EOL during his internship.



Summer 2015 EOL SUPER interns.

Our SUPER and TIP internship programs provide solutions to EOL engineering and science support problems, while at the same time educating students on career opportunities of which they might not otherwise be aware.

NEXT PRACTICES WORKSHOP

EOL partnered with the Deutschen Zentrums für Luft- und Raumfahrt (DLR, the German Aerospace Center) to organize the *Observations in Atmospheric Sciences – “Next” Practices: Conducting Field Operations in a Changing World* workshop, which took place from 21-23 April 2015 in New Orleans, LA. Close to 40 participants from the U.S., Europe, and South Africa attended the meeting to discuss various approaches to field operations, covering a range of issues such as modes of operations, feasibilities and risk assessments, implementation and conduct of campaigns, media interactions, student participation, and the use of new technologies. The agenda was a mix of short, focused presentations, plenary and small breakout sessions, as well as invited keynote speakers, and accommodated specific discussion items that different groups may bring to the table.

A significant amount of time was spent on understanding what kind of support each group provides to its respective science community. Two of the highlights of the workshop were a series of short presentations focused on “Oh No!” experiences and extensive discussions about how to conduct research in challenging countries such as Brazil, China, and India. The group agreed to continue this newly established collaboration by finding a way to share documentation and information that could be of interest to everybody, meeting annually, and potentially exchanging personnel. Participants included representatives from NASA ESPO, NOAA/AOC, DOE/ARM, DOE/PNNL, DLR, FAAM, CNES, SAFIRE, CSWR, UND, and the University of Wyoming.

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FRONTIER I

*Improve observing capabilities for weather and climate phenomena with high socio-economic impact*

AIRBORNE PHASED ARRAY RADAR (APAR)

EOL’s highest new instrumentation development priority is the Airborne Phased Array Radar (APAR), a new and unique C-band airborne radar with dual-Doppler and dual-polarimetric capabilities designed for a large fuselage aircraft such as the NSF/NCAR C-130. After the decommission of the Electra Doppler Radar (ELDORA), the scientific community has strongly voiced the need for an airborne radar for studies of clouds over open ocean or other hard-to-access parts of the Earth. APAR is our response to that need. This frontier development takes advantage of significant in-house scientific and engineering expertise and is an exceptional opportunity for EOL to make significant contributions to a next-generation radar capability in collaboration with current and future development partners.

In FY 2015, EOL continued work to develop a novel APAR with dual-Doppler and polarimetric capabilities to be operational on the NSF/NCAR C-130 aircraft. APAR presents an opportunity to provide simultaneous measurements in kinematics, microphysics, water vapor and chemical species from aircraft, in time and space. The plan is to use four removable, flat C-band Active Electronically Scanned Arrays (AESAs) strategically placed on the fuselage, which requires some modest airframe modifications. The large surface area on fuselage permits a C-band radar with a beam width comparable to ELDORA. This design could also be adapted to other agencies’ C-130s, including the US Air Force hurricane reconnaissance fleet. The potential to improve hurricane track and intensity forecasts by continuously assimilating APAR data from those reconnaissance missions into operational numerical models may provide even greater societal impacts for the general public beyond the benefits to be gained by the scientific research community.

As described in Imperative III, the APAR team worked in FY 2015 to further develop, build up and test the APAR “brick” Transmit/Receiver (T/R) module. This included prototyping printed circuit boards that form the “brick” Line Replaceable Unit (LRU) and evaluating them. We also formed the APAR Advisory Panel, in order to solicit community input, and held its first meeting in March 2015.

Development of APAR requires substantial effort and resources and is a multi-disciplinary effort, requiring the skills of scientists, technicians, instrument makers, and mechanical, electrical, antenna, RF and software engineers. Input from the community is a critical part of APAR development and EOL will seek collaborative partners for it.

HIAPER CLOUD RADAR (HCR)

In FY 2015, EOL completed the development and field tests of the HIAPER Cloud Radar (HCR). HCR’s maiden voyage was the 5-day Rapid Response Deployment on the Nor’easter project in February 2015. When HCR was flown above both a cyclone and a frontal system, unprecedented data were collected from several weather features, such as initiating convective cells, gravity waves along a frontal boundary, a melting layer, etc. HCR was also successfully deployed in CSET (1 July - 15 August 2015) to study kinematics and microphysics within the stratocumulus clouds between California and Hawaii that are critical to the global energy cycle.

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FRONTIER II

*Provide new or significantly strengthened capabilities to support observational research in key areas where support needs are growing in importance*

EOL’s support of climate system science research has a deep history and we have much to offer in this realm; however, as needs and opportunities change, so is there motivation to change the nature of our support. The opportunities for global-scale observations provided now by HIAPER (e.g., during the HIPPO campaigns) are significant, and we see potential for longer-term observations through instrumentation such as CentNet. These build on EOL’s history and experience in process studies, and we will continue to serve the needs of the climate community for such observations.

The weather forecasting and climate research communities also have a clear need to obtain improved measurements of water vapor, as accurate, high-resolution, continuous measurements of water vapor are a key observational gap. EOL’s collaboration with Kevin Repasky (EOL Affiliate Scientist) of Montana State University (MSU) on the development of a Water Vapor Differential Absorption Lidar (WV DIAL) will help address this need. The WV DIAL will provide measurements of water vapor from the surface to 6 km and of aerosols to 12 km, and system will have a relatively low cost due to the use of commercial off-the-shelf components.

EOL, partnering with MSU, has and will continue to upgrade the prototype low-cost, eye-safe diode laser-based micro-pulse WV DIAL to profile water vapor and aerosols in the lower troposphere. EOL and MSU are working together to enhance the system for operating in the field unattended and for long periods of time that would be required for use in a field campaign (see Imperative III).

This instrument will fill a national long-term observing facility gap and greatly benefit studies of micro- and meso-scale meteorology, water cycle, carbon cycle and, generally, biosphere-hydrosphere-atmosphere interaction research at weather and climate variability time scales. In FY 2015, EOL deployed a prototype WV DIAL to PECAN for a seven-week period (1 June - 15 July 2015; see Imperative II). The WV DIAL collected high temporal vertical profiles of water vapor up to 6 km altitude and documented evolution and diurnal cycles of water vapor in the lower troposphere. Verification of the water vapor data with other existing water vapor systems will continue in FY 2016.

LASER AIR MOTION SYSTEM

As described in Imperative III, LAMS will allow wind velocity measurements using a continuous-wave laser that in undisturbed air is focused about 20 meters ahead of the NSF/NCAR GV; that should, for the first time, allow for measurements of turbulence in the air unaffected by the presence of the aircraft. LAMS has already demonstrated a major capability to improve the calibration of temperature and pressure in the difficult flight environment. It may prove to be an alternative to calibrations using the cumbersome trailing cone technique.

NEW DATA INITIATIVES

EOL has embarked upon an ambitious plan to assign Digital Object Identifiers (DOIs) to all EOL-managed LAOF and datasets, and in FY 2015 made strong steps in this direction (see Imperative IV). This effort is a key in our goal to make science more easily discoverable and repeatable for generations of scientists to come.

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FRONTIER III

*Develop new capabilities that focus on processes at interfaces in the atmosphere*

Understanding processes at interfaces continues to grow in importance and is prominent in many assessments of needs for the future. The air-sea interface, the air-land interface, and the tropopause have diverse observational needs, and there are many possible measurement tools and observational opportunities for these interfaces. These could include: controlled towed vehicles to extend the reach of research aircraft closer to the surface; ocean sensors like Airborne eXpendable BathyThermographs (AXBTs) for studies of the upper layer of the ocean; measurements of fluxes of trace gases to or from the lower surface (land or sea); new sensors on dropsondes for characterizing the chemistry of the tropopause region; the development of remote sensors that measure profiles of trace gases and for measurement of fluxes (e.g., via combining a DIAL with a Doppler lidar); and development of large arrays of sensors to increase coverage and resolution of measurements. Other areas with potential include using Unmanned Autonomous Systems (UASs) for boundary-layer studies, the remote measurement of 3-D wind, tethersonde capability to increase the altitude range of boundary layer measurements, and higher-response measurements from research aircraft to measure fluxes and probe the fine-scale structure of turbulence. To address some of these needs, EOL is developing CentNet for greater boundary layer coverage through longer timeframes, broader areas, and complex terrain. Sensor simplification and miniaturization are leading to new opportunities in this area.

There is also now broad recognition within the geosciences that the multi-scaled features characterizing landscapes present unique challenges that hinder progress in multiple fields connected to climate, air quality, atmospheric composition, surface hydrology, and ecology. To make scientific progress on these challenges requires measuring and modeling spatial gradients in state variables and their concomitant fluxes at unprecedented spatial scales.

A large network of ground-based sensors would help address these challenges and would facilitate research in the biogeosciences, hydrology, and urban meteorology, in addition to the mesoscale meteorological research traditionally supported by tower networks. EOL therefore is designing and prototyping CentNet, a network of up to 100 stations that can be deployed on spatial scales from 1 m to 100 km in support of surface exchange research and a wide variety of bio-geophysical field studies – more of this development is described in Imperative III. CentNet would allow direct research-quality measurements of all components of the surface energy and water budgets, complemented by measurements of key elements of the carbon budget. The CentNet system could also be used for both weather and climate process studies. This development builds on EOL’s current Integrated Surface Flux System (ISFS), expanding it to include an array of semi-autonomous sensor stations that can be deployed in a variety of spatial patterns and for a wide range of time periods.

CentNet is designed to minimize set up and maintenance time, with Radio Frequency (RF) communications used as much as possible to reduce cabling, and two-way communication via the Internet for each station for real-time data display and control. The system is also designed to have the ability to cycle power on any sensor, e.g. one that is not reporting. In FY 2015, a small CentNet array was used for the Characterizing the Atmospheric Boundary Layer (CABL) educational deployment (see Imperative V).

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## FRONTIER IV

*Develop new calibration and testing facilities, including testbed capabilities, for the community, either in collaboration with other agencies or specifically for NSF-supported research*

### FRONT

The Front Range Observational Network Testbed integrates Colorado State University’s (CSU) CHILL and EOL’s S-Pol radar systems to streamline engineering development and operations for expanded science, research and education opportunities.

In FY 2015, the MASCRAD project used FRONT to meet its scientific objectives (see Imperative II). EOL also operated S-Pol at the Firestone FRONT to test the radar’s remote operation and monitoring systems ahead of the PECAN campaign, reducing the efforts and staff participation in supporting that project.

### CALIBRATION FACILITIES

EOL and the community have need for calibration facilities for water vapor sensors; an environmental chamber with precise pressure and temperature control for testing instruments over a wide range of these parameters; and a wind tunnel test facility for aircraft inlets to which EOL would have access, perhaps operated by EOL. Associated with these needs, is the need for more attention to measurement science: calibration, uncertainty characterization, and documentation of instrument characteristics. In FY 2015, EOL moved forward with the purchase of a new environmental chamber that will allow for testing instrumentation with a variety of pressure and temperature parameters, and will install that chamber in FY 2016. The new chamber will have the ability to control altitude up to 100,000 ft, temperature from -70° C to 170° C, and humidity from 20% to 95%.

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DIRECTOR'S REPORT

It is with great pleasure that we present the 2015 Annual Report of the High Altitude Observatory (HAO), the solar-terrestrial physics laboratory of the National Center for Atmospheric Research (NCAR). Through its research, leadership, and service to the community HAO strives toward a better understanding of the relentless interaction between the atmospheres of the Sun and the Earth.

HAO has a broad group of stakeholders: the National Science Foundation (NSF) and other government agencies; the world-wide solar-terrestrial physics community (including the solar physics, heliospheric physics, magnetospheric physics, and upper-atmospheric physics communities); higher education facilities; the rest of NCAR and UCAR; our own staff, visitors, and students; and the wider public. In support of these stakeholders, HAO's staff has set to work on a new strategic plan that establishes a number of goals: to solve critical scientific problems in solar-terrestrial physics; gain a better understanding of space weather and space climate domains to improve attribution for forecast; deploy state-of-the-art observational facilities and scientific data services; develop and support advanced models of the Sun-Earth system; to support the education and training of early-career researchers; and to provide advocacy for solar-terrestrial physics, promoting its results, and articulating its societal importance.

Our blended program of research, instrumentation, education, and mentorship straddles the deep solar interior and the origins of heliospheric magnetism, through the Sun's photosphere and chromosphere, into the corona and interplanetary space, to the magnetosphere, and the upper atmosphere of the Earth. This report highlights our team over the past year in these areas and, while it is not intended to be comprehensive, it covers the spectrum of efforts that we pursue.

Over the reporting year, several colleagues have gained promotions: Matthias Rempel and I were promoted to NCAR Senior Scientists; Alfred de Wijn moved to the ladder track as Research Engineer II (the first research engineer in HAO's ranks); Amy Knack was reclassified to Administrator II and Phil Oakley was reclassified to Systems Engineer III. Each of these staff members have been recognized for their effort and commitment to HAO, NCAR, and to the broader community. In the past year we also celebrated the elevation of two of our recently retired colleagues. Bruce Lites became an NCAR Distinguished Scholar in recognition of his efforts in solar spectro-polarimetry, and Maura Hagan became an NCAR Scientist Emerita in recognition of her work in upper atmospheric modeling as she took up her role as Dean of the School of Physics at Utah State University. We hope that both Bruce and Maura continue their connections with HAO.

This has been a very busy year for us. In the early part of 2015 we conducted a number of small-group



HAO Director Scott McIntosh

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strategic planning meetings around specific areas to inform the discussions at our strategic planning kick-off retreat in May. Following this meeting writing groups sharpened the goals collectively deliberated at the retreat before a draft plan was put together for consideration in the final quarter of the year for implementation in 2016 and beyond. We had a packed summer of workshop organization, hosting, and participation following which, on September 1-3 2015, we celebrate our 75th birthday! The event had an incredible level of attendance over the three days in an open event that spanned the community, our stakeholders, celebrated HAO’s beginnings, its proud history, staff, our community, and laid the foundations for future activities. It was a meeting that allowed us to reflect on what this fine organization has accomplished over its history; for old friends to reconnect; let the younger generations hear about and meet fabled HAO staff of the past; and to look at the growth and vitality of Boulder’s solar-terrestrial physics community. The organizing committee excelled in putting together an engaging, emotional and informative event. Finally, we hosted new External Advisory Committee in October - who engaged in very positive discussions around HAO and its plans for the future.

In 2015 we made significant progress in the development of the thermosphere and ionosphere extension of NCAR’s Whole Atmosphere Community Climate Model (WACCM-X) as a replacement for the “TI\*GCM” class of models as HAO community models of the Earth’s upper atmosphere that have served our community so well for decades. The Visible Spectro-Polarimeter (ViSP), a first light instrument for the National Solar Observatory’s Daniel K. Inouye Solar Telescope (DKIST), passed its Comprehensive Design Review and has started construction. The Coronal and Solar Magnetism Observatory (CoSMO) Large Coronagraph passed its Preliminary Design Review - an essential step towards a replacement cutting-edge observatory for HAO and the community. These are just a few of the major milestones achieved over the year and says little of the hundreds of scientific papers written and presentations made by the staff - some material of which you will see in the accompanying pages.

Finally, I add that the endeavors described herein would not have been possible without the tremendous effort put into the laboratory by our Administrative Team, Computer Systems Management Team, and others who unfalteringly work in service of the laboratory, center, and stakeholders.

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HAO 75 YEAR CELEBRATION

In early September of 1940 a specialized high-altitude observing station was commissioned in Colorado to observe the Sun’s corona. Soon, with the entry of the US into World War II they were making the first attempts to make practical use of solar observations in understanding the potential impact of solar activity induced geomagnetic activity on the ionosphere. This activity saw the birth of what we would now call space weather forecasting. From these humble beginnings that observing station evolved into the High Altitude Observatory and grew substantially after the war before moving the bulk of the effort off of the continental divide to the relatively less harsh conditions in Boulder where we still reside.

Fast forward several decades...

In early September of 2015 over 600 scientists, engineers, administrators, and members of the general public gathered over three days to celebrate HAO, its people, and the vision of Walt Orr Robert, the original HAO pioneer and Director. From kick-off public planetarium shows at the University of Colorado’s Fiske Planetarium (<https://fiske.colorado.edu/>), public lectures, a temporary museum of HAO instrumentation, photographs and important documents, an extensive range of posters, talks, and other oral histories, the people of HAO gathered to reminisce and look forward with members of Boulder’s solar-Terrestrial physics community that has grown up since 1940—somewhat due to the influence that HAO has had over the years.

Day one focused on HAO’s past. A broad array of



Karen Simmons, Shirley Hansen, Sabine Schaffner, and Richard Hansen.



HAO retiree and NCAR Emeritus Scientist Dr. Bruce Lites who was elevated to NCAR Distinguished Scholar (HAO’s first).

presentations focused on the people of HAO, the innovations that they made, the breadth of breakthrough science that they conducted, the instruments and models that they needed to build to achieve those breakthroughs. The day’s activities culminated with a two fantastic presentations. The first by recent HAO retiree and NCAR Emeritus Scientist Dr. Bruce Lites who was elevated to NCAR Distinguished Scholar (HAO’s first) in recognition of his efforts in remotely sensing solar magnetism through spectro-polarimetry. The final presentation of the day came from former HAO senior scientist, and President of UCAR, Dr. Tom Bogdan—a renown and enthusiastic student of HAO’s early history—whose talk “HAO History: The Early Years” left the audience spell-bound.

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The activities of day two revolved around HAO and the broader Boulder-based organizations in solar-terrestrial and related fields. Many of the presentations highlighted scientific breakthroughs in our understanding of magnetism: how we observe, measure and forecast it and how impactful magnetic eruption can be on the Earth, especially in this day and age of technology dependency. We were addressed by Congressman Ed Perlmutter who spoke on the challenges of funding science in Washington. Doug Duncan from Fiske Planetarium gave a talk about the total solar eclipse that will bring the continental US to a grinding halt in August of 2017 - the first of its kind in 29 years, the path of the total eclipse runs from Oregon to North Carolina and there are potentially 100,000,000 people within a reasonable distance from the path of totality, although almost all of the continental US will experience partial eclipse. The second day of HAO 75 was wrapped up by NASA's Associate Administrator for the Science Mission Directorate, Dr. John Grunsfeld, at CU's Glenn Miller ballroom. John gave an excellent public lecture on Space Exploration and Research (<https://youtu.be/ytjQITRJDn4>). Everyone experienced a tour de force from the astrophysicist astronaut that covered his career in space, highlights of current NASA missions and visions of those to come.



Dr. Tom Bogdan left the audience spell-bound when he presented "HAO History: The Early Years".



Members of the 75th organizing committee.

The third and final day of the event focused on the future of HAO and solar-terrestrial physics in general. Presentations on HAO's priorities in developing CoSMO (the Coronal and Solar Magnetism Observatory), CSAC (the Community Spectropolarimetric Analysis Center) and WACCM-X (the Thermosphere/Ionosphere Extension of NCAR's Whole Atmosphere Community Climate Model) were broadly balanced by those on next-generation observations of the inner heliosphere (with Solar Probe Plus and Solar Orbiter) and terrestrial environment using small-satellite technology. HAO Director, Scott McIntosh, closed the event with a discussion of the need for HAO to use its historically-honed skill-base to build capability that benefits the community and general public. That presentation embodied the philosophy

of our upcoming strategic plan.

All in all, HAO 75 was a tremendous success. HAO is more than a building (or series of buildings), HAO is all about its people. To see them, to hear them, to reflect on what they achieved, and then to demonstrate how we have grown as a community from the roots sewn 75 years ago was a tremendous opportunity, if not a little overwhelming.

The team that made HAO 75 happen were simply tremendous. Their efforts were recognized by being awarded the 2015 HAO Director's Award for outstanding achievement. The team comprised of, with affiliation in parentheses: Joan Burkepile, Greg Card, Rebecca Centeno-Elliott, Joanne Graham, Wendy Hawkins, Don Kolinski, Alice Lecinski, and Sheryl Shapiro (all HAO), Greg Kopp (LASP) and Doug Duncan (CU/Fiske). In addition, HAO owes a debt of gratitude to the Boulder Solar Alliance who contributed to the day two agenda throughout the last twelve months and to Kim Nesnadny and Ron Lull who were ever present during the three day celebration in order to ensure transitions between speakers worked smoothly. Thanks to everyone who contributed!

Interested in learning more about HAO 75? Visit our dedicated website

(<https://www2.hao.ucar.edu/HAO-75th-anniversary>) to watch videos, explore content, and see pictures from the event.

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SCIENTIFIC DISCOVERY AND INNOVATION

HAO conducts a comprehensive program of solar-terrestrial physics. This program encompasses the physics of the Sun, Heliosphere, and Geospace to that of the Earth's Magnetosphere, Ionosphere, Thermosphere, and upper atmosphere. Research in these areas areas is pursued using a combination of state-of-the-art numerical models, theoretical, and observational efforts that study the response of the terrestrial system to electro-magnetic, particulate, and impulsive phenomena.

The following are some of our scientific highlights from fiscal year 2015.

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MODELING HIGH-SPEED FLOWS IN THE EARTH'S MAGNETOTAIL

The magnetosphere is created by the interaction between the solar wind and the Earth's magnetic field. On the dayside of the Earth pressure from the solar wind compresses the Earth's dipole magnetic field and on the night side this interaction stretches it out forming a region of space commonly referred to as the magnetotail. Depending on the direction of the magnetic field in the solar wind, mass, momentum, and energy can be transferred into the magnetotail making it a highly dynamic region full of high-speed plasma flows. HAO scientist Michael Wiltberger, working with colleagues at Dartmouth College and John's Hopkin's University, used the Lyon-Fedder-Mobarry global magnetosphere model in its highest resolution mode to simulate these dynamic flows.

Figure 1 shows a scientific visualization of the magnetotail as the interplanetary magnetic field (IMF) goes from northward to southward. Southward IMF allows for the most energy transfer from the solar wind into the magnetosphere. The visualization shows the magnetotail with a colored plane cut through the center of the Earth. On this plane the difference between dipole magnetic field and the current value is illustrated with the green/purple color scheme. You can see the compression of the Earth's dipole field on the dayside at the beginning of the movie. As the movie progresses, the magnetotail becomes dominated by numerous high-speed flows that propagate from the further down the tail towards the Earth. The colored arrows in the visualization illustrate the strength and direction of these flows. A larger redder arrow represents stronger flows. The green concave feature at the leading of these flows represents a compression of the magnetic field. This compression returns the field to a more dipolar magnetic field configuration and is the origin of the name dipolarization fronts that scientists use for these features.

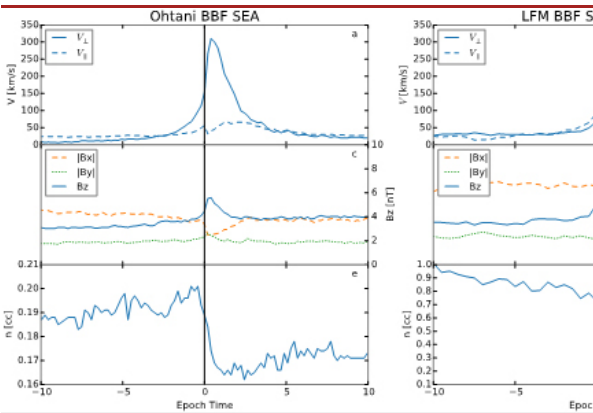


Figure 1: Wiltberger, M., V. Merkin, J. G. Lyon, and S. Ohtani (2015), High-resolution global magnetohydrodynamic simulation of bursty bulk flows, *J. Geophys. Res.*, 120(6), 4555–4566, doi:10.1002/2015JA021080.

These dipolarization fronts are often observed in the magnetotail by various NASA spacecraft. A challenge in comparing these observations with the simulation results is that because the flow is nearly turbulent it is difficult if not impossible to have the spacecraft exactly the same spot in the real magnetotail and the simulation. The investigators overcome this challenge by making a statistical comparison between the observed flows and the simulation results. Figure 2 illustrates the results of using the same selection criteria to observe high-speed flows in the simulation and real magnetotail. On the left hand side of Figure are results for the flow speed, magnetic field, and density observed by the Geotail mission while it was in the magnetotail. On the right hand side are results from the high-resolution LFM simulation. The flows show a slightly broader profile than the observations with similar peak value. The magnetic field shows the compression of the BZ field in both the simulation and observations. There is a density drop in both sets of data, but the magnitude is much larger in the simulated results. This is likely due to the preconditioning of the magnetosphere in the simulation. In general, these results are in good agreement and provide verification that the high-resolution simulations are doing a good job of capturing the dynamics of the magnetotail.

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STUDYING ATMOSPHERE COUPLING USING MESOSCALE-RESOLVING WACCM

An important pathway for the terrestrial weather to affect the space weather is through atmosphere waves, such as atmospheric tides, planetary waves and gravity waves. The impacts of the planetary-scale waves have been extensively studied observationally and numerically. The gravity waves, in spite of their increasing significance at high altitudes in causing large disturbances in the thermosphere and ionosphere, are poorly quantified in the global context. This is mainly due to the very broad scales of these waves and the wave impacts, and it is a major challenge to capture such broad scales in observations and numerical models. To address this challenge, a mesoscale-resolving whole atmosphere general circulation model has been developed for the first time. This was accomplished using the National Center for Atmospheric Research Whole Atmosphere Community Climate Model (WACCM) with 0.25° horizontal resolution and 0.1 scale height vertical resolution above the middle stratosphere (higher resolution below). This was made possible by the high accuracy and high scalability of the spectral element dynamical core from the High-Order Method Modeling Environment (HOMME). The latitude-height structure and the magnitudes of the temperature variance, reflecting the gravity wave potential energy density, compare well with those deduced from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) observations.

The simulation reveals the increasing dominance of gravity waves (GWs) at higher altitudes through both the height dependence of the kinetic energy spectra, which display a steeper slope ( -3) in the stratosphere and shallower slopes above, and the increasing magnitude and spatial extent of GWs (including a planetary-scale extent of a concentric GW excited by a tropical cyclone) at higher altitudes (Figure 1). GW impacts on the large-scale flow are evaluated in terms of zonal mean zonal wind and tides: with no GW drag parameterized in the simulations, forcing by resolved GWs does reverse the summer mesospheric wind, albeit at an altitude higher than climatology, and only slows down the winter mesospheric wind without closing it. The hemispheric structures and magnitudes of diurnal and semidiurnal migrating tides compare favorably with observations.

In addition to NSF base funding on Award #M0856145, this work was supported by NSF AGS-1138784, NASA LWS NNX09AJ83G, NNX13AE20G, and base fund.

Source: Liu, H.-L., J. M. McInerney, S. Santos, P. H. Lauritzen, M. A. Taylor, and N. M. Pedatella (2014), Gravity waves simulated by high-

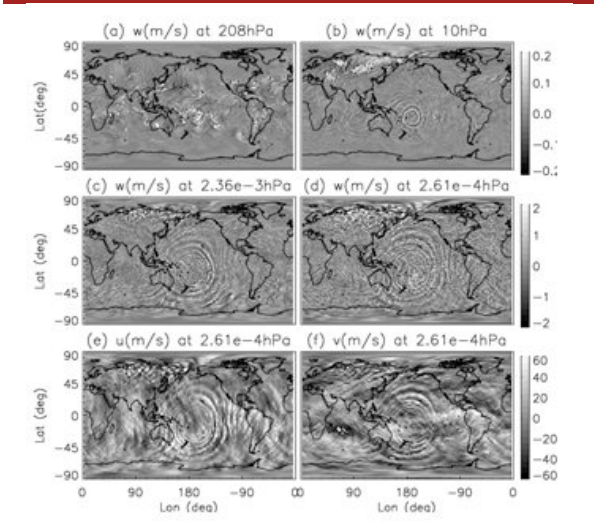


Figure 1: WACCM simulation results on 4 February at 21:00 UT. (a-d) Vertical winds at 208 hPa ( 11 km), 10 hPa ( 30 km),  $2.4 \times 10^{-3}$  hPa ( 87 km), and  $2.6 \times 10^{-4}$  hPa ( 100 km), respectively. (e-f) Zonal and meridional winds at  $2.6 \times 10^{-4}$  hPa. The contour range is smaller than the actual range of the winds to better visualize the wave structures. In Figure 1a the maximum upward wind over the tropical cyclone is  $4 \text{ m s}^{-1}$ ; in Figures 1b-d the maximum values of the vertical winds are  $0.6 \text{ m s}^{-1}$ ,  $9 \text{ m s}^{-1}$ , and  $7.5 \text{ m s}^{-1}$ , respectively; in Figures 1e and 1f the maximum values of the horizontal winds are  $162 \text{ m s}^{-1}$  and  $114 \text{ m s}^{-1}$ .

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resolution Whole Atmosphere Community Climate Model, Geophys. Res. Lett., 41, 9106–9112, doi:10.1002/2014GL062468.

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## A TIEGCM SIMULATION OF THE ANOMALOUS ELECTRON HEATING EFFECT ON THE E-REGION IONOSPHERE

In the ionospheric E-region, the electrons are magnetized because their frequency of rotation around the magnetic field is much greater than their frequency of collisions with the neutrals. Thus, the electrons drift mostly perpendicular to the electric fields. In contrast, the ions are unmagnetized because their frequency of rotation around the magnetic field is smaller than the frequency of collisions between the ions and neutrals, and thus neutral winds can drag the ions to move in the direction of winds. This differential motion between the electrons and the ions becomes much larger during geomagnetic storms and can excite the Farley-Buneman (two-stream) instability. This instability leads to turbulent electric fields and plasma density perturbations. The interaction of the electrons with the turbulent electric fields caused by the Farley-Buneman (F-B) instability produces anomalous electron heating (AEH) in the auroral region. Incoherent Scatter Radar observations have shown dramatic enhancements of the electron temperature in the auroral electrojet region as a result of AEH during strong geomagnetic storms. This electron temperature enhancement typically takes place at around 105-125 km in height and raises the electron temperature by up to a factor of 8, from 300-500 K to ~4000 K.

To fully assess the impact of AEH on the E-region ionosphere and on the coupling between the magnetosphere and ionosphere, HAO postdoctoral scientist Jing Liu, in collaboration with the scientists from HAO, Boston University, Dartmouth College, and the Applied Physics Laboratory in the Johns Hopkins University, has implemented the AEH rate in the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM). The AEH rate formula is obtained from a kinetic model of the electron energization within the high-latitude electrojet due to the Farley-Buneman instability that is developed by the scientists at the Boston University. Two TIEGCM simulations were carried out for an idealized strong geomagnetic storm event: the first one was the default TIEGCM run without AEH and the second one with AEH caused by the F-B instability (Figure 1). The TIEGCM simulation with AEH reveals large electron temperature enhancement effects (red lines) at high latitudes. This enhancement occurs at locations where large high-latitude convection electric fields are present. The magnitude of the enhancement can be greater than 2000 K, which is consistent with radar observations.

The TIEGCM also shows that there are noticeable increases in E-region electron densities and conductivity when AEH is included in the model simulation. This change of ionospheric density and conductivity, in turn, affects the coupling between the magnetosphere and ionosphere by modifying the field-aligned

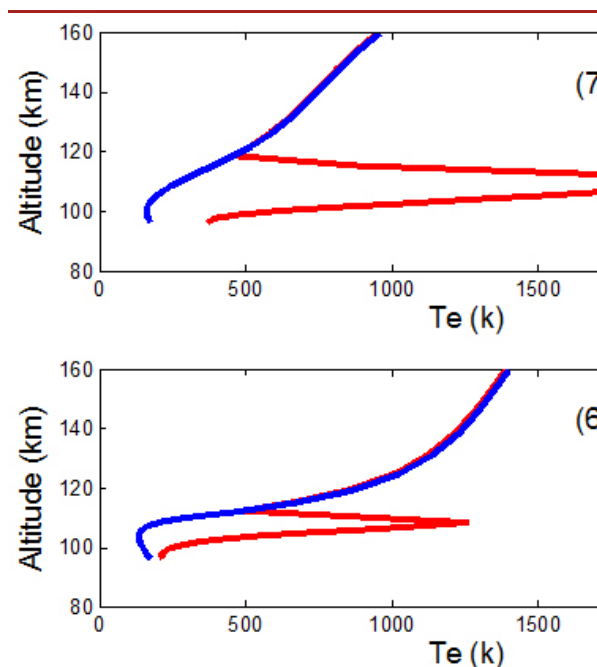


Figure 1. Electron temperature profiles at two high-latitude locations simulated by the TIEGCM. The blue lines are the results from the default TIEGCM run without AEH and the red lines are the results with AEH caused by the F-B instability.



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currents and high-latitude convection pattern. This can further alter Joule heating and ion drag, and the global thermospheric and ionospheric response to major geomagnetic storms.

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This work is supported by the following grants: NASA grants NNX14AI13G and NNX14AE06G.

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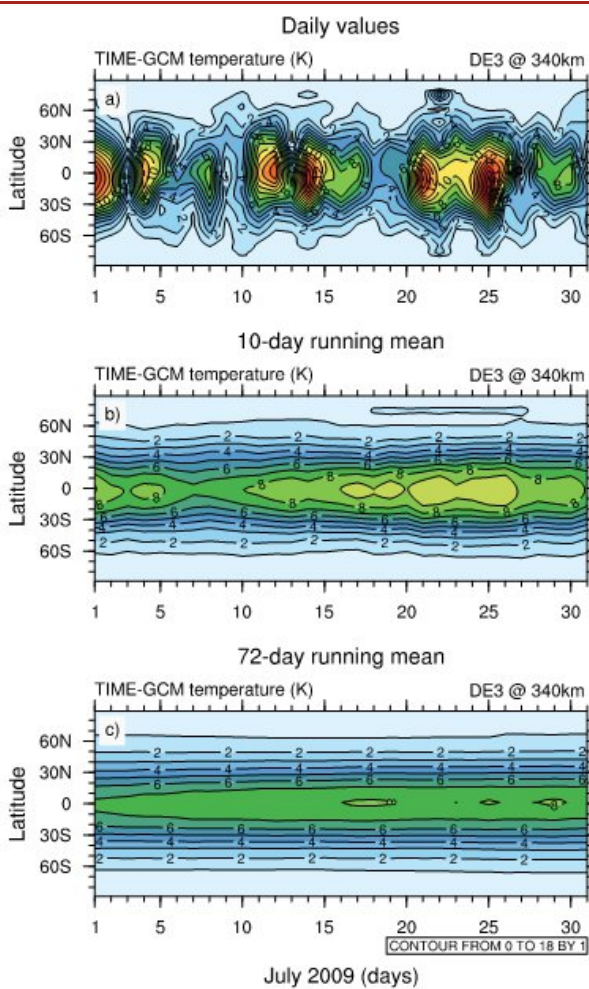
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CHALLENGES IN OBSERVING SHORT-TERM TIDAL VARIABILITY

Modeling the upper levels of the Earth's atmosphere, is one of the strengths of the Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM) supported as a community model by scientists at the High Altitude Observatory.

In order to model the complicated interactions occurring with in this region it is necessary to include forcing from above and below. The forcing from above includes changes in solar activity and dynamics within the magnetosphere. The forcing from below includes impacts from lower atmosphere a major portion of which are communicated via tides. Using the data from Modern-Era Retrospective Analysis for Research and Application (MERRA) HAO scientist Maura Hagan and colleagues including postdoctoral scientist Kathrin Hausler a new method for including these tides was developed for the TIME-GCM. The 3-hour MERRA data inherently includes realistic daily variations both the diurnal and semi-diurnal tidal fields. As the top panel of Figure 1 shows this method allows the model to capture eastward propagating diurnal tide as seen in the peaks of neutral temperature. These features are not as clearly evident in version of the model that utilize climatological tidal data as the lower boundary condition.

Simulations such as these provide a unique opportunity to assess the ability of observing platforms such as the CHAMP and GRACE missions to measure these tidal variations. Since satellite mission like these can only monitor the region of space they are current flying through in order to produce a global picture like that shown in the top panel of Figure 1 they need to produce a climatology by average data over many orbits together. The second panel shows the result of doing this averaging over 10-days. In this panel only a weak trace of the diurnal temperature variation is present. Unfortunately, the produce a global picture the CHAMP and GRACE mission need to average the data over a 72-day interval and the result of doing that averaging on the TIME-GCM simulation results is shown in the bottom panel of Figure 3. As is clearly evident the figure this level of average completely removes the signal of the tidal variations.



The Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM) is a strong method for modeling the upper levels of the Earth's atmosphere.

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IMPACT OF ENERGETIC PARTICLES ON THE UPPER ATMOSPHERE

Energetic particles, namely electrons and protons, released from the magnetosphere cover a wide range of energies from a few electron volts (eV) to hundreds of milli-electron volts (MeV). Precipitating electrons of several kilo electron volts (keV) are deposited in the 90-150 km altitude range, and they are mostly responsible for producing auroras and creating the E-region ionosphere. Though protons with energies less than 30 keV also produce auroral emission at higher altitudes, they contribute less than 20% of the total energy input in the auroral zone. More energetic electrons of a few hundred keV can penetrate to the lower thermosphere and mesosphere. Modeling studies have demonstrated that these energetic particles can significantly enhance the D-region electron density and also alternate the chemical compositions between 70 and 80 km altitudes. Solar energetic protons (SEPs), particularly those with energies > 1 MeV, penetrate even deeper into the atmosphere, and their effects have been seen down to the upper stratosphere. To understand and elucidate the effects of the different energetic particles on the upper atmosphere, the Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIMEGCM), together with observations from the NOAA Polar Orbiting Environment Satellites (POES) and the Geostationary Operational Environmental Satellites (GOES), are used to delineate and understand how the various energetic particles affect the upper atmosphere during the well-known Halloween storm of October 2003.

The SEP effects on the upper atmosphere are illustrated in Figure 1, which shows the difference plots of HOX, NOX and O3 over Eureka in northern Canada and over McMurdo in Antarctic. The differences are between the TIMEGCM runs with and without the GOES-11 SEP data input while auroral precipitation is kept the same and MEPED data are excluded in the two runs. The increase in HOX by SEPs is short lived due to its short lifetime, and is concentrated between 40~60 km in the northern polar region. The vertical distribution of the SEP-produced HOX in the southern polar cap extends to a broader altitude range from 40 km up to 80 km. This hemispheric difference is largely owing to the seasonal difference between the winter northern polar cap and the summer-like southern polar cap. Though the enhanced SEPs last only a few days in duration, their impact on the upper atmosphere can be seen over several months after the storms. Precipitating SEPs cause significant increase in NOX in the altitude range of 35-70 km initially over both polar regions, which then slowly diminish while being transported downward in the northern hemisphere due to mesospheric circulation. By the end of the year, the remnant of increased NOX can still be seen in the upper stratosphere around 35-40 km in the northern

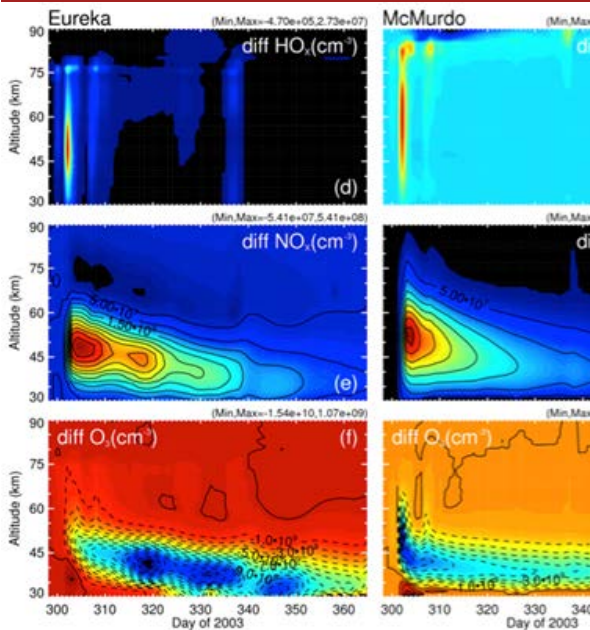


Figure 1: Difference plots between simulations including and excluding SEPs. (left column) Difference HO<sub>x</sub>, NO<sub>x</sub> and O<sub>3</sub> over Eureka in northern Canada and (right column) difference HO<sub>x</sub>, NO<sub>x</sub> and O<sub>3</sub> over McMurdo in Antarctic from 25 October to 31 December 2003. The maximal and minimal values are indicated in the upper right corner of each panel.

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polar cap. The vertical distribution of the difference NOX in the southern polar cap lies about 5 km higher than that in the northern polar cap, and the magnitude of the southern NOX change is also smaller. NOX is one of the most important constituents that catalytically destroy ozone. Indeed, significant O3 reduction is found below 55 km that persists throughout the rest of the year and even into early 2004. The difference O3 by SEPs also displays large hemispheric asymmetry, with the O3 reduction being much larger in the northern polar cap than in the southern polar cap and also the downward transport being more prominent. The hemispheric asymmetry in the NOX and O3 response shown in Figure 1 is a seasonal effect, and has been confirmed by several satellite observations during the same event.

This work was sponsored in part by the Heliophysics Guest Investigators program under NASA grant NNN09AK621, by the Living With a Star program under NASA grant NNX14AE08G, and by the U.S. Participating Investigator (USPI) Program under NASA Grant NNX12AD26G.

Source: Lu, G. (2015), Energetic and Dynamic Coupling of the Magnetosphere-Ionosphere-Thermosphere System, AGU monograph on Magnosphee-Ionosphere Coupling in the Solar System, edited by Rich Chappell, Bob Schunk, Jim Burch, Richard Thorne, and Peter Banks, in press.

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## FINDING A GRAND MINIMUM

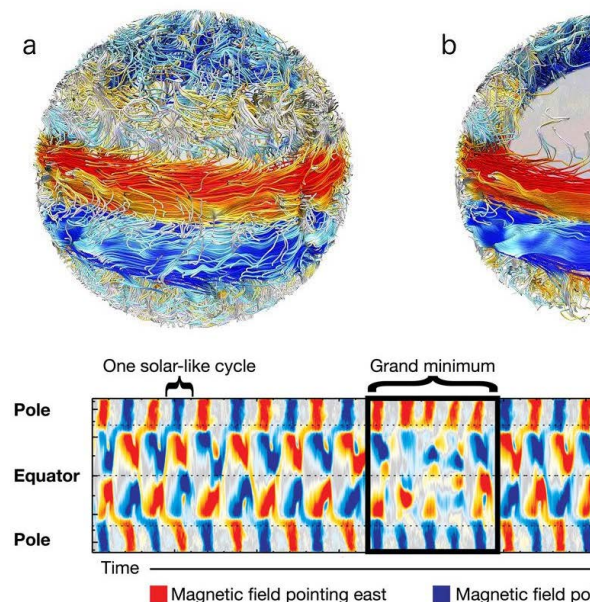
Four hundred years ago astronomers viewed the Sun through a telescope for the first time. Galileo was among this intrepid group but he was probably not the first. They projected the solar disk onto a flat surface to spare their eyes, and what they saw was breathtaking. They did not discover sunspots - Chinese astronomers had known about them for centuries - but they began to glimpse their intricate structure in exquisite detail. The pattern was different every day, as tantalizing new spots continually appeared, morphed, and faded. This was an exciting and momentous time in the history of astronomy.

Then the Sun played a cruel joke. Within forty years of these first telescopic observations, the sunspots vanished. Generations of astronomers approached their telescopes day after day with eager anticipation, only to find a featureless disk. This went on for seventy years. Then, just as mysteriously, the spots came back.

This period of unusually low solar activity from 1645-1715 is now referred to as the Maunder Minimum. Though this was the most extreme manifestation ever witnessed by humans, we now know that the Sun has gone through multiple similar episodes over the last ten thousand years during which there were few, if any, sunspots for decades at a time. We call these Grand Minima to distinguish them from the more typical, temporary dip in the number of sunspots that occurs every 11 years as part of the solar cycle. Grand Minima represent sporadic and unpredictable disruptions of the normal 11-year sunspot cycle.

A team led by HAO scientists Kyle Augustson and Mark Miesch has recently captured a Grand Minimum in an unprecedented computer simulation of the solar dynamo. Others have modeled grand minima before with varying degrees of sophistication, but what sets this simulation apart is its scope. Whereas previous studies have used simplified models guided by solar observations, this simulation solves a fundamental set of three-dimensional equations that more faithfully mimics the intensely turbulent conditions of the solar plasma, independent of any empirical coercion. And, it is the first such simulation to slip into and out of a Grand Minimum.

The solar magnetic field is a delicate balance between order and chaos. The patent order of solar cycle exists amid a chaotic tangle of magnetic fields that permeates the solar surface. This simulation exhibits



Order and chaos in a computer simulation of the solar dynamo. (a) At any instant, the 3D magnetic field lines are tangled and complex, permeating the entire turbulent convection zone. Yet, amid this chaos, opposing wreaths of magnetism straddle the solar equator, as indicated by the colors which represent magnetic field pointing eastward (red) or westward (blue). (b) Cutting away some of the tangled magnetic field lines provides a better look at the magnetic wreaths. (c) As time proceeds, the wreaths migrate toward the equator and then periodically reverse their sign, reminiscent of the solar cycle. Meanwhile, higher-latitude toroidal fields migrate toward the poles. This regular magnetic cycle is suddenly disrupted by a period in which the low-latitude wreaths fail to form and the high-latitude fields fail to reverse. After the disruption, referred to as a grand minimum, the cycle resumes.

Order and chaos in a computer simulation of the solar dynamo.



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a similar tangle but from the chaos emerges striking order; wreaths of magnetism that encircle the Sun, with opposite directions in the northern and southern hemispheres (see Figure).

Though the simulation does not produce sunspots explicitly (this would require more powerful computers), it does capture these magnetic wreaths, which are thought to be sunspot breeding grounds. The wreaths undergo regular magnetic cycles much like the solar cycle, drifting toward the equator at low latitudes and toward the poles at high latitudes. After each cycle, the direction of the wreaths in each hemisphere reverses (from east to west or vice versa), as in the Sun.

The appearance of such regular magnetic cycles in a simulation such as this is remarkable in itself. Even more remarkably, the cycles are interrupted by an extended period in which the generation of low-latitude magnetic wreaths (and by implication, sunspots) is suppressed. This grand minimum spans about five cycles, similar to the Maunder Minimum (see Figure). Then the cycles continue as before.

Researchers will use this and similar computer models to help them understand the origins of the solar cycle and how it changes over the course of decades and centuries. When will the sunspots vanish again? Only time will tell, but supercomputers may give us some clues.

This research was published in the Astrophysical Journal on August 20, 2015 (K. Augustson, A.S. Brun, M.S. Miesch & J. Toomre, 2015, "Grand Minima and Equatorward Propagation in a Cycling Stellar Convective Dynamo", Astrophys. J., vol. 809, no. 149, 22 pp).

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## NUMERICAL SIMULATIONS OF SUNSPOT MOAT FLOWS

Sunspots are the prominent manifestation of solar magnetic activity on the visible solar surface. While the first recorded "naked-eye" observations of sunspots date back to about 325 B.C. it was not until the beginning of the 20th century that the true physical nature of sunspots was revealed in a series of landmark observations. In 1908 George Ellery Hale discovered that sunspots have strong magnetic field (about 3000 G, for comparison the Earth's magnetic field is about 0.5 G). The effect of the strong magnetic field goes beyond a simple suppression of convective energy transport (explaining their dark appearance on the solar surface); it causes in addition large systematic flows within and around sunspots. The most prominent flow was discovered in 1909 by John Evershed within the sunspot penumbra (Evershed flow), later in 1969 it was discovered by Neil Sheeley that sunspots are surrounded by outflows outside the penumbra region that extent to about 2 sunspot radii (moat flows). Whether the moat flow and the Evershed flow are dynamically related and which role they play for the overall structure and stability of sunspots has been an ongoing debate since then.

Numerical sunspot models have been advanced substantially over the past decade and most remarkably, comprehensive sunspot models that self consistently explain the origin of the Evershed flow became available in 2009 exactly 100 years after its discovery. Addressing the Evershed flow—moat flow connection in numerical models is challenging since it requires a combination of all factors that make a numerical model very expensive: high resolution, a large domain size and long simulated time evolution. Recently M. Rempel addressed this challenge through a set of numerical simulations that compare a sunspot (with penumbra and Evershed flow) to a so-called "naked spot" in which penumbra and Evershed flow are absent. Fig 1 shows intensity images for the simulated sunspot and naked spot. White lines indicate smoothed intensity contours that correspond in the case of the sunspot to the approximate boundary of umbra and penumbra (45% and 90% of the average granulation brightness). The corresponding radial flow structure is given in Fig 2.

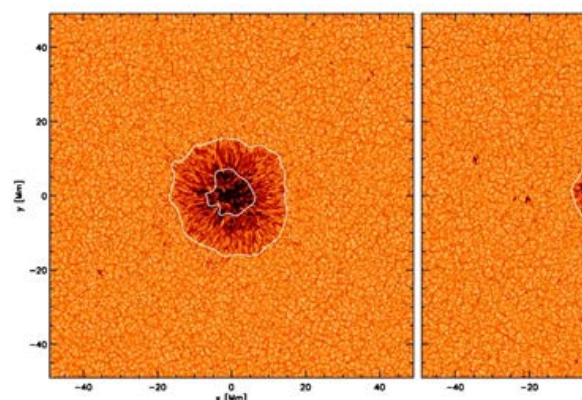


Figure 1: Comparison of sunspot (left) and naked spot (right) through intensity images. White contours indicate the approximate boundary of the umbra and penumbra for the sunspot and equivalent intensity contours for the naked spot. From the sunspot simulations of Rempel 2015.

While the sunspot has a strong Evershed outflow reaching average amplitude of 3-4 km/s, the naked spot has near its outer boundary an inflow of 1-2 km/s. Despite this difference both spots are surrounded by outflows extending on average about 10,000 km beyond the spot boundary. These simulation results strongly suggest that there is no direct dynamical connection between Evershed and moat flow. While the Evershed flow

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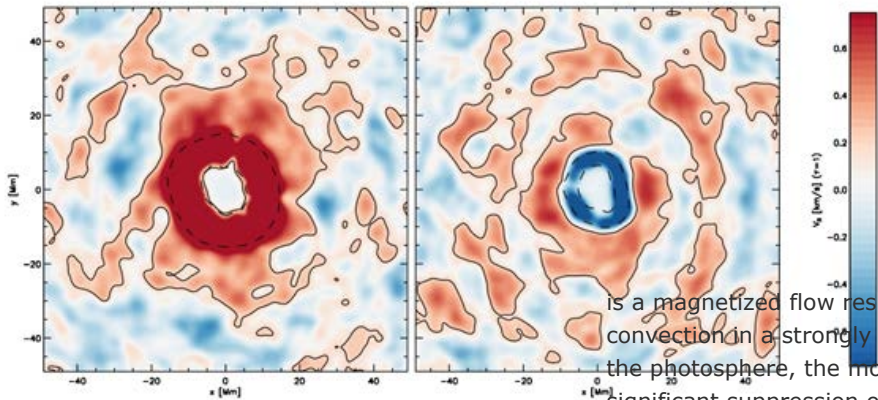


Figure 2: Comparison of large flows in and around the sunspot (left) and naked spot (right) (25 hr averaged in time and spatially smoothed). Positive values (red colors) correspond to outflows. In the photosphere the sunspot shows the strong Evershed outflow in the penumbra, whereas the naked spot shows a strong inflow near its outer boundary. Nonetheless both spots are surrounded by an outflow extending on average 10,000 km past the spot boundary (moat flow). From the sunspot simulations of Rempel 2015.

is a magnetized flow resulting from overturning convection in a strongly inclined magnetic field in the photosphere, the moat flow results from a significant suppression of downflows underneath both spots. The resulting perturbation of the vertical mass flux balance requires a large-scale flow diverting upflowing mass away from the spots. This effect is present (albeit with different amplitude) regardless of whether the spot has penumbra and Evershed flow or not.

This research was partially supported through NASA contracts NNN09AK02I and NNN12CF68C. Computing time was provided by provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation, under project NHAO0002 and from the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center under project s9025.

Publication: Rempel 2015, ApJ in press <http://adsabs.harvard.edu/abs/2015arXiv151101410R>

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THE BEST EVER OBSERVATIONS OF A SOLAR FLARE

The first known record of a solar flare was made by two English observers in 1859. Many people now know that the Sun flares up from time to time, that the flares release a lot of stored energy very quickly (over periods of minutes), in the biggest explosions in the solar system. The energy of a large flare ( $10^{32}$  erg) is equivalent to all the energy in a 10 km radius asteroid, slamming into the earth. Such an asteroid may have finished off the dinosaurs. Most people do not know, however, that physics has yet to provide and answer to the questions of what triggers the sudden release, and of how energy is transported to and from the site of the energy release.

An X-class flare occurred on 29th March 2014. In mid morning, National Solar Observatory's Dunn Solar Telescope observer Mike Bradford and scientists Lucia Kleint (University of Applied Sciences and Arts Northwestern Switzerland) and Alberto Sainz-Dalda (HAO) pointed to a particular region of the Sun. Kleint's real-time adjustments were necessary to obtain unique data sampling the tiny and elusive regions of intense energy release. Kleint and colleagues were observing at visible and infrared wavelengths using two state-of-the-art instruments called spectropolarimeters. The combination of polarimetry and spectroscopy has yielded both answers and more questions.

Perhaps the most remarkable result was presented in a paper in the Astrophysical Journal by Judge (HAO), Kleint, Donea (Monash University), Sainz-Dalda and Fletcher (U. Glasgow). They were able to assess the energy transport through the solar atmosphere. The flare's thermal effects (heating) were seen down to roughly 100 km above the solar visible surface, but no deeper. Yet the analysis by Donea showed that significant mechanical energy had been transported down to generate a "sun-quake." Curiously, the quake's energy is entirely beneath the solar surface. Mechanical energy transported by sound and/or magnetic waves were demonstrably an order of magnitude too small, as measured through the spectroscopic and spectropolarimetric signatures. The null result was entirely unexpected.

The mystery of what transported energy from the overlying corona into the solar interior remains. By augmenting the DST data with data from three spacecraft (SDO, IRIS, RHESSI), Judge and colleagues suggest that, by a process of elimination, protons and perhaps alpha particles carry the energy down, accelerated by electric fields in the corona to roughly one hundred MeV energies. Such energetic particles, although rare, are occasionally going outwards from the Sun into interplanetary space.

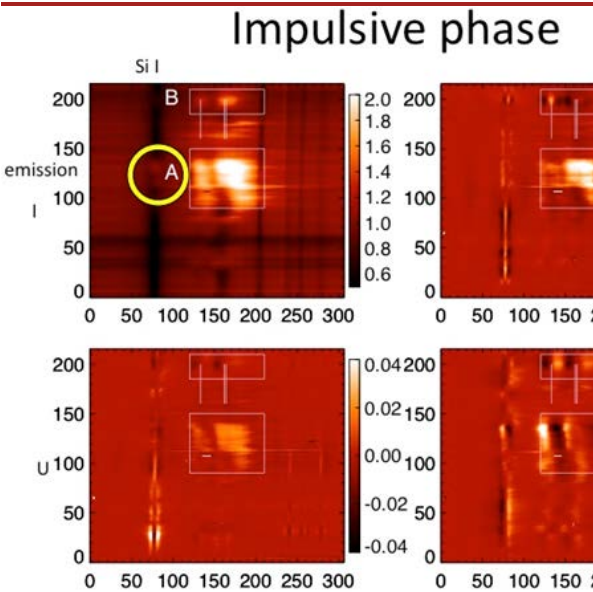


Figure 1: Spectral profiles are shown for a region near 1083 nm wavelength. The top left panel shows brightness as a function of wavelength and position along the solar surface. The flare is seen in the bright patches seen in spectral lines of Helium. The other three panels show light broken into different states of polarization. These data constrain tightly the amount and modes of energy propagating through the solar atmosphere.

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The puzzle of energy transport in flares is not a mere a curiosity. Flares are special because observers on earth have a chance of identifying individual mechanisms in operation, because there is a clear sequence of cause and effect, and it is unlikely that many different mechanisms are happening at the same time. Such conditions are generally not present outside of a flare. Thus by understanding a flare, we will be well on the way to understanding energy transport responsible for energizing the corona, and for causing troublesome "space weather" events at Earth.

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ADVANCES IN CHROMOSPHERE MAGNETISM DIAGNOSTICS

The solar chromosphere is a region of the Sun's atmosphere where the structure and dynamics of the magnetized plasmas undergo dramatic changes. This part of the solar atmosphere spans approximately nine pressure scale heights, and the gas temperature goes through a minimum of only a few thousand K, before suddenly rising to the million K temperatures of the solar corona. Accordingly the plasma conditions in the chromosphere change, over the span of only about 1 Mm, from a gas-pressure dominated regime, marked by the turbulent convective motion observed in the solar photosphere, to a dominance of the magnetic pressure (low plasma- $\beta$  regime), where anisotropic plasma processes are more likely to occur, and where the excitation conditions of the plasma ions significantly depart from local thermodynamic equilibrium. At the same time, the spatial and temporal scales at which plasma processes can be assumed to be stationary shrink dramatically, and the evolution time of the solar chromosphere down to the typical length of the photon mean free path turns out to be just a handful of seconds.

This complex physical scenario poses several big challenges to the observation and the modeling of spectral line diagnostics that are formed in the solar chromosphere. On one hand, the small spatial and temporal evolution scales demand the use of specialized, high-resolution and high-throughput, solar instrumentation (such as the NSF sponsored Daniel K. Inouye Solar Telescope). On the other hand, the 3D distribution of the solar radiation that excites the chromospheric ions becomes increasingly important, as the gas density drops, and the excitation conditions become strongly correlated with the degree of anisotropy of the radiation. As a consequence, the decreasing role of particle collisions in thermalizing the atomic populations allows for exotic quantum effects to become apparent in the spectral and polarization signatures of the solar chromosphere.

One important, but theoretically challenging, aspect of the modeling of chromospheric spectral lines is to account for the increasing temporal coherence between the processes of absorption and re-emission of the solar radiation by the tenuous chromospheric plasma. This condition of partially coherent scattering, which is fostered by the peculiar physical conditions of the solar chromosphere, gives rise to a plethora of phenomena that affect the shape and the polarization of the chromospheric spectral lines (typically dubbed as partial frequency redistribution effects, or PRD), and which need to be taken into account in order to confidently infer the strength and topology of the magnetic fields permeating the solar chromosphere.

At HAO, we recently made good strides in understanding the fundamental physics governing the

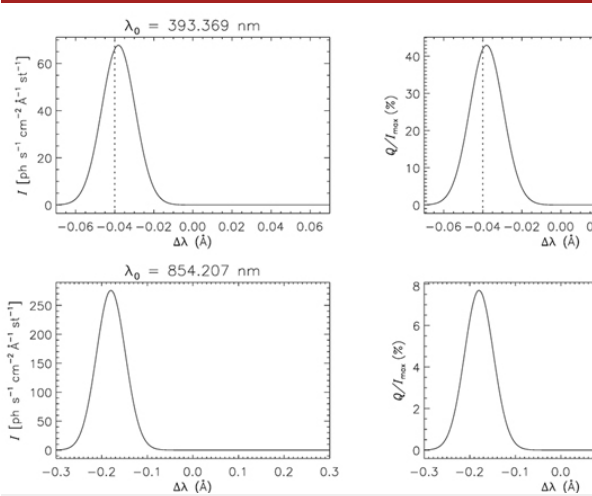


Figure 1: Scattering polarization of the Ca II K line at 854.2 nm (bottom panels) produced in a 3-term atom illuminated by a monochromatic UV radiation nearly resonant with the Ca II K line at 393.4 nm. The top panels show the corresponding resonance radiation of the Ca II 393.4 nm line in this case. The dashed vertical lines in the intensity and polarization plots represent the tuning wavelength of the incident UV radiation. This simulation is for a 90-degree scattering geometry in an optically thin plasma with temperature  $T = 1000$  K and no magnetic field. The intensity is given in units of number of photons per unit of time, emitting surface, wavelength interval, and solid angle.



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mechanism of partially coherent scattering in a magnetized medium, and we have initiated modeling the variety of spectral signatures that are produced in this process. The example shown in the figure is rather academic, but it serves well the purpose of illustrating the type of complex intermixing between fully coherent scattering and complete redistribution of radiation frequency that can happen in the presence of strongly modulated spectral radiation. The model describes the simultaneous formation of the “interlocked” sets of spectral lines of the Ca II ion, known in the solar spectrum as the Ca II H and K (around 395 nm) and the Ca II Infrared triplet (around 857 nm). These lines share the same upper atomic term, and connect it respectively to the Ca II ground state and a different metastable state. The animation in the figure shows the evolution of the intensity and polarization of the Ca II K line (top) and the Ca II IR 854.2 nm line (bottom), when the spectral domain of the former is “scanned” by a wavelength-tunable beam of monochromatic UV radiation. In response to this radiative excitation, one must expect not only the resonant re-emission in the K line, but also the Raman scattering towards the metastable state via the Ca II 854.2 nm line. The most notable result of this modeling is the manifestation of coherence effects in the profiles of the Ca II 854.2 nm line through excitation of the interlocked Ca II K line. In particular, we see how both lines change from a condition of purely coherent (i.e., Rayleigh) scattering, for large values of the de-tuning of the UV input radiation, to one of completely redistributed radiation centered at the resonance wavelength, when the frequency of the input radiation lies in the proximity of the natural frequency of the K line.

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DEVELOPING PREDICTIVE SOLAR CAPABILITIES AND UNDERSTANDING THEIR IMPACTS

One of HAO’s key activities is to develop an understanding of solar phenomena to the point where forecast skill and predictive capability can be realized. We study how a broad range of these phenomena—from electromagnetic radiation that is continuously emitted by the Sun, to the energetic particles in the solar wind, and the large eruptive events like flares and CMEs—impact the Earth. Understanding the state of the solar and terrestrial atmospheres will ultimately allow us to forecast how these “space weather” phenomena impact the Earth and how the Earth responds on scales of minutes to centuries.

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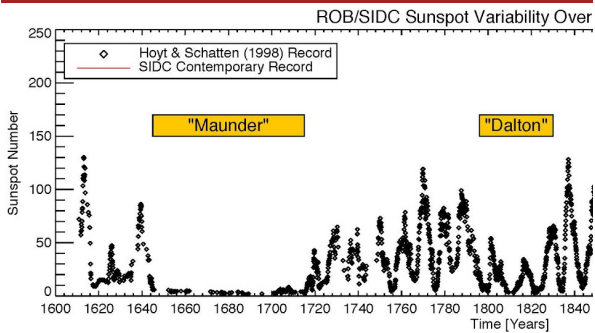
ARE WE HEADING INTO A NEW GRAND MINIMUM?

It is a long-held belief that the regional cooling experienced in northern Europe during the seventeenth century, or “Little Ice Age” as it has been popularized, was directly related to the dearth of spots on the Sun over the same period of time. The 75 year long profound and persistent drop in the number of sunspots is referred to as a “grand minimum” of solar activity, this one was called the “Maunder Minimum” after the famous solar astronomer E. Walter Maunder. For reference, the typical spell of time over which sunspots disappear (in the course of the standard 11-ish year solar activity cycle) is only two or three years. While no records exist of how the Sun’s radiation changed over that period of time, something that does affect atmospheric heating and cooling, the occurrence of sunspot reduction and a prolonged cold snap at the same time, would seem to connect them.

We believe that the drop in spots was the result in of a profound change in the Sun’s magnetic activity [SEE EARLIER ARTICLE ON GRAND MINIMA]. As a result of this drop, there must have been a corresponding reduction in the amount of light that bathes, and warms, the Earth’s atmosphere. While the physical and chemical details remain difficult to nail down for the seventeenth century it would seem possible that the drop in the Sun’s magnetism (and hence its radiation) led to the cooling experienced in Northern Europe.

As you can see from Fig. X there has been a significant drop in the number of sunspots that the Sun is producing currently. The number of spots has gone down by about 25% over each of the last three solar cycles. We have observed a corresponding downward trend in tracers of the Sun’s energetics over the same time: such as the light it produces, the particles it ejects, and even the number of storms that it produces. If these downward trends continue, based on a very simple extrapolation of these numbers, then we would expect that the next solar minimum, starting in 2017 or 2018, should have energetic levels much lower than those of 2008. That may indeed signal that we are on a path to significant prolonged minimum in solar activity and be in a unique position to evaluate the impact that the Sun’s radiation can have on the Earth’s atmosphere as never before. Will it be like the Maunder Minimum? We’ll just have to wait and see.

Scientists at HAO, in collaboration with partners in ACOM and CGD (NCAR’s atmospheric chemistry and climate laboratories, respectively) we are currently running simulations of the downward trend in solar energetics, their downward trend, and the response of the Earth’s atmosphere globally and regionally to that change based on observations that help us to map out decadal, or longer, scale trends in data. We will be able to assess the impact that solar radiation can have on an atmosphere where there is a increasing injection of anthropogenic pollutants. In this sense, our experiment could be seen as a forecast of climatic conditions for the next century.



Variations in total sunspot number over the past 400+ years. In this record we see the prevalent ~11-year quasi-periodicity of the solar cycle in addition to possible, longer period, envelopes of activity. Two of the most prevalent downturns in sunspot activity over this epoch were dubbed the “Maunder” and “Dalton” minima, so-called grand minima. The decline in sunspot activity over the past three decades is clear, but will it continue? Source: WDC-SILSO, Royal Observatory of Belgium, Brussels.

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Want to read more about the Maunder Minimum and Little Ice Age? We suggest that you read the wonderful article written by former HAO scientist John “Jack” Eddy in 1988 “The Maunder Minimum.” [http://tinyurl.com/MaunderMinimum]

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## CLIMATE, SPACE CLIMATE, AND COUPLINGS BETWEEN

The 2015 Advanced Studies Program (ASP) Summer Colloquium brought together students and researchers from across NCAR and its university partners to study the interrelated subjects of earth and space climate, and the response of both to long-term solar variability and climate change.

Since 1966, NCAR's ASP summer colloquium has provided opportunities for graduate students in the atmospheric and related sciences to gather for in-depth study of subjects representing new or rapidly developing areas of research. Such subjects often do not have traditional course material available, and may cross disciplinary boundaries making a comprehensive treatment challenging.

This year's colloquium subject was both timely and cross-disciplinary. Earth climate science is a mature science, with well-developed community models and observations. However, although the effect of long-term solar variability on tropospheric climate is not expected to be large, uncertainties remain in particular regarding sensitivities to short wavelength radiation from the Sun. Space climate (the long-term variability in the earth's space environment and upper atmosphere) is far more sensitive to changes in solar drivers. It is unclear how decadal to centennial changes, both at the sun and in the earth's atmosphere as greenhouse gases increase, will affect technological systems that are increasingly vulnerable to space weather. Finally, the two regimes cannot be considered in isolation, since they are linked through couplings between the earth's upper and lower atmospheres. Progress towards these open questions requires a broad approach that takes into account the entire sun-to-earth system.

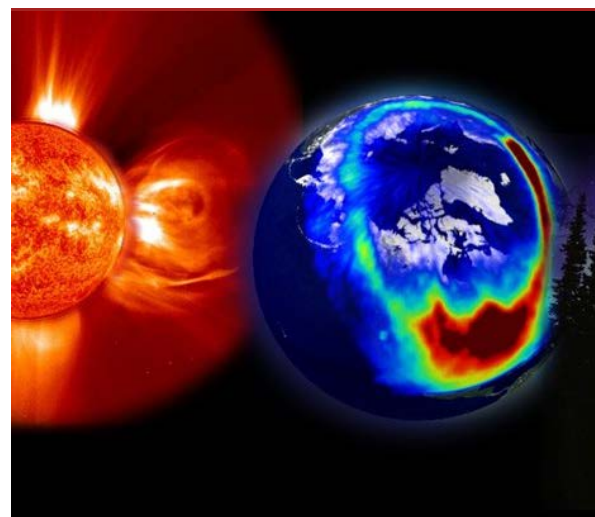


Figure 1. From Sun to Earth, a range of physical processes drive terrestrial and space climate (image credit: NASA).

Working across disciplines can be challenging, not least because of differences in background knowledge and sometimes even familiarity with subject jargon. An overarching goal of the colloquium was to develop a cohort of young researchers with sufficient basic knowledge of each other's field—framed in the context of their own field—to facilitate communication and collaboration across disciplines in future. The 23 graduate students participating in the program came from either Atmospheric Sciences or Solar and Space Physics departments. The lecturers and organizers likewise included representation from both scientific disciplines and included members of all three HAO sections, four NCAR labs, and 12





Figure 2. ASP colloquium students on field trip to RAF (image from Scott Briggs—maybe check with him about any issues regarding its use).

universities.

The program was structured to first lay a foundation of shared knowledge through subject tutorials and labs, to next build understanding of connections between the fields through synthesis and current research talks, and finally, to provide hands-on experience working as teams to interpret climate simulations, whole atmospheric models, and solar cycle proxy databases.

The students were enthusiastic participants in the program throughout, and finished the two-week program with presentations by four cross-disciplinary teams. The scope of these presentations was impressive, and it is clear that the students made connections—both scientific and personal—that will enable their future contributions to solving pressing problems requiring a sun to earth approach. The benefits of cross-disciplinary interaction was not limited to the students: in the words of one lecturer, “I learned a lot about research fields that I sit on the fringes of, and departed feeling very positive about the possibilities for the future.”

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COMMUNITY MODELING AND DIAGNOSTIC TOOL DEVELOPMENT

One of the cornerstones of HAO’s activities lies in the development and support for a series of numerical models that are freely available to the broad research community. Among the models supported are the Thermosphere-Ionosphere-Electrodynamic General Circulation Model (TIE-GCM), the Coupled Magnetosphere Ionosphere Thermosphere Model (CMIT), and the Extended Whole Atmosphere Community Climate Model (WACCM-X). HAO’s staff support these models and welcome the community to collaborate on research projects, participate in development, or use them in independent research

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DEVELOPMENT OF IONOSPHERIC MODULES FOR WACCM-X

It has been increasingly recognized that the space environment is affected by solar and magnetospheric forcing from above, and dynamical and transport processes from below. The NCAR Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X) is an integrated model system that extends from the Earth surface to the upper thermosphere, and has been developed in close collaboration with colleagues at ACOM and CGD to investigate causes of space environment variability on weather and climate scales as related to these two types of forcing. In the past year, an ionospheric electrodynamics module and an O+ transport module have been developed and implemented as interactive components of WACCM-X. The electrodynamics module solves the global electric potential in geomagnetic coordinates to generate electric fields responsible for low to middle latitude ionospheric structure. The O+ transport module was ported from TIE-GCM and calculates the transport due to ExB drifts, field-aligned advection and ambipolar diffusion. With these modules, WACCM-X now produces zonal and vertical ExB drifts and equatorial ionization anomaly (EIA) that are in general agreement with climatology (Figure 1).

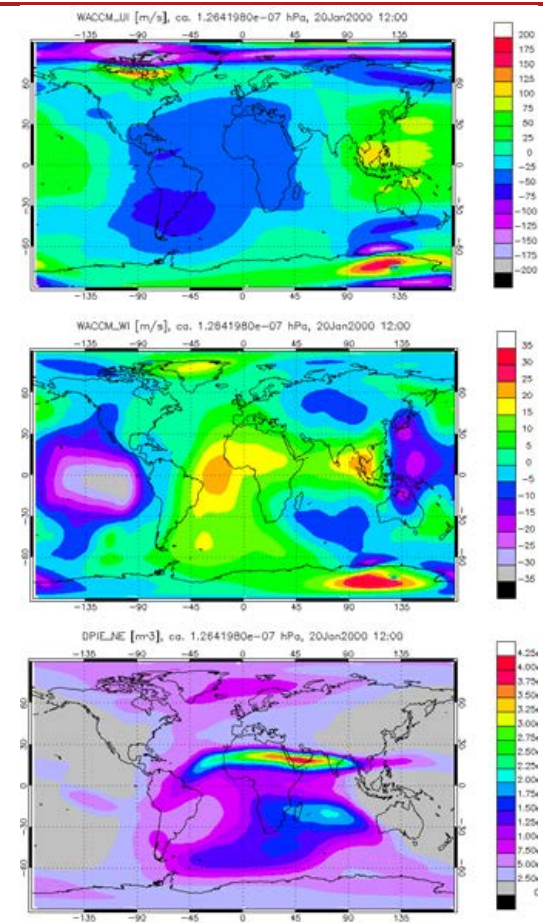


Figure 1: Zonal (upper panel) and vertical (middle panel) components of ExB drifts, and electron density (lower panel) at ~320km from WACCM-X simulations under solar maximum conditions.

This development was supported by NSF AGS-1138784, NASA LWS NNX09AJ83G and base fund.

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## OBSERVATIONAL FACILITIES AND DATA SERVICE

Observations and observationally driven science are central to the vision and mission of HAO, as is the delivery and utility of products from those observations. To this end, HAO maintains the Mauna Loa Solar Observatory (MLSO) on Hawaii and a network of Fabry-Perot Interferometers (FPI), which provide daily information on the state of the solar atmosphere and Earth’s upper atmosphere, respectively.

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RESEARCH TO APPLICATIONS

It is part of HAO’s mission to foster and transfer scientific knowledge and technology resulting from its fundamental research to benefit society and humanity. HAO will continue to collaborate with university partners, other research and government organizations, and private sectors to further space weather model development.

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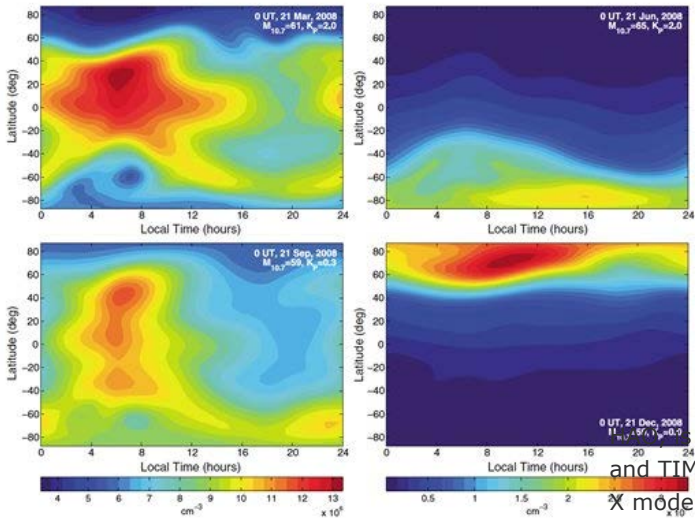
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Global distribution of helium number densities at 250 km altitude during each season for solar minimum conditions (2008), as calculated by TIE-GCM. (left) Equinox plots share a common color scale, as do (right) solstice plots.

Pilinski, M. D., and G. Crowley (2015), Seasonal variability in global eddy diffusion and the effect on neutral density, J. Geophys. Res. Space Physics, 120, 3097, doi:10.1002/2015JA021084.

Sutton, E. K., J. P. Thayer, W. Wang, S. C. Solomon, X. Liu, and B. T. Foster (2015), A self-consistent model of helium in the thermosphere, J. Geophys. Res. Space Physics, 120, 6884, doi:10.1002/2015JA021223.

now a standard part of both the TIE-GCM and TIME-GCM, and is being added to the WACCM-X model.

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EDUCATION AND OUTREACH

Education and pro-diversity activities are vital to the future of our community. HAO is committed to developing and using existing engagement opportunities to foster STEM (Science Technology Engineering and Mathematics) awareness and to cultivate greater "diversity of thought" in the general public when it comes to the Sun and its interaction with our planet.

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## HAO VISITOR HIDEYUKI HOTTA

HAO has a long and proud tradition of sponsoring a very active visitor program which brings collaborators from all over the world to HAO to work on scientifically pressing issues. Following is a highlight from Fiscal Year 2015.



Hideyuki Hotta has been a frequent visitor to HAO since 2010. While working on his PhD under supervision of T. Yokoyama at the University of Tokyo he visited HAO in 2010, 2011, and 2012 in order to work on thesis projects with M. Rempel. During this time he also started working on the Reduced Speed of Sound Technique (RSST) and its application to stellar convection and dynamo problems. Typically low Mach number stellar convection problems are simulated using the anelastic approximation, which filters out sound

waves. Hideyuki's approach keeps the sound waves, but artificially reduces their propagation speed in the deep interior in order to minimize the computational expense. The approach remains fully explicit and allows for excellent scaling on large super computers. Furthermore, the approach remains fully compressible and can be also applied to the near surface layers of the Sun. As part of his PhD Hideyuki implemented this approach in a new global MHD code, AMaTeRAS, which has been used for the highest resolution global convection and dynamo simulations of the solar convection zone to date. After his PhD Hideyuki received a prestigious fellowship from the Japan Society for the Promotion of Science (JSPS) and came to HAO as a postdoc from April 2014 to August 2015. During this time he used his AMaTeRAS on Yellowstone and the Japanese K- Computer in order to investigate the role of efficient small-scale dynamos on the structure of convection and the operation of large-scale dynamos. Hideyuki returned to Japan, where he holds a tenure-track faculty position at Chiba University since September 2015.

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ASTEROSEISMIC RESEARCH SUPPORTED BY A EUROPEAN IRSES GRANT

On March 7, 2009, NASA launched the Kepler spacecraft to search for rocky Earth-like planets—so-called exoplanets—around other stars like the Sun in the habitable zone. In the intervening years, Kepler has detected around 1030 confirmed exoplanets out of nearly 4700 planet candidates still under study. Kepler detects planets by staring at stars in a fixed patch of sky in the constellations of Cygnus and Lyra and seeing when stars appear to dim because a planet transits in front of them. Before launch, scientists realized that Kepler would also provide a rich data stream for asteroseismic research, i.e., the study of the rich oscillations of stars to probe their interiors.

Since 2011 an International Research Staff Exchange Scheme (IRSES) grant from the European Commission FP7 program has funded 13 visitors to HAO of 7 different nationalities working at 5 different European institutions, in Portugal, France, Spain, Denmark and Poland. The typical length of the visits was one month but some of them extended up to 6 months to collaborate with HAO scientists on asteroseismology and helioseismology projects. This collaboration was very fruitful and a long list of publications and new collaborations are the most visible consequences.

Most of these studies have been driven by the improvement of our knowledge of the dynamical aspects (rotation and magnetic field) of stars and the Sun. Just two examples of results from these collaborations must suffice here. They illustrate the feedback of stellar studies on our understanding of the Sun.

Studying stars that are “solar analogs”—stars that from their observed properties are very similar to the Sun—is very useful for investigating whether or not our nearest star is typical or anomalous. A paper entitled “Photometric and chromospheric magnetic activity of seismic solar analogs” (by David Salabert and co-authors, in preparation) takes the best sample of solar analogs (from asteroseismic and spectroscopic inferences) and studies their activity from the photosphere and chromosphere. The question addressed is: Is the Sun a standard star from the point of view of its surface activity. The researchers conclude that the Sun is a perfect standard star from the surface activity when compared to other pulsating solar analogs. In most of the stars, the levels of activity are well inside the limits of the solar activity exhibited over the solar cycle.

A second example of the research supported by IRSES collaborative exchange visits tests gyro-chronology: the estimation of ages of stars from observing how fast they rotate. This field of study can be traced to pioneering work in the early 1970s by HAO scientist emeritus Andy Skumanich, who found that the rotation rate of a sample of stars decreased as the age of the star to the power of minus half. The fact that stars rotate more slowly as they get older can be understood physically as the effect of stellar winds, which through the medium of magnetic fields take angular momentum away from the star. An earlier Kepler-based study of rotation in stars (García et al. 2014) confirmed the Skumanich result and models used in gyro-chronology. However, in a recent accepted paper (by Jennifer L. van Saders and co-authors), the researchers have looked at the rotation of 25 field stars (i.e., stars not located in stellar clusters) observed by Kepler, including confirmed planet host stars as well as star older than the Sun. They found that the rotation rate for stars of roughly the Sun’s age or older are faster than expected from gyro-chronology models and they explained it as a reduction of the efficiency in the winds when the star reaches a given critical Rosby number (a ratio of rotation period to convective turnover time in the star).

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## HAO-CU BOLD SUMMER INTERNS

In 2015 HAO celebrated its fourth year of partnership with the University of Colorado's School of Engineering and Applied Science BOLD (Broadening Opportunity through Leadership and Diversity) Center to provide summer internships to under-represented student populations within engineering. During the 10-week engineering internship with HAO's Instrumentation Group students were matched with one or more projects in their chosen discipline: electrical engineering, optical engineering, mechanical engineering or software engineering.

This year HAO hosted with three interns. At the beginning of the internship the students attended a Critical Design Review (CDR) meeting for ViSP. This opportunity was timely, allowing students to see the engineering design process in action. The interns found it really fascinating to see all of the collaboration between different engineers and scientists to put together an instrument with a very specific purpose and with a very specific budget. The summer internship teaches not only hands-on engineering skills, but also the organization and teamwork it takes to build a major instrument.

Under the guidance of HAO mentors, interns each developed hardware or software components of the ViSP, including a mounting cell for lenses, and software interfaces (GUIs) for controlling mechanisms in the ViSP instrument. The students also designed hardware and software components for the world's largest solar telescope, DKIST, which is under construction in Hawaii.

In addition the interns had bi-weekly instruction in a variety of skills from business communication - learning compose an elevator speech to describe what they do, to writing cover letters and resumes. The interns were also given some training around communicating science as it relates to engineering. At the end of the summer each student presented a scientific talk to HAO staff.

The hard work and dedication of both interns and mentors lead to another successful summer program. HAO administrator, Megan Delaney, also deserves praise for her behind-the-scenes work that ensured success of the funding as well as an easy transition for the interns coming to HAO.

Two statements from a post internship survey conducted by the UCAR Center for Science Education that hit home for HAO organizers were: "I found out that I love engineering," said one intern, and "it (the program) keeps me motivated to do well in school, so I can get a great engineering job in the future." This is exactly what we want to hear! The next intern cohort competition will begin in early Spring, 2016.

This activity is supported by a combination of HAO and NCAR Diversity funds; both under NSF M0856145.



Figure 1: 2015 HAO-BOLD Interns (left to right) Anthony Anglin, Isis Peguero and Alan Sanchez.



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MMM DIRECTOR'S MESSAGE

Greetings and welcome to the 2015 MMM Annual Report. Early in FY2015, the decision was made to dissolve the NCAR Earth System Laboratory into its three constituent divisions, each of which became a new laboratory. The MMM Laboratory became official on March 1, 2015. On this date, I became the new MMM Director. It is an exciting time to be leading this vibrant laboratory of creative and dedicated researchers seeking "to advance the understanding of the meso- and microscale aspects of weather and climate, and to apply this knowledge to benefit society" (MMM strategic plan). The MMM plan aligns well with the Imperatives and Grand Challenges within the new NCAR Strategic Plan, as well as the strategic priorities of "Dynamic Earth", a vision for geosciences at NSF.



Christopher Davis  
NCAR Associate Director, MMM

The notion of 'community' is integrated throughout the fabric of MMM. This reflects not only the emphasis on community facilities (modeling and data assimilation tools), but also the role MMM staff fill in the NCAR community, and the collaborative and mentoring roles of MMM staff in the broad research community. In keeping with this theme, the slogan on our web page now reads, "weather \* research \* community." In recognition of the desire to involve community members in the strategic decisions about MMM's future, I formed an advisory panel of eight members: Greg Hakim (chair, University of Washington), Ann Bostrom (University of Washington), John Finnigan (CSIRO), Marika Holland (NCAR CGD), Greg McFarquhar (University of Illinois), Ruby Leung (Pacific Northwest National Laboratories), Dave Stensrud (Penn State University), and Jeff Whitaker (NOAA ESRL). This panel met with MMM leadership in May to learn more about MMM and engage with a broad cross section of the laboratory about future directions for MMM.

There were several major research accomplishments in MMM in 2015 that align with the NCAR Grand Challenges. The first was the successful demonstrations of new approaches to the prediction of high-impact weather. These consisted of a convective scale WRF ensemble system and its innovative ensemble based diagnostics for convective scales. The system utilized the Data Assimilation Research Testbed through a collaboration with CISL, and was a highlight of the cross-laboratory Short-Term Explicit Forecast Program (STEP). A second demonstration utilized convection resolving, variable resolution global forecasts provided by the Model for the Prediction Across Scales (MPAS). Through collaborations with NOAA and the University of Oklahoma, the predictability of severe weather out to 5 days was examined. In July, 2015, MPAS was also selected as a finalist for the Next generation Global Prediction System of NOAA.

MMM scientists made significant strides in understanding the coupling of turbulent motions with various surface conditions including ocean waves, canopies and wild fires. The linkage between mesoscale and



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turbulent motions was also explored through large-domain large-eddy simulations within upper ocean fronts, and within the eye-wall of a hurricane. In a step toward developing physical parameterizations that perform well across a range of scales, new representations of cloud physical processes have been developed that are appropriate for large-scale and also convective scale simulations.

As part of an NCAR initiative, MMM became the host laboratory for the new Data Assimilation Program, the goals of which are to conduct fundamental research on data assimilation methods, construct a data assimilation infrastructure for broad community use, and to train the next generation of researchers in advanced data assimilation techniques. The NCAR DA program is fundamentally a cross-laboratory initiative involving every NCAR lab. An initial action decided this year was to support four co-sponsored postdocs across NCAR in FY2016 who will be working with other NCAR data assimilation staff on various components of the overarching system while at the same time satisfying targeted data assimilation needs within labs.

MMM also continued its strong interactions with the research community by hosting workshops such as those for the Geophysical Turbulence Program and the Engineering for Climate Extremes Partnership, as well as tutorials for WRF, MPAS, regional climate and WRF-Data Assimilation. MMM also released a comprehensive community data set devoted to climate downscaling from the Community Climate System Model to WRF.

I invite you to read more details about our recent accomplishments in the following pages.

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Scientists in MMM engage the science of hazard prediction at the basic process level, taking full advantage of new modeling and observational capabilities to understand mechanisms responsible for weather-related hazards including hurricanes, severe convection, and air quality. Hazard prediction work in MMM also includes the research about the impacts of hazardous weather on society and research on strategies for effective communication of hazard information. On longer time scales, regional climate research seeks to identify pathways of improved prediction of the statistics of hazards, especially in a changing climate. The efforts in this area involve the coupling of atmospheric science with social science, mathematics and engineering to achieve progress.



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HURRICANE PREDICTION

The first real-time forecasts using the Model for Prediction Across Scales (MPAS) were conducted in 2013 and focused on tropical cyclones across the Northern Hemisphere. A distinguishing character of MPAS is its variable horizontal resolution and smoothly adapting mesh structure that allows regional resolution refinement. The physical parameterizations and numerical algorithms in MPAS are somewhat similar to those in the Advanced Research Weather Research and Forecast (WRF) model. MPAS is used for (1) predictions involving many scales of motion with clear societal relevance such as tropical cyclones and their global connections; and (2) exploration of practical predictability beyond roughly three to four days, i.e., the effective limit of utility for limited-area models. MPAS has the potential to expand the ability of the research community to conduct fine-scale modeling of moist convection on the globe, and atmospheric motions on scales from regional (e.g., severe thunderstorms and hurricanes) to global (e.g., the Madden-Julian Oscillation). In addition, MPAS offers the capability of providing greater lead time in tropical cyclone forecasts than can currently be achieved using regional models.

In FY 2015, forecasts were conducted with MPAS using both a uniform resolution and variable resolution for tropical cyclones during the period August 1 to November 3, 2014. The variable resolution was chosen to be finest over the Eastern Pacific basin because of the much greater amount of tropical cyclone activity – including both weak and intense storms – in that basin as compared to the Atlantic. MMM staff developed software to identify and track tropical cyclones in MPAS and a new verification method was developed to account for false alarms and missed events. This new method was needed because standard hurricane evaluation methods assume that the storm is present at the start of the forecast.

It was found that the variable and uniform-resolution MPAS produce similar skill in predicting tropical cyclones over the eastern Pacific in 2014. This was likely due to the relatively slow growth of differences between variable and uniform-resolution MPAS over the tropical eastern Pacific, shown in the figure below. The tropical cyclone environment in both configurations was similar for 6-7 days, and this allowed similar development and movement of the TCs in both configurations.

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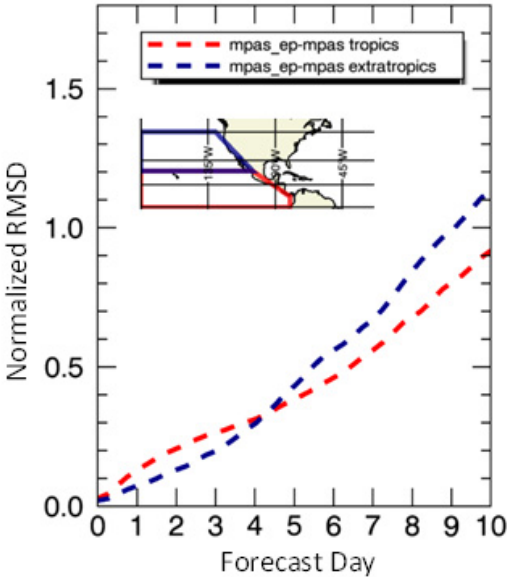


Figure: Root mean squared differences between variable and uniform resolution MPAS in the tropics (red) and extratropics (blue). Differences are normalized by the average spatial standard deviation in their respective regions. The plot shows that, where the resolution of the two configurations is similar, differences grow more slowly in the tropics between days 2 and 7 than differences in mid-latitudes.

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COMMUNICATING WEATHER- AND CLIMATE-RELATED RISK FOR USE IN DECISIONS

To enhance the use and value of weather-related information, MMM scientists conduct research to understand and improve the communication, interpretation, and use of weather forecasts and warnings, as well as how information about weather is used in the context of climate variability and change. In FY 2015, this research included investigations of how weather and climate risks are communicated, interpreted by various groups, and used in decisions. It also included building understanding of the public's perceptions of weather-related risks, underlying vulnerabilities, and other contextual factors that influence weather and climate decision-making. The research applies social science concepts and methods to atmospheric science issues, facilitating interdisciplinary work within the broader community.

Scientists continued investigating how different members of the U.S. public perceive, interpret, and anticipate responding to different test hurricane forecast and warning messages. Using analysis of data from a survey of residents of coastal south Florida areas that are at high risk from storm surge, they found that recipients of test messages about storm surge height and extreme impacts from storm surge had higher evacuation intentions, compared to non-recipients (see figure below). However, recipients of the extreme-impacts message also rated the information as more overblown and the information source as less reliable. These and other findings from the survey illustrate the importance of considering unintended effects and different audiences when deciding how to convey weather information (Morss et al. 2015, WAF). In collaboration with researchers at Rutgers, MMM scientists helped design and implement a survey testing hurricane risk messages in coastal zones in the northeastern U.S. after Superstorm Sandy, and began analyzing the data.

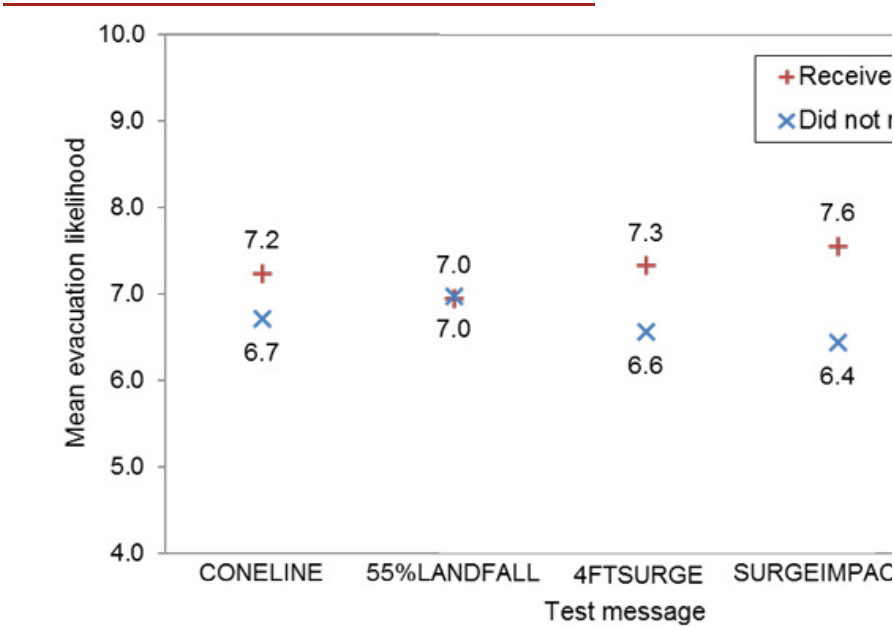


Figure: Comparison of mean evacuation likelihood between respondents who did receive and those who did not receive each of the five hurricane warnings messages tested in the survey. Evacuation

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intentions were significantly higher for respondents who received the 4FTSURGE message (“There will be storm surge of 4 feet or higher along coastal areas, reaching as much as a mile or more inland.”;  $p=.03$ ) or the SURGEIMPACTS message (“This storm surge will be extremely violent, destructive, and deadly. If you live in an area at risk from storm surge and you stay in the area, you may die. Essential services such as food and water, electricity, transportation, communication, etc. may not be available for several weeks or longer.”;  $p=.002$ ). (Morss et al., 2015 *Wea. Forecasting*)

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In an effort to evaluate different measures of people’s past tornado experience and investigate the relationship between people’s hazard experiences and their perceptions of hazard risks, MMM scientists completed the design and implementation of a survey of members of the public who reside in the tornado-prone central U.S. These data, along with those from an earlier survey, were used to identify dimensions of respondents’ most memorable and multiple tornado experiences, and explore the link between different aspects of people’s tornado experiences and their tornado risk perceptions (Demuth, 2015, PhD dissertation).

Other work focused on building culturally and decision-relevant understandings of drought risk, including developing interdisciplinary approaches for combining physical and social data about drought impacts, by analysis of stakeholder interviews, observational and climate model data from the Arbuckle-Simpson region of Oklahoma. The analyses find that drought risk perceptions are complex and often conflicting. Although community members largely agree that water management is important, they disagree about who has authority to enact management measures (Lazrus, 2015, *Human Ecology*). The research also examines how risk perceptions of drought can have implications for water management (Towler et al., 2015, *Climatic Change*). Work was continued to develop and report on the interdisciplinary framework for linking knowledge about locally significant drought impacts and risk perceptions with advances in climate research to enhance drought risk information and decision making.

NCAR scientists also advanced understanding of how people interpret and respond to information about approaching hazardous weather risks in the context of the modern information environment, using multiple research methods. As part of this effort, MMM scientists examined storm surge predictability across multiple time scales by conducting experiments using the Advanced Circulation (ADCIRC) model driven by perturbations of hurricane best track observations. With collaborators at Arizona State University, they completed development of version 1 of a spatially-explicit agent-based model (ABM) of how forecasts and other information about approaching hurricane risks propagate through networks of social actors and influence protective decision making. They also began using the model as a virtual laboratory to explore how changes in hurricane forecast information and in the information environment may affect patterns of protective decisions. With collaborators at University of Colorado, they continued analysis of Twitter data collected during Hurricane Sandy. This included development of a coding scheme for examining weather-risk-communication concepts (sentiment, information-seeking and sharing, preparatory actions, etc.) in the Sandy Twitter data and beginning to apply the coding scheme to analyze how people’s perceptions of and responses to risk evolve as a hurricane approaches and arrives. In addition, scientists identified neighborhoods in New York City that were significantly affected by Hurricane Sandy in 2012, are home to more vulnerable populations, and had fewer geolocated users in the Sandy Twitter data, and then designed and organized focus groups to examine hurricane risk communication among these populations.

This work advances knowledge of how weather-related information is communicated, interpreted, and used in decision making, and of how weather-related experiences, cultural worldview, and other factors influence people’s perceptions of and responses to weather and climate risks. Through collaborations with NOAA and other stakeholders, NCAR scientists are working to utilize this knowledge in ways that improve usability of weather and climate risk information and enhance its societal value.



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## CLOUDS AND PRECIPITATION

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MMM scientists organized a group of university investigators in the United States and abroad to study the role of dust in ice production in clouds. The experiment, called the Ice in Clouds Experiment- Dust (ICE-D), is a successor to two earlier ICE field programs. Dust is considered to be a primary ice nucleus in clouds globally; its activity has been studied primarily in the laboratory but only cursorily in natural clouds. Additional study of the natural ice production process is central to understanding the glaciation process in convective clouds. In FY2015, scientists in MMM's Physical Meteorology Section and an NCAR Affiliate Scientist, participated in the ICE-D field program, based out of Cape Verde Africa, with a group of British investigators. The UK Met Office BAE146 flew research missions into often dust-laden clouds off the west coast of Africa. Researchers will draw upon the British dataset to build a large dataset to study the effects of dust for climate modeling studies for many years to come. In collaboration with the UK ICE-T team, MMM scientists and affiliates have already begun to characterize the microphysical processes that occur in dust-laden versus no-dust conditions. These data will form the foundation for characterizing the role of dust microphysical processes in climate models. The NCAR ICE-D efforts will improve prediction of ice production and glaciation in clouds globally and will provide reference data to improve weather and climate model simulations of the effects of dust on droplet and ice-particle nucleation.



Andy Heymsfield climbing on board the UK Met Office BAE146 research aircraft during the Ice in Clouds Experiment-Dust (ICE-D) based out of Cape Verde, Africa in August 2015. The picture was taken by Jacob Fugal of Germany, a participant in the field program.

Working together with scientists in RAL, MMM is completing simulations of a squall line event on May 20, 2011 during the Mid-latitude Continental Convective Clouds Experiment (MC3E), using three different state-of-the-art bin (spectral) microphysics schemes coupled with the WRF model in a three-dimensional framework. The goal of this effort is to identify and document key microphysical processes that influence

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the structure of a squall line, especially the stratiform region and evolution, through model/observation comparisons. The well-defined squall line that developed on May 20 was sampled by the Citation Aircraft during a GPM-sponsored field program in which MMM scientists participated. They have now thoroughly analyzed the thermodynamic and microphysical data from the aircraft in-situ observations to evaluate model output from just above to just below the melting layer. These data are being used to evaluate the microphysics and dynamics predicted using the different microphysics schemes. It is anticipated that this work will lead to improvements in the representation of ice microphysics—and the resulting predictions of squall line dynamics, in the WRF model.

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BOUNDARY-LAYER TURBULENCE AND SURFACE EXCHANGE

Atmospheric boundary layers (ABLs) and, more fundamentally, boundary-layer turbulence, are essential components of weather and climate. They regulate crucial fluxes of momentum, heat, and scalars between the atmosphere and land surfaces, the cloudy atmosphere and ocean, and at stably stratified interfaces separating more turbulent boundary layers from the overlying, less turbulent troposphere. NCAR’s boundary-layer turbulence research continues to emphasize an increased understanding of the coupling between three-dimensional, high-Reynolds-number turbulence and a variety of physical processes with a goal of improved parameterization.

MMM scientists analyzed momentum and scalar transport in the marine atmospheric boundary layer using a newly developed large-eddy simulation (LES) model (Sullivan et al., 2014, *J. Atmos. Sci.*). The LES model allows a broadband spectrum of time-varying finite-amplitude surface waves to be imposed at its lower boundary. Weakly-unstable boundary-layers are simulated with geostrophic winds increasing from 5- to 25-m/s with wave age varying from swell dominated to wind-wave equilibrium. The simulations illustrate cross-scale coupling as wave-impacted, near-surface turbulence transitions into shear-convective rolls with increasing distance from the water. In a regime with swell, low winds, and weak heating, wave-induced vertical velocity and pressure signals are readily observed well above the standard 10-m reference height. At wind-wave equilibrium, the small-scale wave-induced signals are detectable only near the water surface. The LES wind profiles deviate from Monin-Obukhov similarity theory in non-equilibrium wind-wave conditions, and entrainment is greatly enhanced by shear-induced engulfment events. A 3D animation illustrating the effect of fast moving swell on boundary layer winds can be found at <https://www2.ucar.edu/atmosnews/perspective/17759/looking-swells-3d>.

Over the past year, NCAR scientists also analyzed 28 large-eddy simulations of turbulent flow over water waves propagating in directions different from the wind direction with the objective of determining wind speeds for offshore wind energy applications. The analysis suggests that in the presence of fast-moving swell the atmospheric boundary layer grows more rapidly when waves propagate opposite to the winds compared to when winds and waves are aligned. Pressure drag increases by nearly a factor of two relative to the turbulent stress for the extreme case where waves propagate at 180-degrees compared to the pressure gradient forcing. Net wind speed reduces by nearly 15% at a height typical of a wind turbine for the 180-degree case compared to the 0-degree case, and turbulence intensities increase by nearly a factor of two. These impacts diminish as the winds and waves approach an equilibrium state. A parameterization incorporating these influences has been implemented in the WRF model.

MMM scientists also continued to analyze the coupling between canopy and ABL turbulence using five state-of-the-art large-eddy simulations. Their analysis suggests that the large eddies in the ABL impose their signature at canopy top creating regions where high-momentum fluid is brought down to canopy top at scales tied to the ABL-depth; this modifies the horizontal distribution of vertical shear and places controls on momentum and scalar exchange between the canopy layers and the overlying ABL (see figure). Analysis further shows that the momentum and scalar length scales in the vicinity of the canopy respond to changes in atmospheric stability and the organized ABL-scale motions. Because leaves respond relatively rapidly, organized ABL-scale structures also interact with plant physiology to generate spatially varying leaf temperatures and scalar sources. The analysis confirms the hypothesis that changes in ABL-scale organized turbulent motions across stability variations from near-neutral to free convection significantly alter turbulent exchange at the canopy-atmosphere interface (Patton et al., 2015, *J. Atmos. Sci.*). The following figure shows that organized boundary-layer scale motions (which evolve with

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atmospheric stability: rolls for near neutral stability, left; and, convective cells for highly unstable conditions, right) control momentum and heat transfer between the canopy layers and aloft.

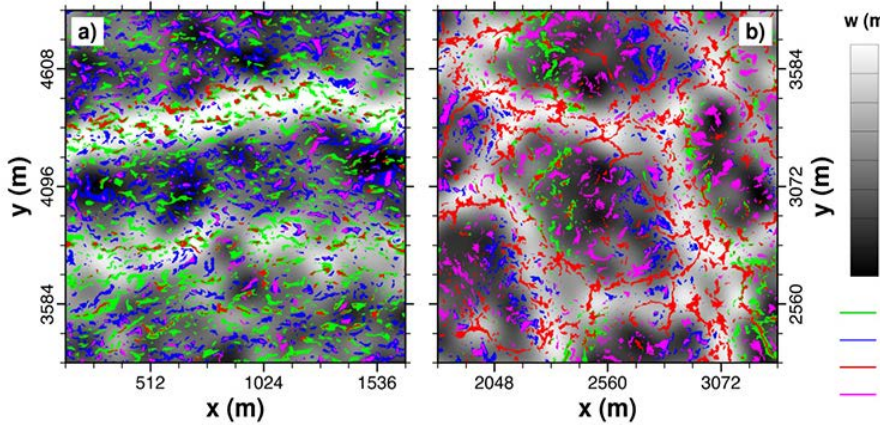


Figure 1: Instantaneous horizontal slices of low-pass filtered vertical velocity at six times the canopy height (gray scale) from two simulations. In the simulation on the left (a), turbulence production largely occurs through wind shear. In the simulation on the right, turbulence is largely buoyancy driven. Regions of negative  $u'w'$  and positive  $w'\theta'$  at the top of a plant canopy and broken down by quadrants are overlaid in color. Using notation such that for any variable  $\chi$ ,  $\chi^+$  signifies  $\chi$  perturbations greater than zero and  $\chi^-$  signifies  $\chi$  perturbations less than zero. Green regions depict  $u^-w^+$ , blue regions depict  $u^+w^-$ , red regions depict  $w^+\theta^-$ , and pink regions depict  $w^-\theta^+$ . In a), only regions with  $[u^-w^+, u^+w^-]$  more negative than  $[-1, -1] \text{ m}^2 \text{ s}^{-2}$  and  $[w^+\theta^-, w^-\theta^+]$  larger than  $[1, 1] \text{ m K s}^{-1}$  are shown. In b) only regions with  $[u^-w^+, u^+w^-]$  more negative than  $[-0.3, -0.4] \text{ m}^2 \text{ s}^{-2}$  and  $[w^+\theta^-, w^-\theta^+]$  larger than  $[0.4, 0.3] \text{ m K s}^{-1}$  are shown. To note in these figures is: With increasing importance of buoyancy, turbulent exchange of momentum and heat between the canopy layers and aloft becomes increasingly de-correlated as a result of the larger boundary-layer scale motions creating regions of convergence/divergence and high/low shear at canopy top.

MMM research in FY 2015 also focused on improving the Coupled Weather-Wildland Fire Environment (CAWFE) model and WRF to simulate evolution of wildland fires and their impacts on the land surface and air quality. Fire remote sensing data from satellite and airborne fire mapping instrumentation was used to evaluate CAWFE coupled weather-wildland fire simulations of California’s King Fire. The King Fire exemplified a poorly understood type of fire – events driven by fire-induced winds. By capturing the nature of the airflow at hundreds of meters grid spacing and including the feedbacks from the fire, CAWFE captured how the King Fire ran 14 miles during one afternoon – behavior not forecasted by operational tools. Simulated maximum heat flux, assumed to be a proxy for burn severity, has been compared to burn severity metrics derived from satellite remote sensing data and photographs. The simulated heat flux compares well with locations of topographically tied areas of increased mortality and consumption as shown in photographs. As shown in the following figures, model results also compare well with the spatial patterns of satellite-derived severity.

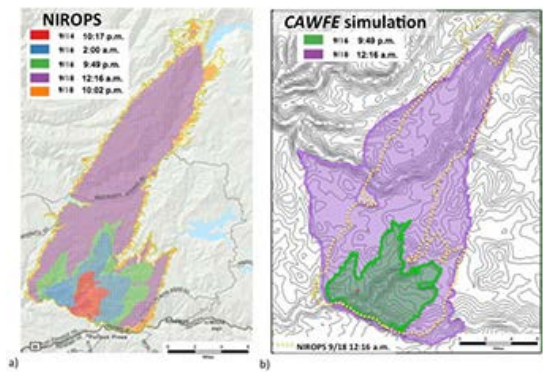


Figure 2: a) Progression of King Fire from September 14-18, 2014, as mapped by National Infrared Operations. (Figure courtesy of USDA Forest Service and CAL Fire.) b) Simulated fire progression with the fire initialized using the September 16, 2014, NIROPS fire map until September 18 at 10:02 p.m. The NIROPS-mapped fire extent at that time (dotted yellow line) is shown for comparison.

Other research included the development of the HOckey-Stick Transition (HOST) hypothesis based on observation analyses by MMM scientists collaborating with Northwest Research Associates. The hypothesis emphasizes the important impact of finite turbulent eddies in turbulent mixing. Due to the increasing contribution of these large coherent eddies with wind speed in reducing vertical temperature gradients at night, the turbulent momentum transfer increases with wind speed dramatically at a given height (see figure). The positive buoyancy from the heated ground surface during daytime contributes additional turbulent mixing besides wind shear. They also found that these large coherent eddies are related to the vertical gradients of wind and temperature over a finite depth, which is significantly different from the traditional turbulence parameterization used in Monin-Obukhov similarity theory (Sun et al., 2015, *Bound.-Layer Meteor.*). The HOST hypothesis also explains the generation of intermittent turbulence by atmospheric gravity waves near the ground (Sun et al., 2015, *J. Atmos. Sci.*; Sun et al., 2015, *Rev. Geophys.*), provides insight into the observed wind turning towards high pressure (Sun et al., 2013, *J. Atmos. Sci.*), and suggests a new turbulence parameterization near the ground across all stabilities. The HOST hypothesis is being evaluated using observations collected over various surface types, and tested in a simple numerical model for its implementation into WRF to improve the turbulence parameterization in the atmospheric boundary layer.

Other work in FY 2015 included performing large-domain LES of tropical deep convection and using it as a benchmark to develop scale-aware SGS (subgrid-scale) transport in kilometer-grid cloud resolving models. This is collaborative work with a team of researchers at the NSF sponsored Center for Multiscale Modeling of Atmospheric Processes (CMMAP).



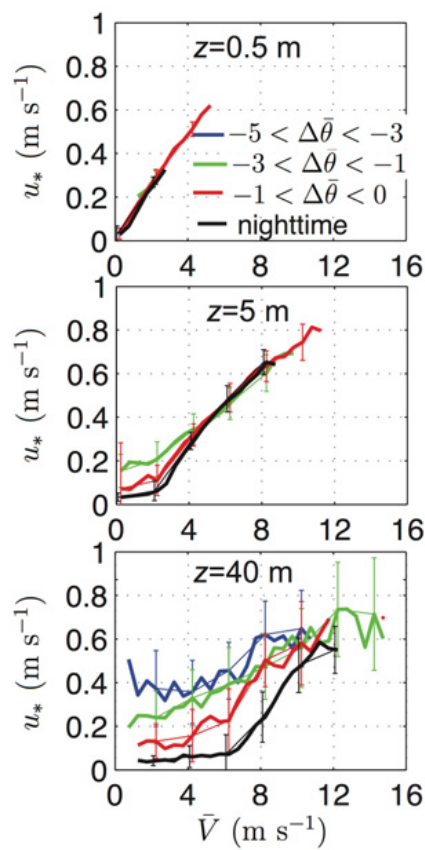


Figure 3: Composite daytime relationships between  $u_*(z)$  (the square root of the turbulent momentum transfer) and wind speed,  $V(z)$ , compared to the averaged nighttime relationship based on the entire CASES-99 30-min dataset at three selected observation heights. The daytime relationship is further subdivided into three bulk temperature differences  $\Delta\theta$  between the observation height and 0.23 m. The thin vertical lines represent the standard deviations within each 4 ms<sup>-1</sup>  $V(z)$  bin.

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CHEMICAL AND BIOLOGICAL METEOROLOGY

Scientists across NCAR are conducting research in this interdisciplinary topic through efforts such as: the Deep Convective Clouds and Chemistry (DC3) field campaign, which links the cloud physics and dynamics, electricity, and atmospheric chemistry communities. DC3 field campaign analysis studies included characterizing the outflow of the 22 June 2012 case that had a biomass-burning plume ingested into the storm (see figure 1), determining the scavenging efficiencies of soluble trace gases via data analysis and modeling, characterizing the wrapping of stratospheric air around anvils associated with mesoscale convective systems (*see figure 2*), and contributing to colleagues’ papers. Analysis of DC3 data enhances understanding of how convection affects tropospheric composition, especially ozone, which acts as a radiatively active greenhouse gas in the upper troposphere. These efforts are expected to improve model parameterizations of convective transport, production of nitrogen oxides from lightning, and wet deposition of chemical species.



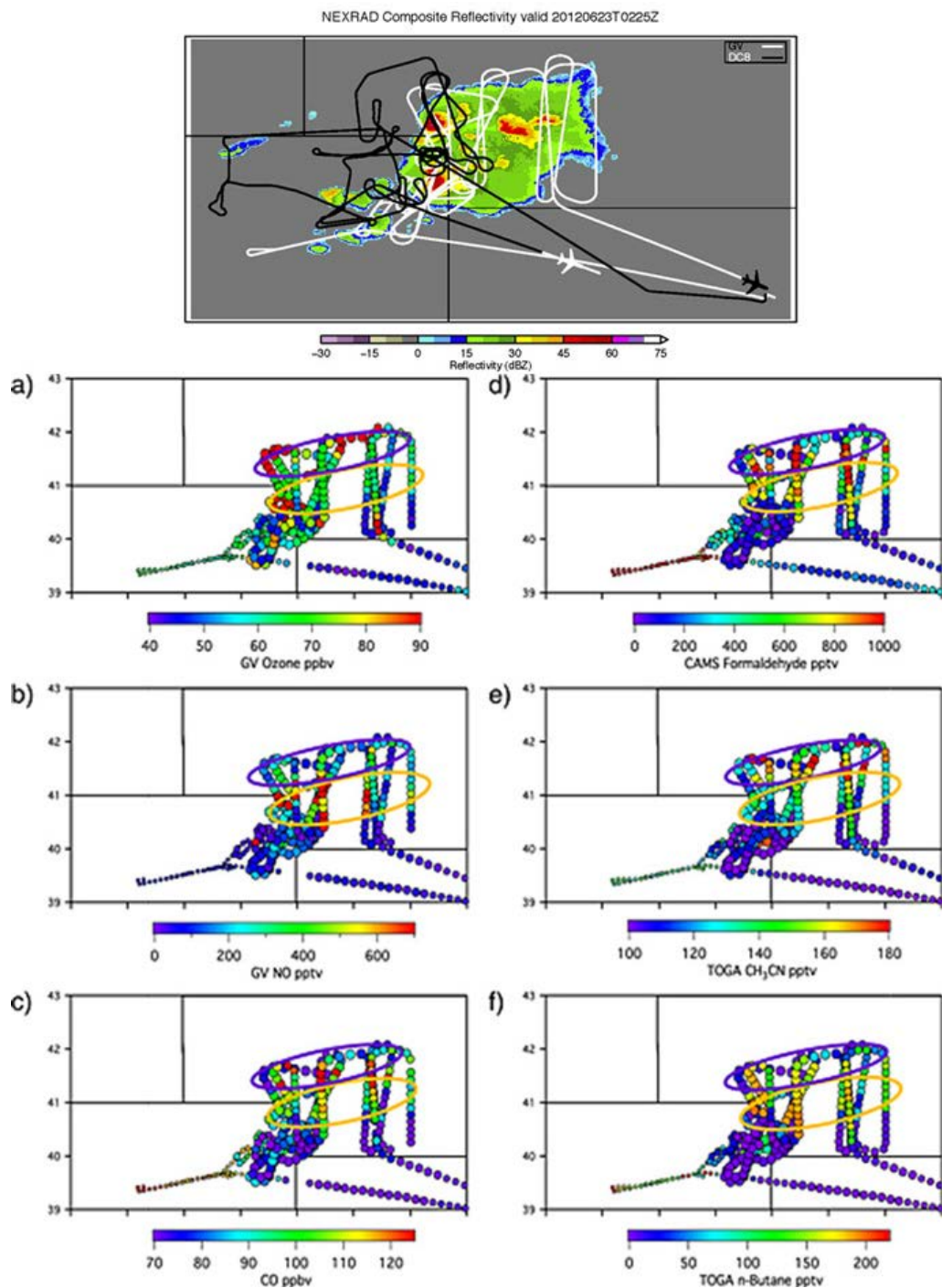


Figure 1: (Top panel) NEXRAD radar composite reflectivity of the Colorado-Nebraska convection studied during the 22 June 2012 research flights. The image is overlaid with DC-8 and GV flight tracks. The far left red circle indicates the High Park fire origin. The purple oval indicates the approximate location of the north storm outflow, and the gold oval the south storm outflow. Panels a-f): GV measurements along the flight track color coded according to the species mixing ratio and sized with altitude (small filled circles are at low altitude). (a) Ozone, (b) NO, (c) CO, (d) formaldehyde, (e) acetonitrile, and (f) n-butane. These results show high ozone just to the north of the storm anvil, low ozone within the anvil. NO and n-butane are higher in the south storm outflow than the north storm outflow, while CO, formaldehyde, and acetonitrile are higher in the north storm outflow. Acetonitrile is a marker of biomass burning, indicating that the north storm ingested biomass burning from the High Park fire. Model calculations of the chemistry in the two storm outflows report more ozone production occurring in the south storm outflow over the next 48 hours than in the north storm outflow, because of the higher NO in the south storm outflow. Apel, E. C. et al. (2015), Upper tropospheric ozone production from lightning NO<sub>x</sub>-impacted convection: Smoke ingestion case study from the DC3 campaign. *J. Geophys. Res. Atmos.*, 120, 2505–2523. doi: 10.1002/2014JD022121.

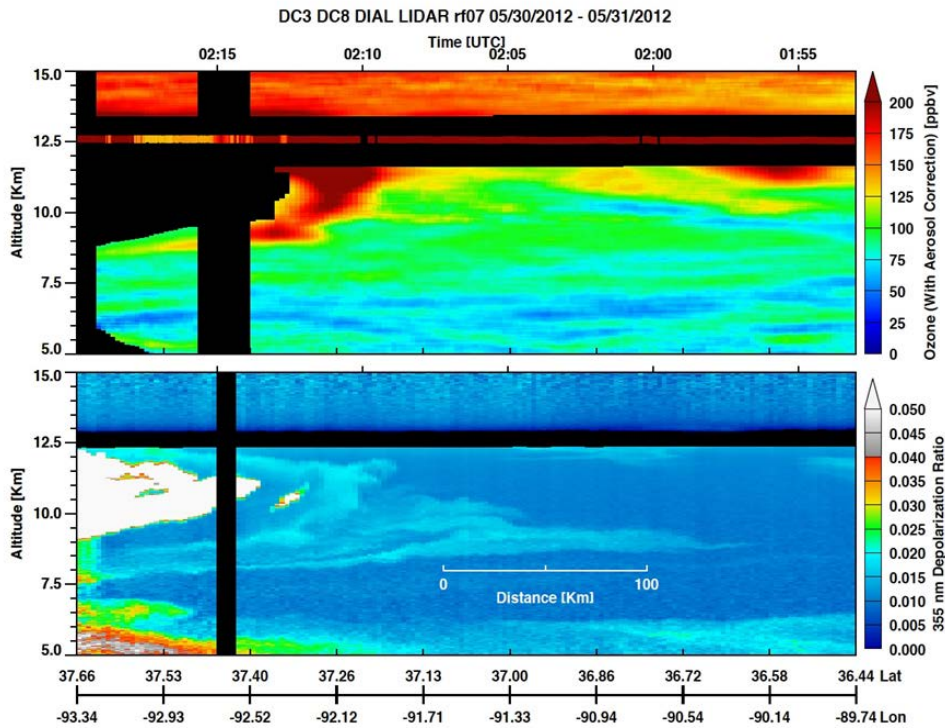


Figure 2: The vertical distribution of upper tropospheric ozone mixing ratio (upper) measured by DIAL along approximately 30 minutes (~400 km in distance) of the DC-8 flight. Note the cross section is shown in reversed time scale to illustrate the cross section from west to east. The black color indicates the region when the DIAL ozone channel produced no data due to cloud attenuation. In situ ozone is shown by the color of the flight track. The depolarization ratio (lower panel) from the DIAL 355 nm wavelength channel provides a signature of cloud/storm edge and outflow pattern in the neighborhood of the storm. The outflow structure shown in light blue is most consistent with low number density of ice particles, which complements the stretching and shedding shown in the ozone structure (upper panel).

Pan, L. L. et al. (2014), Thunderstorms Enhance Tropospheric Ozone by Wrapping and Shedding Stratospheric Air, *Geophys. Res. Lett.*, 41, 7785–7790, doi:10.1002/2014GL061921.

The biome has considerable effects on weather and atmospheric composition on a variety of time scales. Diurnally varying interactions of canopies with the near-surface layer of the atmosphere fundamentally alter the transport of constituents into the atmosphere. In the extreme case of wildfire, modeling requires turbulence resolving models interacting with complex physics of fire. The basic process of these surface/canopy/atmosphere interactions requires detailed investigations to quantify how their aggregate effects can be incorporated into earth system prediction efforts.

Analysis of canopy turbulence observations and simulations improves understanding and modeling of turbulent momentum, energy, and trace gas exchange between vegetation and the atmosphere. In FY 2015 the role of tree phenology on atmospheric turbulence parameterization over tall deciduous vegetation was investigated and quantified using observations from the Canopy Horizontal Array Turbulence Study (CHATS) field experiment to establish the dependence of the turbulent exchange of momentum, heat, and moisture, as well as kinetic energy on canopy phenological evolution through widely used parameterizations based on: a) dimensionless gradients, or b) turbulent kinetic energy (TKE) in the roughness sublayer. Observed vertical turbulent fluxes and gradients of mean wind, temperature, and humidity are used in combination with empirical dimensionless functions to calculate the exchange coefficient. The analysis shows that changes in canopy phenology influence the turbulent exchange of all quantities analyzed (see figure 3). The turbulent exchange coefficients are twice as large near the canopy top for the leafless canopy than for the fully leafed canopy under unstable and near-neutral conditions. This difference in the turbulent exchange coefficient is related to different penetration depth of the turbulent eddies organized at the canopy top, which increases for a canopy without leaves. Analysis of the TKE and its dissipation under near-neutral atmospheric conditions shows that TKE exchange increases for a leafless canopy due to reduced TKE dissipation efficiency compared to that when the canopy is in full-leaf. The study closed with discussion surrounding the implications of these findings for parameterizations used in large-scale models.

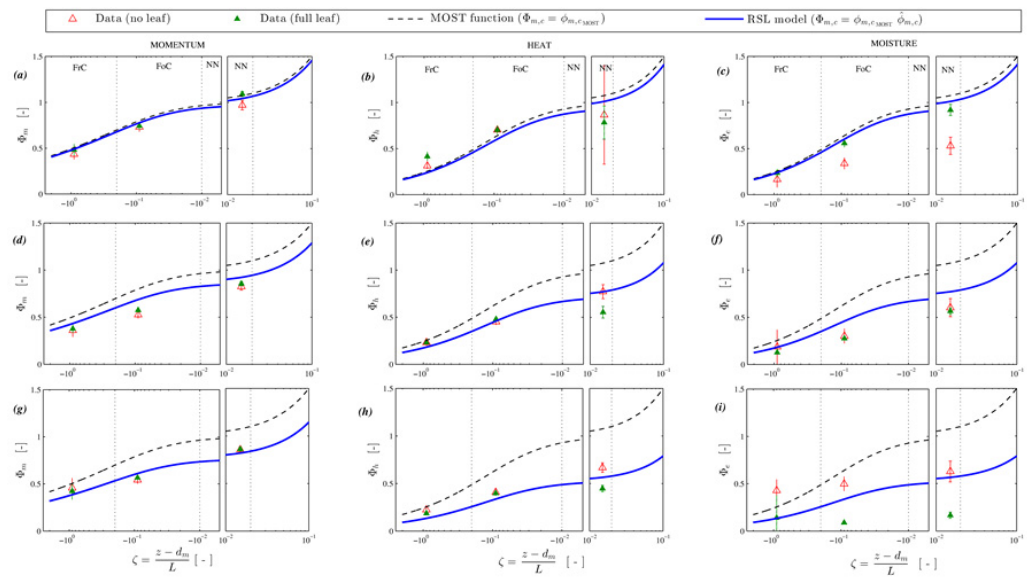


Figure 3: Evolution of the dimensionless gradients for momentum, heat and moisture at 2.3 (a, b, c, respectively), 1.4 (d, e, f, respectively) and 1.1 (g, h, i, respectively) times the canopy height above a walnut orchard during the CHATS field campaign; the open red and full green triangles represent the observations during periods when the canopy was leafless and with-leaves, respectively; the black dashed lines represent the traditional Monin-Obukhov Similarity Theory (MOST) formulation relating a wind speed gradient to the momentum flux, while the solid blue solid lines show dimensionless gradients for momentum and scalars modified to account for canopy-induced modification to MOST. (Shapkalijevski et al., *J. Appl. Meteorol. Clim.* accepted.)

In another related effort, MMM and ACOM scientists analyzed ground based and aircraft observations of the photochemistry of isoprene (C5H8) and related chemical species in the sunlit daytime convective boundary layer (CBL) from the Southern Oxidant and Aerosol Study (SOAS), which focused on the coupling between biogenic and anthropogenic reactant sources on secondary organic aerosol production above a mixed forest. Fluxes of isoprene and monoterpenes were quantified at the top of the forest canopy using a high-resolution Proton Transfer Reaction Time of Flight Mass Spectrometer (PTR-TOF-MS). Both ground-based and airborne collected volatile organic compounds (VOC) data are used to constrain the initial conditions of a mixed layer chemistry model (MXLCH), which is applied to examine the chemical evolution of the O3-NOx-HOx-VOC system and how it is affected by boundary layer dynamics in the CBL. The chemical loss rate of isoprene (~1h) is similar to the turbulent mixing time scale (0.1-0.5 h), which indicates that isoprene concentrations are equally dependent on both photo-oxidation and boundary layer dynamics (see figure 4). Budget analyses suggest that diurnal evolution of isoprene inside the CBL is mainly controlled by surface emissions and chemical loss.



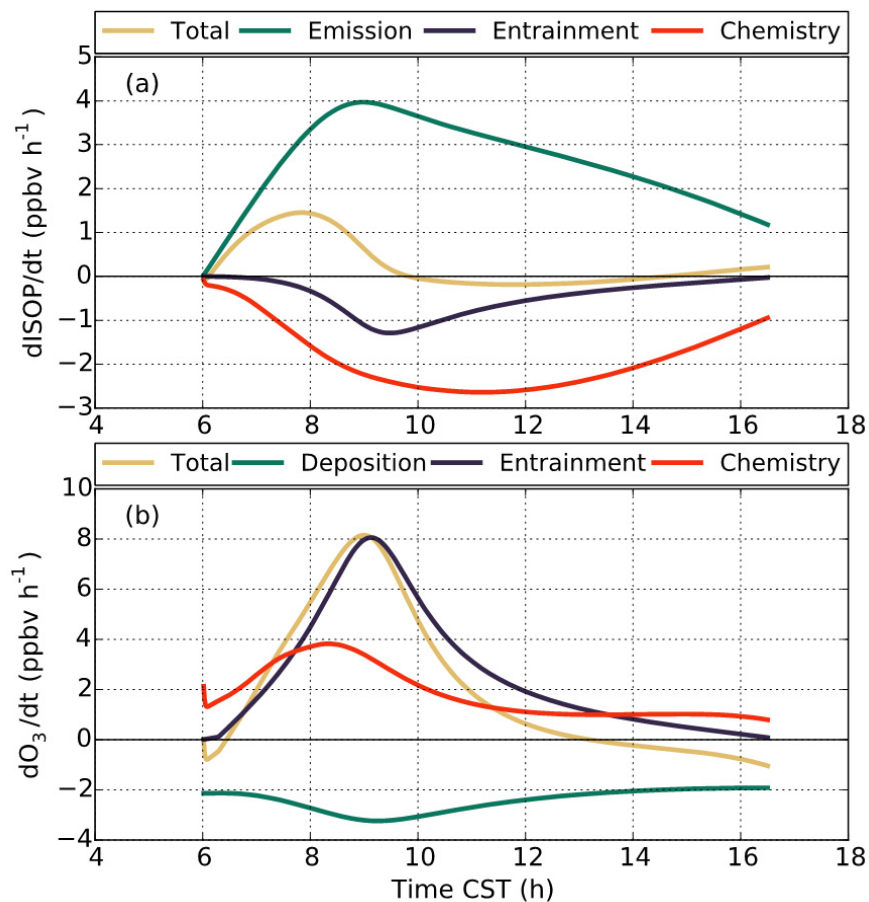


Figure 4: : Model output showing the influence of dynamics and chemistry on the time evolution of isoprene and ozone in the boundary layer during an ideal clear-day during the SOAS experiment that took place near Centreville, AL in June-July 2013. These results emphasize the clear influence of boundary layer entrainment on the diurnal cycle of key atmospheric constituents. (Su et al., *Atmos. Chem. Phys.*, submitted.)

Other work in FY 2015 included implementation of a multi-level roughness sublayer parameterization in an offline version of the Community Land Model (CLM). Preliminary testing of the parameterization using AmeriFlux observations to drive CLM reveals distinct improvement in predicted momentum, sensible, and latent heat fluxes (see figure 5). Further testing over crops and tropical forest regions are ongoing.

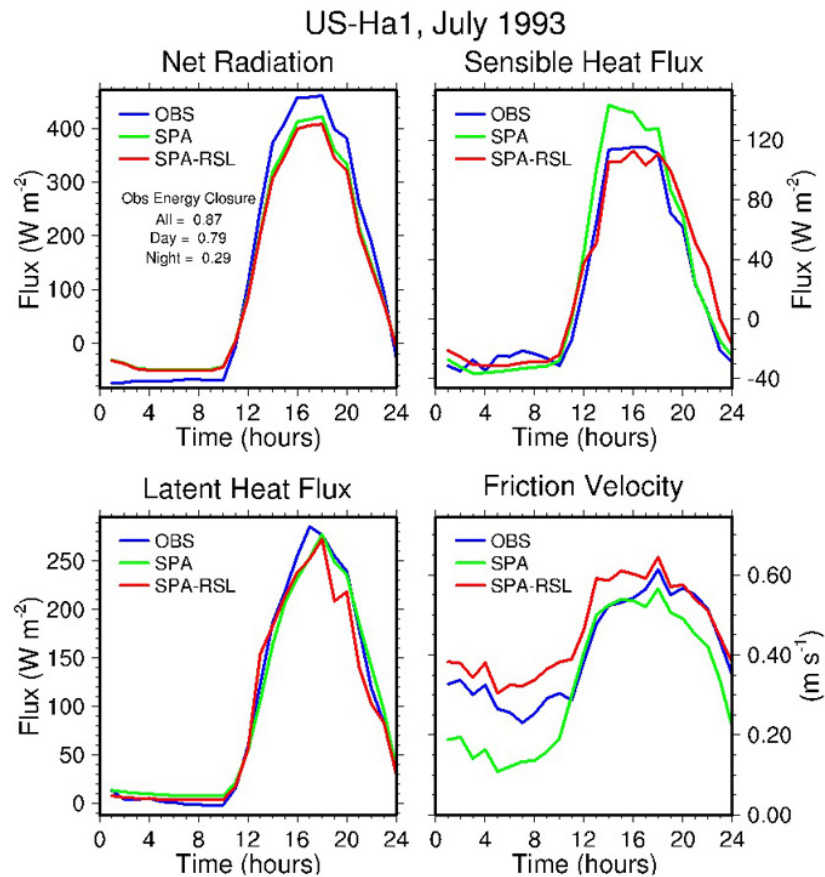


Figure 5: An average diurnal cycle of surface exchange predicted by an offline version of the Community Land Model modified to predict stomatal conductance by linking leaf water-use efficiency and water transport along the soil-plant-atmosphere (SPA) continuum. The green line represents results produced by driving the SPA version of CLM with observed variables above the canopy at Harvard Forest during July of 1993. The red line represents surface exchange predicted by the SPA version of CLM driven

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Communicating Weather- and Climate-Related Risk for Use in Decisions

Clouds and Precipitation

Boundary-Layer Turbulence and Surface Exchange

Chemical and Biological Meteorology

Dynamics of Mesoscale Weather Systems

Interdisciplinary Science Challenge 2: Determine the Inherent Predictability of the Earth System with Respect to Weather, Climate, and Air Quality

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# DYNAMICS OF MESOSCALE WEATHER SYSTEMS

A particular emphasis in MMM has been high-impact convective weather systems, such as squall lines, hurricanes, and tornado-producing thunderstorms. In a recent series of studies, MMM scientists showed how numerical models could produce hurricanes with wind gusts greater than ever observed, despite very realistic initial conditions. They found that a particular combination of thermodynamics and flow structure in hurricane eyewalls acts as a form of atmospheric front in which mesoscale gradients are enhanced. Turbulent phenomena called “eyewall mesovortices” form in this region, and can limit the tendency to enhance gradients, but MMM scientists showed that extraordinarily small horizontal grid spacing ( $< 100$  m) is needed to accurately simulate this process. Utilizing the Yellowstone supercomputing system, researchers have studied these eyewall mesovortices dynamics and their effects on the mesoscale structure of hurricanes.

MMM scientists continue to explore and document the dynamics of numerically simulated mesovortices in idealized hurricanes, by evaluating model output against observational data collected and analyzed by colleagues at NOAA’s Hurricane Research Division. In one study scientists examined model output and found that the strongest wind gusts occur within shallow ( $< 1$  km) mesovortices, which are coincident with strong updrafts along the eyewall of the simulated hurricanes (see figure below). A thorough analysis of the entire NOAA dropsonde database was conducted, and dropsondes with windspeed  $> 90$  m/s were identified for future comparison with numerical model simulations.

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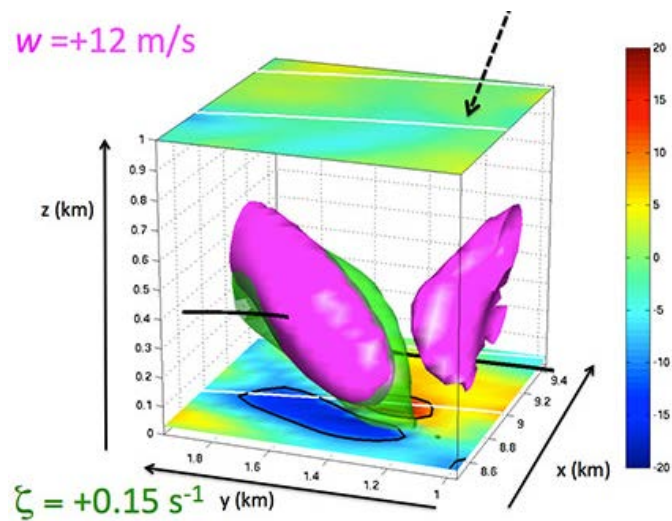


Figure: Three-dimensional visualization of coherent structures associated with a strong (90 m/s) wind gust in a simulated hurricane. Purple shading illustrates strong updrafts (vertical velocity > +12 m/s), and green shading shows strong vertical vorticity (a region of rapidly rotating air; in this case, vertical vorticity > +0.15 s<sup>-1</sup>). Color shading at the bottom denotes wind-speed perturbation, showing +20 m/s perturbations from the mean flow.

In another study, advances in computing resources were utilized to simulate phenomena more accurately through higher resolution and more advanced physical parameterizations. As an example, several advanced subgrid turbulence parameterizations for large eddy simulation (LES) have been developed as part of this work. Two subgrid turbulence models have been added to the CM1 numerical model and evaluated as part of this project. The Nonlinear Backscatter and Anisotropy (NBA) model was found to have a minimal effect on results. However, the Two-Part subgrid model of Sullivan et al. (1994) improves near-surface profiles of wind speed; specifically, shear in the lowest 100 to 200 m above the ocean better matches observed profiles from dropsonde observations.

MMM scientists continue to share the tools developed from studies of the dynamics of mesoscale weather systems. When possible and appropriate, lessons learned from simpler numerical models are transferred to WRF and/or MPAS. Last year code was developed for this work and has been shared with a team of researchers at the University of Miami, who have an NSF grant to study the structure and dynamics of tornadoes with grid spacing < 10 m.

MMM scientists, in collaboration with NOAA’s Hurricane Research Division (Dr. Sim Aberson), continued research on extreme winds in hurricanes, focused on the analysis of extreme wind gusts and updrafts in dropsonde data. NOAA has been particularly interested in this study because they conduct routine aircraft surveillance into hurricanes and are sometimes impacted by severe gusts and updrafts. Additionally, based on this work, several modifications were made to the CM1 numerical model to improve stability of the code at high wind speeds. CM1 is used by several university collaborators for a variety of applications, including research and education.



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INTERDISCIPLINARY SCIENCE CHALLENGE 2: DETERMINE THE INHERENT  
PREDICTABILITY OF THE EARTH SYSTEM WITH RESPECT TO WEATHER, CLIMATE, AND  
AIR QUALITY

MMM scientists are leading efforts to quantify atmospheric predictability and develop advanced techniques of data assimilation methods appropriate for fine scale prediction of hazardous weather. Data assimilation development is part of an NCAR-wide Data Assimilation Program hosted by MMM that seeks to build a common infrastructure for the research community that will include the most advanced data assimilation methods. The use of ensemble-based methods is being explored specifically for the purpose of understanding the limitations of predicting severe thunderstorms and heavy rainfall and flooding hazards.

<a href="#">&lt; Dynamics of Mesoscale Weather Systems</a>	<a href="#">up</a>	<a href="#">Data Assimilation &gt;</a>
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## DATA ASSIMILATION

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Data assimilation provides initial conditions for weather forecasts and thus is an essential component of any forecasting system. Because it routinely and systematically compares model predictions to large and diverse observational datasets, data assimilation also has a central role in the continued improvement and refinement of forecast models, for example, by identifying model biases. Moreover data assimilation can inform improvements to the observational network through observing-system simulation experiments. MMM is recognized for its unique expertise in modeling, assimilation, and observing of mesoscale and convective processes and for

MMM continues to develop and support data-assimilation systems for community use, particularly focused on the WRFDA (WRF Data Assimilation). In FY 2015 development emphasized unified ensemble-variational systems for WRF and evaluation of the MPAS performance in cycling data assimilation at higher resolutions (60 km). Capabilities for cycling data assimilation with MPAS were extended to the Gridpoint Statistical Interpolation (GSI) system that is operational within NOAA, complementing ongoing work with MPAS/DART (Data Assimilation Research Testbed). Month-long cycling data-assimilation tests revealed important biases in MPAS, including a cold bias near the model top and warm bias in the tropical mid-troposphere; fixes for these issues are being investigated.

Real-time experiments with WRFDA and WRF/DART were performed and led to refinements of both systems, such as bias correction for aircraft observations used in WRF/DART. The WRFDA analyses supported the STEP (Short Term Explicit Prediction) Hydromet field experiment, while the high-resolution ensemble forecasts from WRF/DART, which continue to be available today ([ensemble.ucar.edu](http://ensemble.ucar.edu); see two figures below), are now used informally in multiple forecast offices of the National Weather Service. The existing cloud-analysis system, which employs simplified cloud radiative transfer and treats cloud fraction as a tracer in forecasts, was improved by implementing a particle-filter algorithm in the assimilation step.

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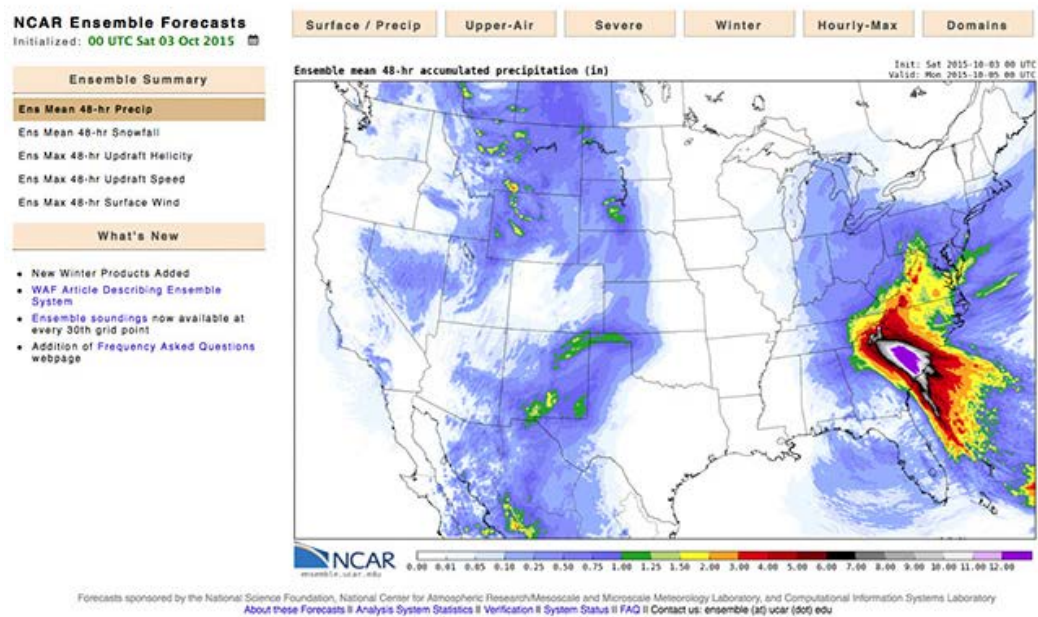


Figure 1: Screen shot of the NCAR Ensemble Forecast website at <http://www.image.ucar.edu/wrfdart/ensemble/>.

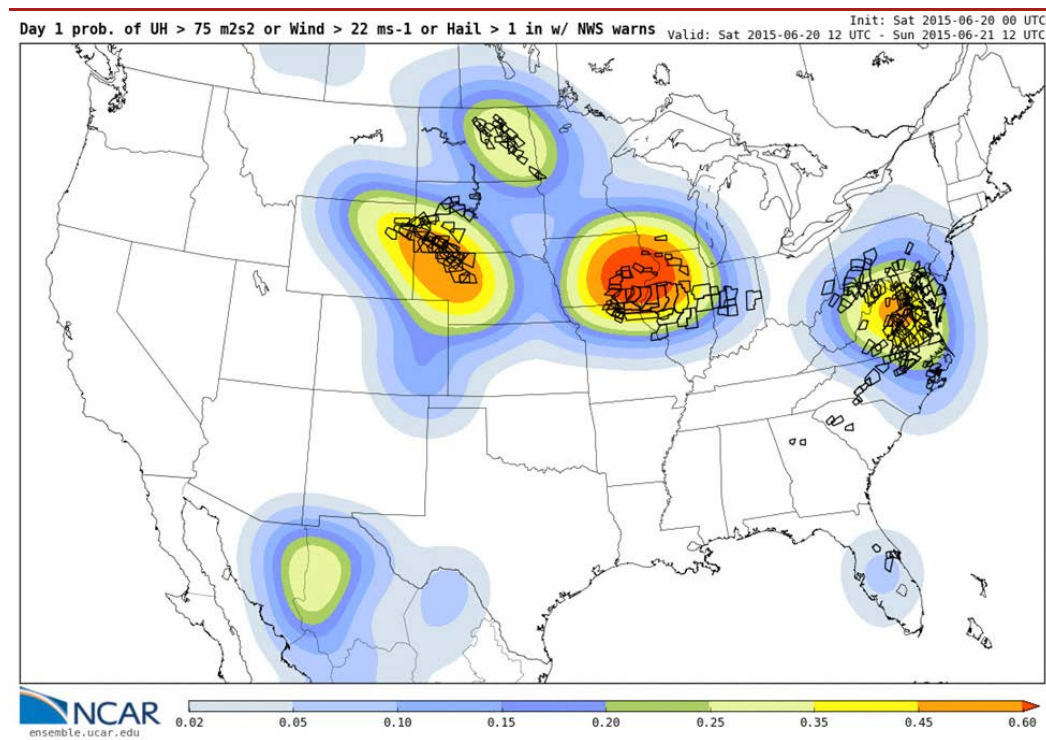


Figure 2: 24-hour forecast probabilities of severe weather (color contours) from the NCAR ensemble forecast system valid 12 UTC 20 June 2015 through 12 UTC 21 June 2015. National Weather Service severe weather warnings are overlaid (black polygons), indicating the areas where severe weather was likely to have occurred.

Fundamental research in data assimilation was continued and included techniques that account for nonlinearity and non-Gaussianity, which provide bias correction and parameter estimation and account for forecast-model error. Rigorous asymptotic bounds on the performance of particle filters were established. These show that the required ensemble size increases exponentially with a measure of the size of the assimilation problem, regardless of the choice of proposal density (referring to the distribution from which particles, or samples, are drawn). This demonstrates that several algorithms recently proposed in the literature will not scale effectively if applied to data assimilation for numerical weather prediction.

The development of advanced data-assimilation techniques for WRF, suited to high-resolution analysis and prediction,



including a four-dimensional variational scheme (4D-Var), an Ensemble Kalman Filter (EnKF), and “hybrid” approaches that incorporate elements of both variational and ensemble techniques is of direct benefit to the community. The variational and hybrid schemes are available to the community through the WRFDA system, while the EnKF is implemented through WRF/DART, which is available to and widely used by the community.

In 2015, NCAR initiated a cross-laboratory Data Assimilation Program, housed in MMM. Its goals are to:

- Train new data-assimilation scientists and enhance data-assimilation expertise at NCAR through a postdoctoral program in which postdocs are co-sponsored by the DA Program together with externally funded projects or NCAR Laboratories.
- Develop common tools and infrastructure for data assimilation, emphasizing the existing community data-assimilation systems at NCAR, the DART and WRFDA.

The postdoctoral program and other activities of the DA Program are to fully commence at the beginning of FY2016.

< Interdisciplinary Science Challenge 2: Determine the Inherent Predictability of the Earth System with Respect to Weather, Climate, and Air Quality	up	Convective Weather Prediction >
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# CONVECTIVE WEATHER PREDICTION

An important component of WRF development has been enabled through interrogation of experimental explicit convective weather forecasts (3-km grid resolution, extending to forecast lead times of 48 hours) to better establish the capabilities and limitations of such high-resolution numerical guidance. These forecast exercises have been instrumental in documenting forecast sensitivities and biases for the wide range of physics options generally applied for convective applications, and have especially highlighted initial condition uncertainty as a major contributor to significant convective forecast errors. In light of this, modeling efforts now include data assimilation (incorporating the WRF model with CISL's DART facility EnKF data assimilation system, as well as hybrid analysis methods combining both WRFDA and DART. The inclusion of data assimilation in the evaluation of the WRF model has highlighted key deficiencies, including model bias, which has enabled several physics improvements and a more systematic means of identifying appropriate suites of model physics. The use of high-resolution (3-km grid interval) ensemble forecasts for convective applications has also enabled the development of probabilistic approaches to hazardous weather forecasting.

The above findings provided motivation for the MMM-led Mesoscale Predictability Experiment (MPEX), conducted from 15 May to 15 June 2013, to consider whether experimental, sub-synoptic observations can extend the lead-time of convective-scale prediction over a 6- to 24-hour time span. MPEX used the NCAR GV aircraft to acquire a sub-synoptic scale grid of full tropospheric soundings (using dropsondes and a microwave temperature profiles (MTP)) early in the morning, upstream from anticipated convective outbreaks for later in the day. Observation analysis and forecast sensitivity studies examining MPEX data continue. Additional work is ongoing to examine the long-term performance of a real-time, 10-member, full CONUS ensemble forecast system. This project expands on previous seasonal prediction experiments, and further explores means to visualize probabilistic ensemble guidance.

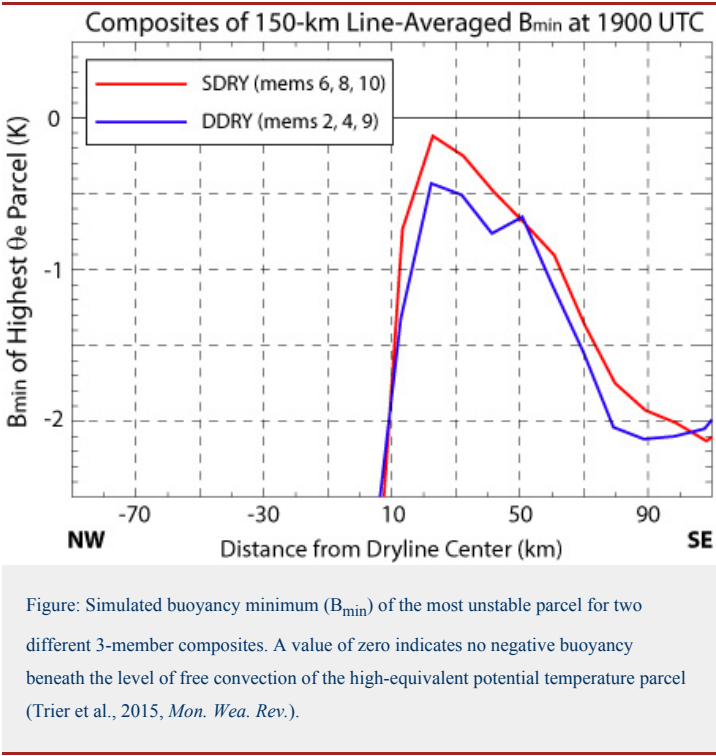
In FY 2015, MMM researchers continued the development and testing of WRF/DART and ensemble forecasting techniques to produce an improved representation of the atmospheric state and its uncertainties for 0 to 48 hour convective forecast applications. A CONUS-scale high-resolution (3-km) 10-member, real-time ensemble forecast system has been developed, offering 0-48h forecasts, initialized daily at 00 UTC. As noted above, output from this forecast system has been made available to researchers and forecasters nationwide, accessible from a first-of-a-kind website (<http://ensemble.ucar.edu>), to be used for critical discussion and feedback on the potential value of such high-resolution ensemble forecast information.

To address whether enhanced observations significantly improve the representation of the atmospheric state prior to severe convective outbreaks, scientists analyzed data acquired during MPEX. The MPEX dropsondes have been incorporated into retrospective ensemble analyses, documenting significant modifications to the mid- and upper-level tropospheric features important to the subsequent convective development for many of the MPEX cases.

In an effort to determine whether MPEX data ingested into the WRF/DART assimilation system improves probabilistic

forecast guidance for severe convective weather over a 6- to 24-hour time period, preliminary analyses of ensemble forecasts was conducted with the incorporated dropsonde data. Modest changes were documented to the forecasted convective evolution for many of the MPEX cases, but only a modest improvement in overall probabilistic forecast accuracy compared to the forecasts without the dropsondes. More significant improvement in forecast accuracy, however, was achieved by increasing the cycling rate for the ensemble analyses.

Convection-allowing simulations with the WRF ensemble system were analyzed for a case of convection initiation along an Oklahoma dryline during MPEX. Convection initiation (CI) occurred within shallow fine-scale PBL circulations that intersected the dryline for each of the 10 members of the ensemble. The minimum parcel buoyancy diagnostic ( $B_{min}$ ) was used to examine mesoscale thermodynamic differences among ensemble members and their influence on model forecasts of CI. Here, the  $B_{min}$  diagnostic was found to be useful in discriminating between members that exhibited differences in the behavior of CI (see figure). This is illustrated by the smaller magnitudes of  $B_{min}$  averaged along the dryline in a 3-member subsensemble SDRY than for another 3-member subsensemble DDRY, where convection was both delayed and less widespread than observed. Further analysis illustrated how a more consolidated thermally-direct mesoscale vertical circulation across the moisture gradient in the SDRY composite, affected greater reductions in  $B_{min}$  magnitude than in the DDRY composite where both the surface moisture gradient and its associated thermally-direct circulation were more diffuse.



Other work focused on development of more robust convective-scale ensemble forecast verification methods to discriminate specific weather hazards and convective mode, leveraging data assimilation methods. Probabilistic verification techniques have been developed using severe weather surrogates from the individual ensemble forecasts, such as updraft helicity, to better document the severe weather potential being forecast by the ensemble system.

The efforts described above are contributing to the development of improved assimilation and model forecasting systems for convective weather applications, and they are helping to better establish the observational needs to reach the practical limits of predictability for severe convective weather. Enhanced forecast verification approaches are being developed using surrogate severe weather indicators to better discriminate forecast skill for specific convective weather hazards.

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## INTERDISCIPLINARY SCIENCE CHALLENGE 3: IDENTIFY AND MODEL THE PROCESSES AND INTERACTIONS THAT GOVERN CLIMATE VARIABILITY

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MMM Scientists are engaged in modeling extreme weather in the context of climate change and climate variability. The primary interest in MMM is on regional climate research. Recently this work has utilized the WRF model, but as the MPAS matures, it will focus increasingly on that model. Regional climate research in MMM is aimed at seeking new ways to predict statistics of extremes and utilize that information to provide society and industry with usable information.

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## REGIONAL CLIMATE RESEARCH

Regional climate research has advanced understanding, assessment, projection and prediction of regional climate and weather, with emphasis on the two-way effects of climate variability and change on high-impact weather and societal consequences. This included providing improved capacity for community investigations of regional climate and establishing new approaches to effective user communication. It included the development of suitable tools (e.g., improved community models (WRF and MPAS), hybrid statistical-dynamical approaches, societal indices, and specialized module approaches to assessing risk and impacts of importance to diverse users), depended on close working ties with societal and industry partners, and provided and maintained regional climate modeling systems for community use.

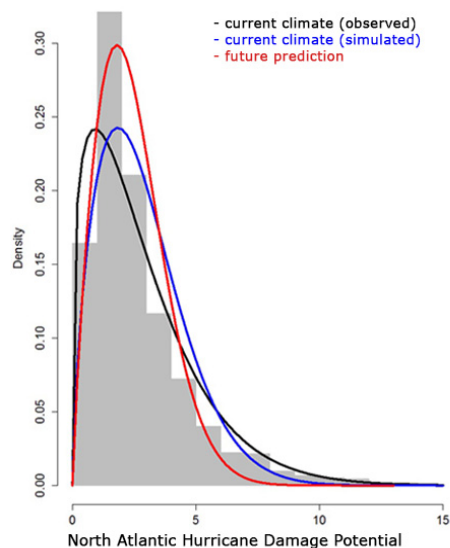
Making a prediction about regional climate does not indicate a complete or successful outcome because users interpret predictions within their own frameworks of risk perception and action. Therefore, to be successful, regional climate research included consideration of the range of communities affected, from Native Americans to commerce. Adapting the research and predictions to consider the communities affected improved the use and utility of weather and climate information. MMM's regional climate research therefore supported community use of data and tools.

One way to advance regional climate research and prediction capacity is to build a hybrid statistical-dynamical weather and climate modeling system. Dynamical weather and climate models such as WRF and MPAS are constrained to finite resolutions and process representations, and typically fail to capture the most extreme events. Fitting theoretical distributions to the simulated distribution allows assessment of the extremes, and a flexible statistical recalibration method was developed without the need for assumptions on the fitted distribution. The figure below shows an example of translating climate information into impact information using a dynamical-statistical approach to assess future changes to hurricanes that have high potential to cause damage.

This emphasis on high-impact weather and climate events provided the foundation for establishing NCAR's Engineering for Climate Extremes Partnership (ECEP, [www.ecep.ucar.edu](http://www.ecep.ucar.edu)). ECEP's mission is to strengthen societal resilience to weather and climate extremes by: bringing together engineering, scientific, cultural, business and government expertise; applying cutting-edge science, engineering and technology; and, providing tools in support of decision-making. ECEP is building relationships with experts from a broad array of communities, including the re/insurance industry (Willis and Zurich), the offshore energy industry (the Research Partnership to Secure Energy for America and Det Norske Veritas), engineering-design consultancies (CH2M) and Native American communities in Hawai'i and Oklahoma. The common thread is concern for the mounting toll taken by extreme weather events, which is expected to worsen with climate change. In FY 2015, a third ECEP workshop was held at NCAR on August 19-21 and provided the opportunity for community members to share best practice and provide feedback on their priorities for research and information needs to facilitate decisions and to enhance community resilience to weather and climate extremes. A goal of the ECEP is to provide improved capacity for the use of weather and climate impacts information by society, commerce, engineering and industry.

MMM continues to maintain community support for regional climate modeling, emulating the success of the WRF model.

Examples include a help desk and running national and international tutorials and workshops. An objective is to develop a structured process for community systems to be incorporated back into the system to ensure broad inclusion and support of a variety of communities and needs related to understanding and planning for regional weather and climate issues.



In FY 2015 a dataset of global bias-corrected Community Climate System Model output data useful for climate downscaling was published, fully documented, and made freely available for community use on the NCAR data server: <http://rda.ucar.edu/datasets/ds316.1/>.

MMM scientists continued research on communicating science to society with a focus on developing effective targeting and framing methodologies specific to unique communities. This included research on understanding the cultural mechanisms through which weather and climate risks are perceived, experienced, and addressed. This work intergrates with an NSF-funded project aimed at exploring the potential societal value of decadal climate predictions by assessing the capacity to develop usable impact predictions. A pilot study showed scope for developing skillful risk predictions on decadal scales by modeling extreme rainfall over the Rio Grande basin using North Atlantic sea surface temperatures (see figure).

Figure: Probability distribution of historical North Atlantic Hurricane Damage Potential for the period 1960-2011 (gray bars). Also shown are the fitted Weibull distributions to historical observations (black line), simulated current climate (blue line), and simulated future climate (red line). A future decrease in high damage potential is predicted. Future work will assess the level of confidence in this single prediction using an ensemble of predictions.

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MMM scientists have continued to develop community models for the prediction and analysis of fine-scale weather phenomena. The emphasis has increasingly been on high-resolution global modeling that will be able to link weather and climate prediction in one system. MMM's community models support university researchers, training for students, and tools for research and applications. MMM is a hub for this activity.

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ENABLING WORLD-CLASS COMMUNITY SCIENCE 1: CONTINUED DEVELOPMENT AND SUPPORT OF NCAR COMMUNITY MODELS

MMM scientists work with a WRF user community that includes thousands of researchers worldwide who create, expand, and apply a spectrum of model capabilities. For example, WRF has been coupled to a variety of other models including streamflow, fire, storm surge, ocean circulation, ocean wave, and air chemistry through extensive collaborations between MMM and other scientists in the community and at NCAR. MMM also provides user support for the WRF system as well as assistance to developers seeking to contribute it.

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## THE WRF MODELING SYSTEM

The Weather Research and Forecasting (WRF) model activities in FY2015 included: providing user support for the core WRF model and related systems, WRFDA and WRF/DART; delivering WRF tutorials; hosting the annual WRF Users’ Workshop; oversight of the WRF repository and WRF Developers’ Committee; testing and incorporation of community-contributed code; and oversight of WRF releases and the WRF Release Committee. MMM personnel conducted WRF-based research, supported field campaigns with real-time WRF forecasts, and undertook basic research and development in numerical modeling and data assimilation. MMM’s weather research and its model development are fundamental to the vitality of the WRF system.

WRF continued to see strong user growth, and new registrations have averaged over 3,000 per year for the past five years. The cumulative number of registered users of WRF is currently over 32,200, with 162 countries represented. The number of subscribers on the WRF e-mail list is over 8,200, and e-mail inquiries to wrfhelp (the WRF user assistance service) average about 350/month. As illustrated in figure 1 below, there has been a significant increase in the number of WRF-related published articles over the past thirteen years.

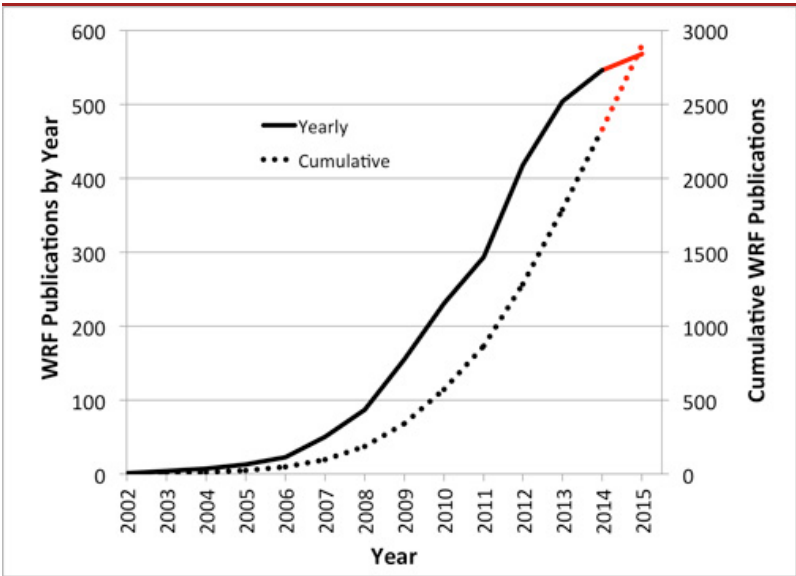


Figure 1: Solid line depicts the number of WRF-related published articles per year and the dotted

line depicts the cumulative total. The red segments are the projection by year-end for 2015 based on data through mid-November.

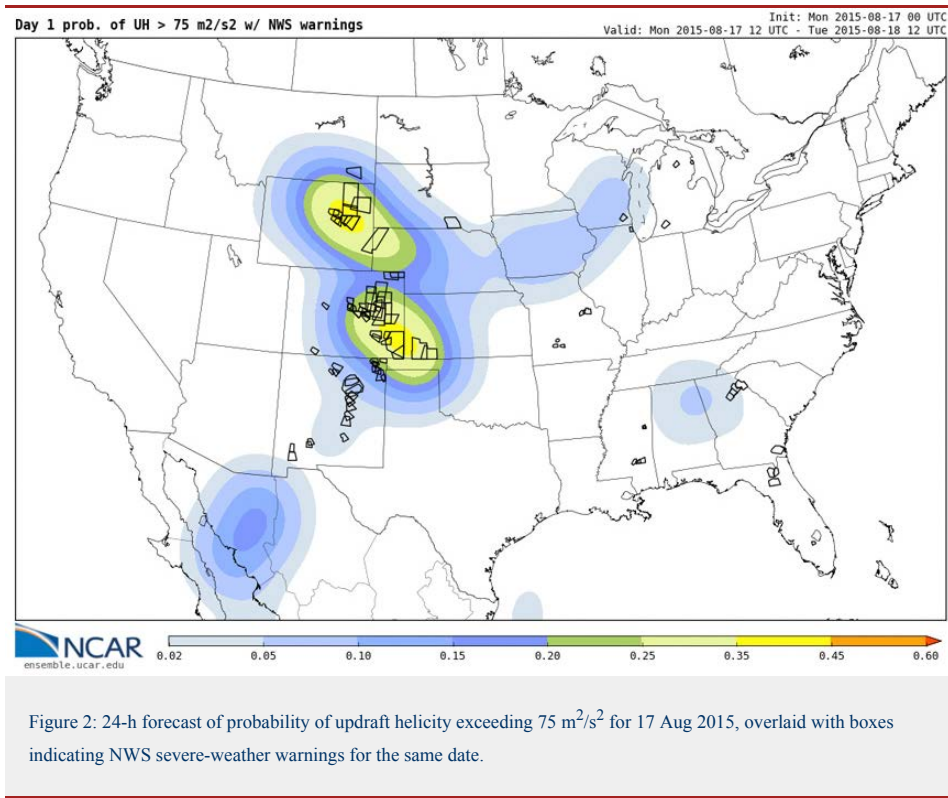
In FY2015 MMM continued to support WRF to the community and released WRF Version 3.7 in April 2015 which included both the WRFDA (see below) and WRF-Chem systems. WRF V3.7 offered a number of enhancements, such as new physical process schemes and software improvements, reflecting contributions from throughout the WRF community. Features of the release included the following.

- Cumulus schemes: New Teidke, new scale-aware Kain-Fritsch, new Wilson YSU shallow convection
- WRF-Hydro V3.0: Hydrological model coupled to WRF
- Microphysics schemes: New NSSL 2-moment scheme, updated Milbrandt, updated Thompson, WSM and WDM interaction with radiation scheme
- LSM: Improvements to Noah-MP, updated RUC LSM
- PBL: Scale-aware YSU scheme
- WRFDA: Overhaul of radar DA capability
- Software and infrastructure: Vertical nesting capability, Enhanced CF (Climate and Forecast) compliance.

In August MMM issued WRF minor release V3.7.1, a bugfix release.

WRFDA V3.7 was also released in April 2015. Its new features included a new background error option (CV7) and new options for assimilating radar reflectivity data. WRFPLUS, the WRF adjoint and tangent linear model, was updated to V3.7 to be consistent with WRF V3.7. In addition, a new microphysics option was added to WRFPLUS, a modified Kessler scheme. WRFDA was also modified to be able to use WRF files with the "lat-lon" (cylindrical equidistant) map projection.

In this reporting period, MMM and IMAGe scientists implemented a real-time ensemble Kalman filter and ensemble prediction system. The system, which is based on WRF and DART, has been running 15-km cycled data assimilation and 3-km, 10-member ensemble forecasts continuously since March 2015. Forecast fields and derived products can be viewed at <http://www.ensemble.ucar.edu>, and these were used as part of the 2015 Hazardous Weather Testbed Spring Forecast Experiment for the National Weather Service. An example is shown in figure 2 below.





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THE ANTARCTIC MESOSCALE PREDICTION SYSTEM (AMPS)

AMPS is a real-time WRF forecasting system run over Antarctica by MMM in support of the U.S. Antarctic Program (USAP) and funded by NSF’s Division of Polar Programs. In FY2015 MMM continued this effort and provided tailored guidance for USAP weather forecasting, scientific field campaigns, and logistical efforts over the continent and Southern Ocean. The work is vital to USAP activities, and the forecasters depend on this robust and flexible system. The effort also facilitates research through provision of the AMPS archive and support to international scientific efforts across Antarctica.

In FY2015 AMPS delivered model guidance to the USAP forecasters through the 2014–2015 field season via the main AMPS web page (<http://www2.mmm.ucar.edu/rt/amps/>), the Antarctic IDD (Internet Data Distribution) service, and a back-up web server supported by CISL. The support included providing WRF products to the forecasters, fulfilling requests for new capabilities, and serving scientific campaigns and special operations. As an example, AMPS responded to focused activity in the WAIS (West Antarctic Ice Sheet) Divide region in West Antarctica with a new 3-km forecast grid. As in previous years, AMPS also served the NSF research vessels *Nathaniel B. Palmer* and *Laurence M. Gould* on their Southern Ocean cruises with forecast output directed to them at sea.

AMPS supported a number of scientific field campaigns over the year. An example was SG-WEX (South Georgia Wave Experiment), a study of the nature, variability, and impact of gravity waves generated by South Georgia Island. AMPS also provided guidance for the 2ODIAC and SCINI-Penguin studies, two projects sharing a field camp off of Ross Island. The 2-Season Ozone Depletion, Ice, Aerosol Campaign (2ODIAC) is making the first simultaneous high-resolution measurements of the physics and chemistry of aerosols and trace gases in Antarctica, while SCINI-Penguin is examining the Antarctic food web and using a remotely operated vehicle (SCINI) to collect data. Lastly, AMPS began supporting the EOL-led ORCAS project (O<sub>2</sub>/N<sub>2</sub> Ratio and CO<sub>2</sub> Airborne Southern Ocean Study). For ORCAS, AMPS will be used by the forecasters for flights of the NCAR HIAPER aircraft out of Punta Arenas, Chile.

In FY2015 AMPS began running a WRF ensemble. The system runs 15-18 members, with the core of these reflecting initial and boundary conditions obtained from NCEP’s Global Ensemble Forecasting System. Figure 1 below presents an example of an AMPS ensemble forecast product, predicted cyclone tracks. The positions of the sea level pressure minima at the forecast time are marked, with the ensemble mean SLP shaded. The AMPS ensemble was also used for testing a hybrid data assimilation approach.

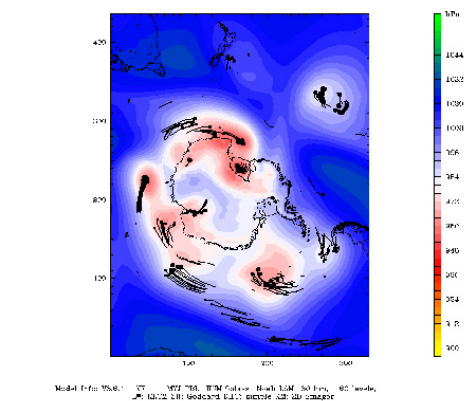


Figure 1: AMPS ensemble forecast cyclone tracks. Black lines mark the paths of the cyclone centers up to hour 48 of the forecast, with dots indicating centers of the lows at the valid time. Shaded field is ensemble mean SLP (mb, scale to right). Forecast hour 48, valid 0000 UTC 19 Sept 2015.

Figure 10 consists of two maps of the Arctic region, labeled (a) and (b), showing the spatial distribution of the maximum value of the normalized wavelet coherence (MWC). Map (a) represents the period 1979-2000, and map (b) represents the period 2001-2019. Both maps include contour lines and labels for various locations and regions. The color scale for map (a) ranges from 0.1 to 204.8, while the color scale for map (b) ranges from 0.1 to 12.8. The maps show a clear trend of increasing MWC values over time, particularly in the central Arctic region.

Figure 2: AMPS MPAS and WRF forecasts. (a) MPAS 120-hr forecast of sea level pressure (solid, interval= 4 mb) and 3-hourly precipitation (mm, shaded, scale to right). Forecast valid 0000 UTC 23 Sept 2015. MPAS mesh over Antarctica approximately 15 km. (b) As in (a), except WRF forecast, 10-km grid.

AMPS contributed to the organization of the 10<sup>th</sup> Antarctic Meteorological Observation, Modeling, and Forecasting (AMOMF) Workshop held in June 2015 in Cambridge, UK. The AMOMF Workshop brings together those with research and operational interests in Antarctic meteorology and weather forecasting. AMPS-related developments and science were featured in

workshop sessions.

The AMPS archive of model output continued to be published through the online Earth System Grid (ESG), a web portal for large databases supported by CISL. The AMPS holdings were updated, and new registrations to access the archive were received regularly. The ESG AMPS archive page can be found at: <http://www.earthsystemgrid.org/project/amps.html>.

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TOWARD MODEL AND DATA ASSIMILATION-SYSTEM DEVELOPMENT FOR WEATHER-  
CHEMISTRY-CLIMATE PREDICTION

MMM scientists are engaged in model development that seeks to unify prediction across a range of scales. In so doing, MMM scientists are grappling with fundamental problems at the interface of weather and climate, and the interaction of turbulence with the mesoscale. MMM scientists are also collaborating with other researchers at NCAR and in the broader community to develop scale-adaptive physical parameterizations and numerical algorithms that can be applied across all scales of interest, as well as to more closely integrate data assimilation with model development and verification.

[< The Antarctic Mesoscale Prediction System \(AMPS\)](#)

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THE MODEL FOR PREDICTION ACROSS SCALES (MPAS)

MMM collaborated with Los Alamos National Laboratory (LANL) to develop the Model for Prediction Across Scales (MPAS), which includes a global non-hydrostatic atmosphere solver and an ocean solver. MMM is responsible for the atmospheric component, LANL the ocean component, and the development of the infrastructure is shared between the two partners. The MPAS solvers are based on spherical centroidal Voronoi meshes (nominally hexagons) that are unstructured and allow for variable resolution meshes that seamlessly transition between fine and coarse mesh regions. Increasing computer capabilities, along with the need to address problems with fixed-resolution traditionally nested models, are the motivating factors behind the MPAS-Atmosphere development effort.

Research in FY 2015 included the completion of tests of MPAS in CESM/CAM5 for an initial Held-Suarez, aqua-planet experiment (APE), and AMIP (Atmospheric Model Inter-comparison Project) (multi-year climate) simulations. Analysis of the AMIP simulations is ongoing. An initial set of Numerical Weather Prediction (NWP) (10-day weather) simulations using CAM5 physics are underway, and are focusing on Atlantic tropical cyclone forecasts for comparison with results from other CAM dynamical cores.

Other work included the completion of comparisons between MPAS-Atmosphere simulations using the WRF-NRCM (Nested Regional Climate Model) physics, the GFS (Global Forecast System) physics (both in stand-alone MPAS) and the CAM5 physics (MPAS in CESM) for the NWP simulations. The results show differences in the forecasts consistent with the known characteristics of the physics. MMM scientists are now in the process of porting the latest version of the NOAA/NCEP GFS physics to MPAS to evaluate its effectiveness in operational forecast configurations within MPAS.

MMM scientists also began testing variable-resolution meshes that span the hydrostatic-nonhydrostatic regime, focusing on explicit forecasts of warm-season high-impact convective weather over the continental United States. Candidate scale-aware, deep convective parameterizations were evaluated in these simulations. MMM scientists also collaborated with scientists from NOAA’s National Severe Storms Laboratory and Storm Prediction Center to evaluate the extended-range convective forecasts produced using MPAS configured with a variable-resolution meshes (50-3 km and 15-3 km) where the 3 km convective-permitting regions centered over North America. MPAS convective forecasts showed some skill at the extended range (days 3-5) in predicting severe storms and flooding that occurred over Oklahoma and Texas (see figure). These forecasts experiments also tested a new scale-aware convective parameterization – the Grell-Freitas scheme. Collaborations with researchers at NOAA Global Systems Division and INPE (Brazil) are being continued on the implementation and testing of the scheme in MPAS.

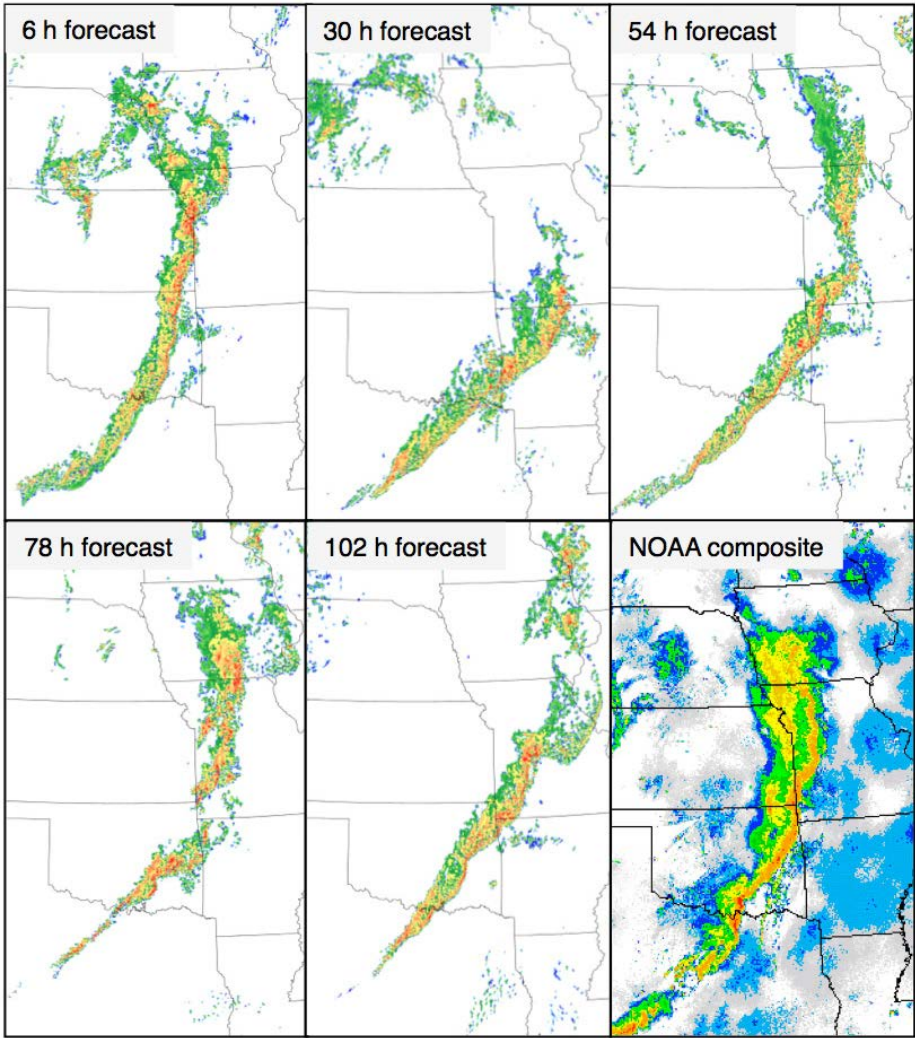


Figure: Radar reflectivity at 1 km above ground level from MPAS forecasts valid 6 UTC 17 May 2015. The NOAA composite radar reflectivity for that time is also shown. This convective event produced significant flooding and tornadoes in Texas and Oklahoma. The global MPAS forecast on a variable-resolution mesh appear to possess some skill in forecasting this convective event even at the longer forecast times of 4 and 5 days.

There are a number of investigators in the university community and in government laboratories that are evaluating MPAS for use in regional climate and numerical weather prediction applications since its release in FY 2013. The variable-resolution capabilities of MPAS provide new and important capabilities in these applications, and the continued MPAS testing and development in FY 2015 provided a firm foundation for these applications. MPAS also serves as a bridge between weather and climate application models. Much has been learned so far by simulating weather in the climate-modeling system (i.e., MPAS in CESM).

Data assimilation using DART is now available for stand-alone MPAS and in the future will be available in CESM/CAM-based MPAS. Many MPAS applications will make use of the variable-resolution capability in MPAS, and DART capabilities in this area are an important addition.

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GEOPHYSICAL TURBULENCE PROGRAM

The broad goal of the NCAR Geophysical Turbulence Program (GTP) is to promote research, education, and awareness of geophysical turbulence both at NCAR and within the broad scientific community. Research on turbulence has been a significant part of the NCAR scientific program since its beginning in the early 1960’s, where it was recognized that understanding relevant turbulent processes is essential to understanding the dynamics of the atmosphere, the ocean, the climate, the Sun, and solar-terrestrial interactions.

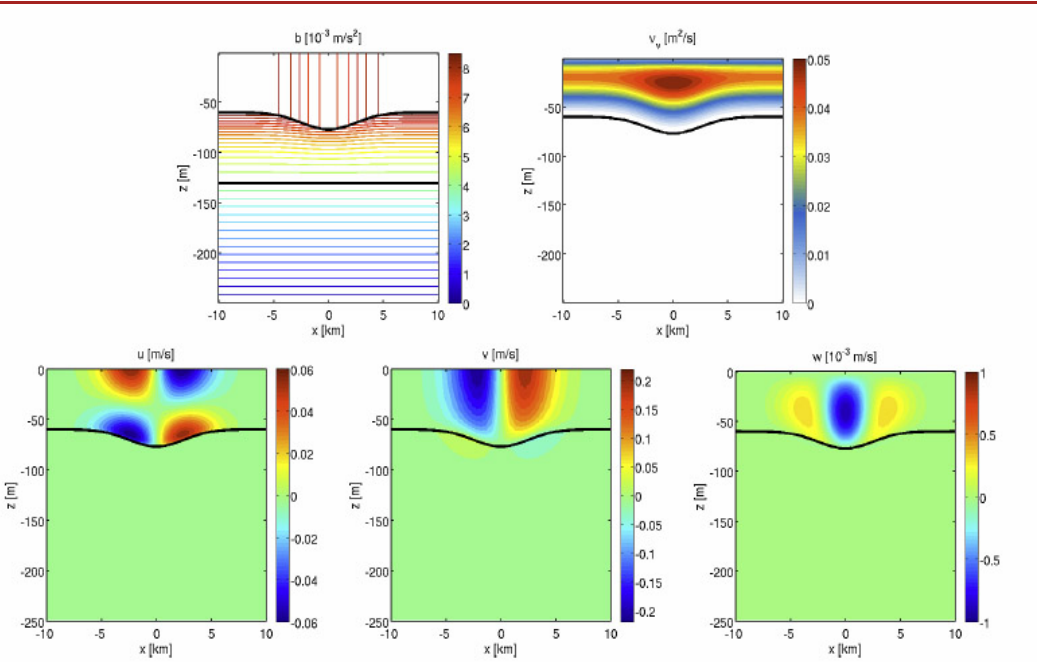
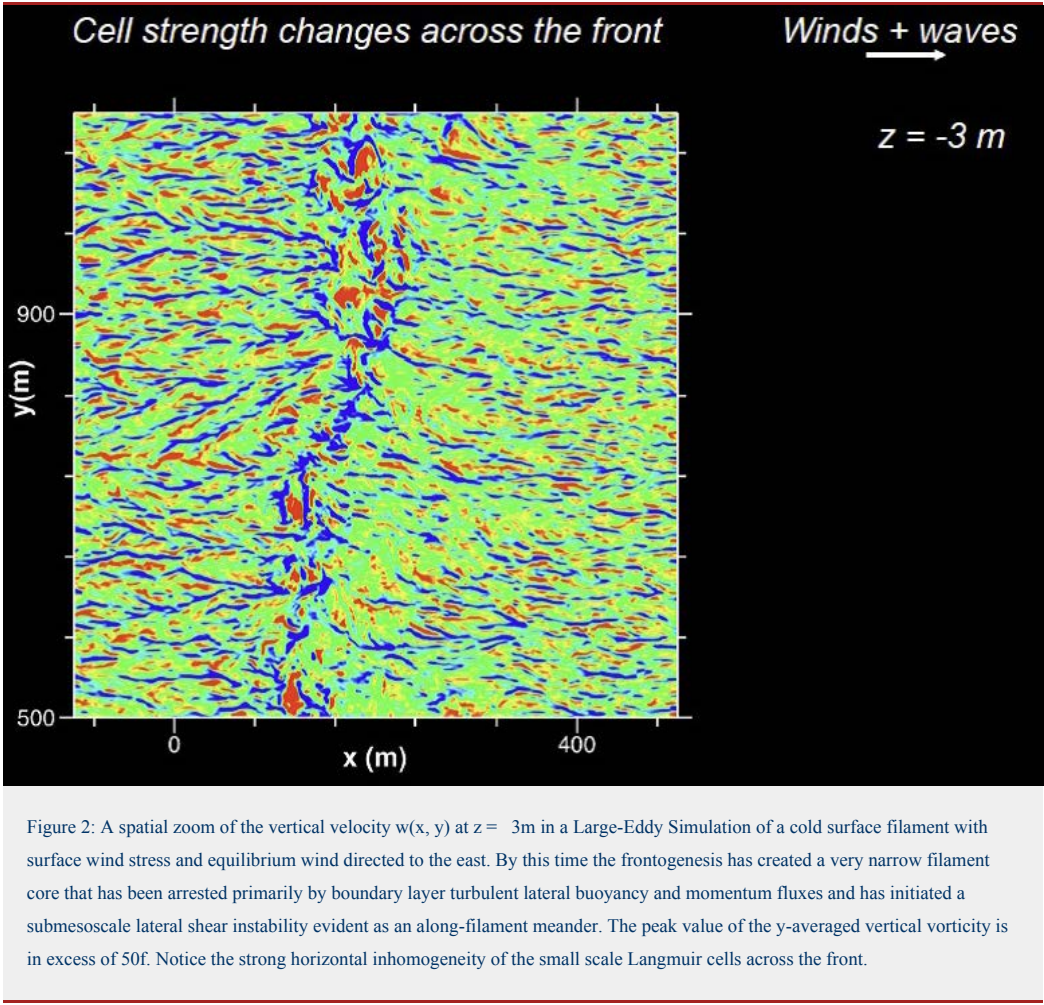


Figure 1: An idealized submesoscale dense surface filament: (top) buoyancy field and vertical eddy Viscosity as prescribed by the K-Profile Parameterization; (bottom) the associated cross-filament, along-filament, and vertical velocities as prescribed in a Turbulent Thermal Wind balance. The black line is the diagnosed boundary layer depth at  $z = -h(x)$ . This secondary circulation is convergent at the surface, hence frontogenetic. The fields are uniform in the perpendicular  $y$ -direction (McWilliams et al, 2015, *J. Phys. Oceanogr.*).

In support of this effort, a three-day workshop titled "Fundamental Aspects of Geophysical Turbulence II" (FGT II) was hosted by the Geophysical Turbulence Program, 5-7 August, 2015 at NCAR. Organizers included an MMM scientist and an MMM visitor. FGT II was a sequel to its 2014 predecessor held in Nagoya, Japan. The workshop featured 18 invited speakers who gave lively presentations on a spectrum of topics, including stratified Kelvin-Helmholtz turbulence, upper ocean dynamics, planetary dynamos, land-surface coupling in atmospheric boundary layers, fluctuating pressure measurements, and peta-scale simulations of forced stably stratified turbulence using grids of  $8192^3$  points. One of the common themes at the workshop was connecting motions across disparate time and space scales. An example is the work described by McWilliams et al. "Oceanic Submesoscale Dynamics: Dense Filament Frontogenesis & Arrest by Boundary Layer Turbulence." These peta-scale computations were carried out on the NWSC machine Yellowstone utilizing  $4 \times 10^9$  gridpoints. Typical results are shown in figures 1 and 2, and illustrate the importance of coupling small-scale boundary-layer turbulence and larger-scale submesoscale motions. Daily attendance averaged more than 40 participants, with attendees coming from NCAR and the broader outside community. Extended abstracts describing all presentations can be found at [http://www2.mmm.ucar.edu/people/sullivan/talks/gtp2/FGT\\_agenda.pdf](http://www2.mmm.ucar.edu/people/sullivan/talks/gtp2/FGT_agenda.pdf).

GTP brings together researchers interested in geophysical turbulence and large-scale flows. In FY 2015 the GTP program provided travel support for 13 scientists to attend the GTP workshop, with 11 from universities and two from research centers. Recent trends in geophysical turbulence were discussed and opportunities for future research in the subject were exposed. This enhanced understanding benefitted the university and broad research communities. The program also supported two longer term visitors who collaborated with NCAR staff on geophysical turbulence research.



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## ENABLING WORLD-CLASS COMMUNITY SCIENCE 3: EXPAND COMMUNITY ACCESS AND USE OF INSTRUMENTS, MODELS, AND DATASETS

MMM scientists are committed to providing model and observational datasets to the greater research community, accompanied with the collective knowledge gained from experience using them. They are also committed to training the next generation of scientists through tutorials on the WRF, MPAS, and WRFDA systems.

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# COMMUNITY TUTORIALS AND WORKSHOPS

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A major community outreach activity is tutorials that train university and other community scientists in the development and application of NCAR’s Community Models. To foster maximum impact, NCAR aspires to accept a student body with expertise over a wide range of scientific disciplines. To further outreach efforts, most tutorials, lectures, and exercises are made available via the web. There are also tutorials (with CISL) that train scientists in the use of the interpreted NCAR Command Language (NCL). Numerous classes are given throughout the year in Boulder, at UCAR-member universities, and at other research organizations around the world. NCL is one of the fastest growing interpreted languages in the geosciences. These tutorials help prepare young scientists with the programming tools they need to easily and effectively analyze model and observational datasets in a variety of formats.

MMM conducted two WRF tutorials at its Foothills Laboratory on January 26-February 3, 2015 and July 27-August 7, 2015. Both featured the basic WRF tutorial, followed by instruction on related systems. The January tutorial covered the MET (Model Evaluation Tools) verification package and was put on by the DTC. The July session included WRFDA and WRF-Chem tutorials. Also, in collaboration with the UK’s National Centre for Atmospheric Sciences (NCAS), MMM conducted a WRF tutorial in Chester, UK September 14-17, 2015. This basic WRF tutorial and one-day WRF workshop was supported by the UK/NCAS.

In addition, a 3-day regional climate tutorial was held at NCAR on July 22-24, 2015. This tutorial provided a broad overview of best practices for developing regional climate data and how it can be used for impact assessments. The mix of lectures and hands-on laboratories attracted approximately 40 participants from diverse backgrounds including academia, governmental organizations, and for-profit industries. A total of 86% of surveyed participants found the tutorial helpful or very helpful. Further details and slides are available at <https://www.mmm.ucar.edu/regional-climate-tutorial>.

NCAR also organized and hosted the 16th WRF Users' Workshop on June 15-19 for over 200 community participants. The first day featured lectures on the fundamentals of WRF dynamics. This was followed by three days of presentations on WRF developments, physics, data assimilation, chemistry, evaluation, and regional climate. Discussions by breakout groups addressed ideas for the future handling of WRF physics. The final day presented mini-tutorials on various model capabilities and topics: HWRF, MMET, VAPOR, NCL, Big Weather WRF, and radar data assimilation.



WRF workshop participants share information during the networking reception.



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## EDUCATION, OUTREACH, AND TRAINING

In FY 2015, MMM continued its tradition of hosting visitors from all over the world with expertise in a wide range of disciplines. This expands collaborative efforts across the global science community and is essential for assuring the health and vitality of MMM’s scientific programs. MMM’s Visitor Program includes students and post docs, including those from ASP’s Graduate Student and Postdoctoral Fellows programs. Many of these efforts tie to NCAR’s Strategic Plan to provide students, early career, and other scientists with exciting opportunities for educational and professional development; support for graduate students may include tuition reimbursement.

MMM’s Non-NSF Base funds support a number of post docs who contribute to MMM research activities. Also, MMM scientists and staff are active in the UCAR SOARS program and support diversity efforts.

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## DIRECTOR'S MESSAGE

Welcome to the Research Applications Laboratory's Annual Report for FY2015. Our mission is to conduct directed research that contributes to the depth of fundamental understanding of the atmosphere and its interaction with society, and to develop and transfer knowledge and technology that expands the reach of atmospheric science and contributes to the betterment of life on Earth. We are, at present, an organization with annual expenditures of approximately \$30M and a staff comprised of nearly 200 scientists, software engineers, and management/administration personnel.

I hope you will enjoy reading this year's Annual Report. As in the past, it follows the outline of our current strategic plan, providing details on our many accomplishments over the past year and our plans for the future. Below, I highlight a number of significant accomplishments of the past year:

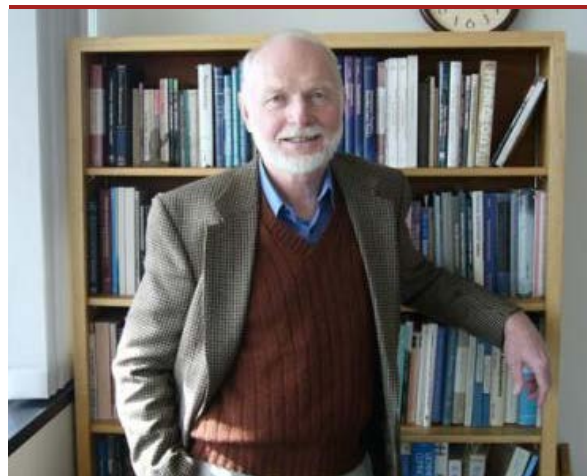
**WRF-Hydro:** The community WRF-Hydro modeling system, developed with NSF base funding under the leadership of Dr. David Gochis of RAL, was selected by the U.S. National Weather Service to provide a unified, high-resolution national water modeling capability for the continental U.S. A new award from NOAA in 2015 provides funding to conduct further model development and model optimization activities and to support the transfer of the model from research to operations with implementation on NOAA's National Centers for Environmental Prediction Weather and Climate Operational Supercomputing System. This work is an important example of the power of leveraging of NSF and NOAA funding in support of national interests.

**ICAR:** The Intermediate Complexity Atmospheric Research (ICAR) model was initially developed as part of the NCAR Water System program; the lead developer is Dr. Ethan Gutmann of RAL. ICAR is a simplified model which runs 100 to 1000 times faster than a traditional regional climate model such as WRF. ICAR is designed primarily for climate downscaling applications, and is the first physically based tool capable of downscaling an ensemble of climate projections for hundreds of years with a high spatial resolution. ICAR has sparked tremendous interest from the university community, the US Army Corps of Engineers, the Bureau of Reclamation, and the USGS, as well as a broad international interest including groups in Norway, Japan, and Canada. It is being published in the *Journal of Hydrometeorology* in fall, 2015.

**MET:** In 2015 we released a new version of the Model Evaluation Tools, a highly-configurable, state-of-the-art suite of verification tools developed using output from WRF. The latest version includes many enhancements to save users time and computational storage. The automated regridding tool, for example, allows users to specify a grid to be verified without generating additional files, saving as much as 60GB to 1TB per month in data storage. Another innovation allows users to read GSI diagnostic files and compute standard statistics, thus determining how their data assimilation system is impacting model predictions. And, in preparation for supporting the Global Model Testbed Center, as well as NCEP's Global Climate and Weather Modeling Branch, MET has been extended to compute scores that are more applicable to global and climate simulation studies.

**Accelerated Micro-scale Simulation:** Until recently the implementation of Large Eddy Simulation code to generate high-fidelity estimates of fine-scale atmospheric processes has been limited by the very large computational resources required to run the models. To address this problem, RAL scientists are exploring the use of new computational components such as graphics processing units (GPUs) which will allow us to run, for the first time, LES simulations in near real-time. These GPU-accelerated microscale simulations are a technological breakthrough with potentially significant impact for national security, renewable energy and aviation applications.

**Urban Futures:** An NSF-funded workshop held in 2013 to bring physical scientists, social scientists, and engineers together



Brant Foote - RAL Director

to address urban carbon issues resulted in the publication of a special issue of the AGU journal, *Earth's Future* in 2015. Four articles were published including a synthesis piece by RAL social scientist, Dr. Paty Romero Lankao, which has subsequently been translated into Chinese; a fifth article was also published this year in *Nature*. Another important outcome from this workshop was the formation within the USGCRP's Carbon Cycle Interagency Working Group of a new Urban Carbon Task Force to advance a research agenda for cities and the carbon cycle.

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# INFLIGHT, GROUND AND ENGINE ICING

## ICING

For the past two decades RAL scientists have worked to improve diagnoses and forecasts of icing conditions that impact aviation. The research areas include icing aloft, jet or turbine engine icing, and ground icing. Much of this work is accomplished as part of the FAA's Aviation Weather Research Program. One outcome from the icing aloft research are operationally-available, automated in-flight icing forecasts over the CONUS and Alaska. At this time, the Current and Forecast Icing Products (CIP and FIP) developed at RAL are running at the National Weather Service's Aviation Weather Center (AWC) and are approved for unrestricted supplementary use. The outputs include expected icing severity, probability of encounter, and potential for supercooled large drop (SLD, those drops with diameters exceeding 50 microns) at 13- km resolution over the CONUS for 0-18 h. The engine icing research falls under the FAA's High Ice Water Content (HIWC) program. This program sponsors research to develop an algorithm called the Algorithm for Prediction of High Ice Water Content Areas (ALPHA) to diagnose atmospheric conditions conducive to engine icing events. Another aspect of the HIWC program is field experiments to characterize the atmosphere where engine icing events will occur. RAL scientists have participated in these experiments that have taken place in Darwin, Australia and Cayenne, French Guiana. The ground icing research is supported by several FAA programs, whose goals are to improve the detection of, and forecasting of, icing conditions in the terminal area both at the ground and aloft. The current focus of the ground icing research is to develop a new freezing drizzle algorithm for use on the Automated Surface Observing System (ASOS) and to determine the variability of snowfall across the terminal area. RAL is also working on a radar-based icing detection algorithm called Radar Icing Algorithm (RaDIA) that makes use of fields from NWS dual-pol NEXRAD radars. This work is based on lessons learned from working with the NASA Icing Remote Sensing System.

## FY2015 ACCOMPLISHMENTS

In 2015 RAL continued work on a number of icing aloft projects for the FAA: 1) MICRO (Model for Icing Conditions in Real-time Operations), which will incorporate a high-resolution NWP model and improved use of sensor data to output the full drop size distribution (DSD) for icing prediction and severity calculations; 2) IPA (Icing Product-Alaska) which will revise CIP and FIP for the Alaska weather and data environments; 3) organization and conduct of a technical interchange meeting with the FAA to discuss the state of icing research and needs of the user community; and 4) evaluations of improvements to icing diagnosis using NEXRAD dual-polarization data. For IPA, the forecast component went under review by the FAA's technical review panel (TRP) for approval as an experimental product. An initial dual- polarization Radar Icing Detection Algorithm, RaDIA, was implemented locally on data streams from two NEXRAD dual-pol radars. Engineers began work to transfer RaDIA to the National Severe Storms Laboratory (NSSL) to integrate into the Multi-Radar/Multi-Sensor (MRMS) system. This new algorithm combines RAL's Icing Hazard Level (IHL) algorithm, tested on research radars, and new work that identifies glaciated areas using ZDR information.

RAL staff working on the High Ice Water Content (HIWC) project joined with members of the European High Altitude Ice

Crystals (HAIC) project to conduct a field study in Cayenne, French Guyana in spring 2015. Staff travelled to Cayenne to run the ALPHA (Algorithm for Prediction of High Ice Water Content Areas) workstation and collaborate with MeteoFrance staff and other HIWC partners to nowcast and forecast HIWC conditions in the area. The HAIC Falcon 20, Canadian Convair, and Honeywell B757 research aircraft were instrumented to sample high ice crystal environments, mostly in the outflow of deep convection. A second field campaign was conducted with the NASA DC8 in August 2015. The ALPHA system was again operated in support of HIWC research flights. The data will be used to assess ALPHA skill in identifying areas of elevation ice water content. The ALPHA concept uses NWP output combined with satellite and radar data to diagnose cold cloud tops, warm atmosphere (compared to a standard sounding), high radar reflectivity below typical flight cruise altitudes, and other factors to determine regions conducive to the high ice water content hazard.

The Terminal-Area Icing Weather Information for NextGen (TAIWIN) project continued to assess freezing drizzle detection instruments and algorithms’ ability to determine the variability of winter precipitation around airports. The NextGen Surface Observing Capability (NSOC) project, also sponsored by the FAA, completed its first year of observations. The highest priority from this evaluation was the detection of winter precipitation at the surface at airports. The focus was primarily on measurements not currently available on the Automated Surface Observing Systems (ASOS), including drizzle, freezing drizzle and ice pellets. The approach has been to determine the ability of the latest generation of present weather type sensors on the market to accurately detect the various types of precipitation. A test site was set up at the NCAR Marshall test facility, as well as at the Volpe Transportation Center in Massachusetts and at the FAA’s Technical Center at Atlantic City, New Jersey. The NCAR team will be installing additional sites in Grand Forks, ND; Pittsburgh, PA; and St. John’s, Newfoundland to ensure enough data in different climate regimes are collected to make a meaningful evaluation of instrument and algorithm capabilities.

PLANS FOR 2016

In 2016 an experimental version of MICRO will be run on a 1000km by 1000km region centered on Cleveland, Ohio. For IPA, the focus will be on the diagnostic component of the algorithm and on working with the FAA to determine the optimal operational setting for IPA. Engineers will be working with NCEP to transfer CIP and FIP to its supercomputing environment WCOSS. The transfer of RadIA to MRMS will be completed.

TAIWIN will move its snow variability study from Denver International Airport to the Boulder-Marshall area. The study will include shielded snowgauges with data collection at sub-minute (6-second) intervals. The project team will also focus on final development of the FZDZ algorithm for use on ASOS. The NSOC team will oversee the installation of the additional sites and provide support for those sites throughout the winter.

Analysis of datasets obtained from HIWC field campaigns in 2014 and 2015 will be a focus of the HIWC Product Development Team. These datasets will be used to evaluate performance of the ALPHA nowcasting tool and tune it to better simulate the measured IWC conditions.

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PREDICTION OF STORM HAZARDS FOR AVIATION

BACKGROUND

The Next Generation Air Transportation System (NextGen) is a national priority designed to meet the air transportation needs of the United States in the 21st century—in particular, a significant growth in demand for air traffic services, possibly on the order of two to three times today's demand levels. Since weather conditions can seriously restrict aircraft operations and levels of service available to system users, the manner by which weather is observed, forecast, disseminated, and used in decision-making is of critical importance.

For the past several years, the NCAR Research Applications Laboratory (RAL) has been engaged in multiple FAA-funded research and development efforts geared toward improved convective weather support for air traffic management en route and in/out of terminals, and more recently for improved airport operations safety from lightning for outdoor workers. In addition, efforts have continued in terms of enhancing understanding of numerical weather prediction model performance, which enables effective harvesting of model predictions for convective storm initiation and probabilistic forecasting.

FY2015 ACCOMPLISHMENTS

The 0 – 8 hour CoSPA forecasts, jointly developed and maintained by MIT Lincoln Laboratory, NOAA Earth System Research Laboratory, and NCAR RAL, continue to be made available to aviation planners (i.e., select FAA and airline industry partners) via a web-based display from April through October (i.e., convective season). The display allows users to overlay airports and associated arrival and departure fixes, route structures, and sectors on current and forecast weather facilitating the product's utility (Figure 1). An initial version of CoSPA is currently undergoing acquisition by the FAA's NextGen Weather Processor. Additional research has been conducted to improve the performance of the CoSPA forecasts, especially with regard to a smoother blending of the heuristic and model-generated storm predictions.

Another major research effort has been focused on the safety risks of

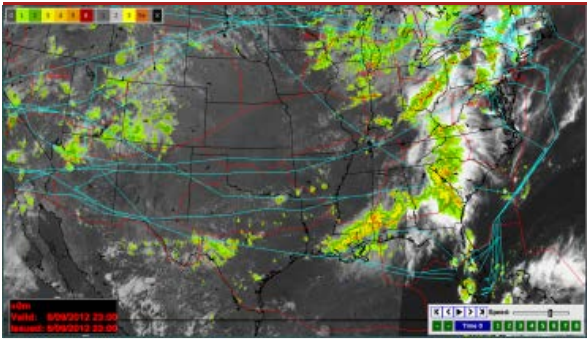


Figure 1. Analysis and forecast products made available to aviation planners via a web-based display.

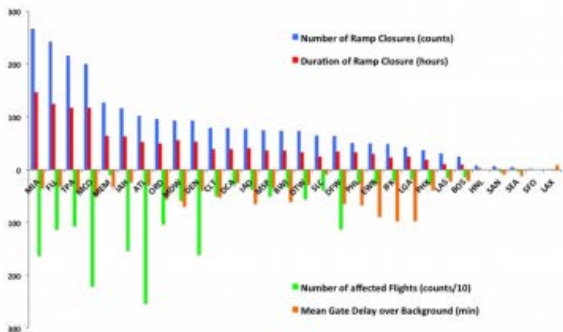


Figure 2. Lightning impacts on ramp operations (number and duration

personnel working outdoors at airports (e.g., baggage handlers, food and fuel suppliers) and the impact on operational efficiency when thunderstorms are in the vicinity that may generate cloud-to-ground lightning strikes. This ongoing collaborative effort with various airport and airline stakeholders has revealed substantial uncertainty associated with the decision-making process for ramp closures (i.e., pulling people inside for safety reasons) due to thunderstorms and lightning in close proximity of concourses/gates. This uncertainty is caused by the various sources of lightning information, differences in procedures applied by the various stakeholders, human cognition and behavior, and the way information is communicated. Moreover, detailed analyses of air traffic data in conjunction with lightning data suggests that lightning-induced ramp closures, especially for prolonged duration or if multiple closures happen in succession, can exert notable impacts on traffic in/out of an airport (Figure 2) and potentially cause ripple effects through the national airspace system. Current efforts are geared toward quantifying the risk of outdoor workers exposed to lightning threats, understanding the causality of the observed delays, and characterizing the propagation of delays through an airline’s schedule as a way to identify opportunities for improved ramp closure decisions and traffic management under thunderstorm impacts.

of closures) and air traffic efficiency (affected flights and average pushback delays) for 30 major United States airports.

Unexpected initiation of large-scale convective storms can exert substantial impacts on air traffic as well. Using data mining approaches and ensemble forecasts, RAL research this past year continued to focus on early identification of areas prone to develop large-scale storms, including assessment of how well numerical weather prediction models capture those storm initiation areas. Unfortunately, numerical weather prediction models continue to experience difficulty in grasping whether a storm should be initiated or not in a particular area and to how it will evolve, given the timing of initiation and whether the storm system remains organized long enough. Scientists observed notable regional differences in model skill (Figure 3), such as the initiation of too many large-scale storms over the Great Plains and not enough of them over the southeastern parts of the United States, including a tendency for large storms to dissipate too quickly. The lessons learned from the assessment of model performance help improve the blending of heuristic and model-generated forecasts for the Consolidated Storm Prediction Algorithm (CoSPA).

This substantial prediction uncertainty provides a reason for developing probabilistic convective storm guidance products using ensemble forecasts. Two probabilistic prediction efforts are underway, one focused on calibrating a probabilistic storm impacts product based on ensemble forecasts for the United States, while the other aims at developing a probabilistic convection guidance product based on global ensemble forecasts for strategic transoceanic air traffic planning (see oceanic weather). Both these tasks include a close collaboration with the NWS Aviation Weather Center (AWC).

FY2016 PLANS

Research and development will likely continue toward improving the CoSPA forecast system, particularly focused on the calibration of model storm intensity, correction of model storm position errors and treatment of storm initiation in the blending algorithm. Starting with this winter season, CoSPA forecasts will now be provided to aviation planners during the entire year.

It is expected that new capabilities and products will be periodically demonstrated to users as technologies mature. A lightning hazard synthesis capability may be developed during the next year and additional air traffic impact analyses conducted in collaboration with AvMet Applications. Development of ensemble-based probabilistic storm impact predictions will continue primarily for transoceanic flight domains.

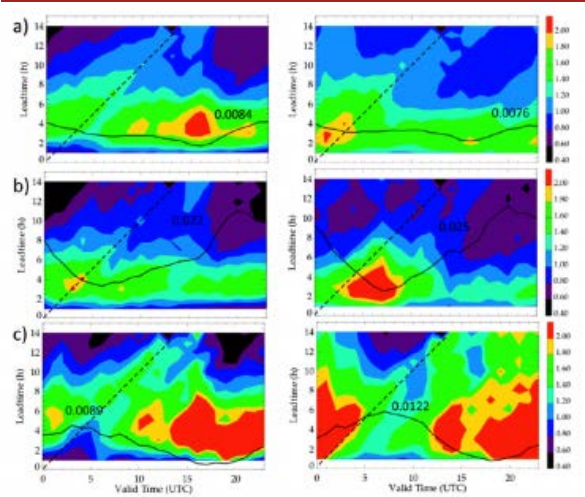


Figure 3. Model bias as a function of lead time and valid time of day in the eastern United States (a), the Southeast (b), and Great Plains (c) during 2012 (left) and 2013 (right). Solid curves indicate relative variations in observed large-scale storm frequency with time of day for a given region. Dashed diagonal lines indicate the lead time/valid time coordinates of the 0000 UTC forecasts.

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# TURBULENCE

## BACKGROUND

Turbulence encounters by general and commercial aviation pose significant safety and flight efficiency concerns. Almost anyone who has flown commercially has had an unpleasant experience with turbulence and has a tale to tell about it. In fact, turbulence encounters account for well over 75% of all weather-related injuries on commercial aircraft and amount to at least \$200M annually in costs, according to some estimates. Consequently, there is an urgent need to provide better turbulence information to pilots and route planners so that the number of encounters can be minimized, or to provide adequate warnings so that passengers and crew can better prepare for an expected encounter.

For more than twenty years, a group of scientists and engineers at the National Center for Atmospheric Research's Research Application Laboratory (NCAR/RAL) has led efforts to address these needs. Working under the sponsorship of the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the Taiwan Civil Aeronautics Administration (CAA) and in collaboration with several universities and private companies, the team has conducted research aimed at improving fundamental understanding of the nature and causes of turbulence and has developed new techniques for better observing and forecasting turbulence.

Efforts have been focused in four areas: (1) Development and implementation of new techniques for obtaining automated *in situ* reports of turbulence encounters from commercial aircraft; (2) development of an automated system for detecting in-cloud turbulence using Doppler weather radar data; (3) development and implementation of an automated turbulence diagnosis, nowcasting and forecasting system called Graphical Turbulence Guidance or GTG; and (4) high-resolution simulation studies of observed turbulence events to better characterize the nature and genesis of free atmosphere turbulence. The products developed at RAL have reached a level of maturity that allows them to be used operationally by pilots and route planners in tactical and strategic planning for avoiding turbulence or mitigating encounters. One important aspect of all products is that they provide an aircraft-independent measure of atmospheric turbulence known as the energy (or eddy) dissipation rate or EDR ( $\text{m}^{2/3}/\text{s}$ ).

## AUTOMATED *IN SITU* MEASUREMENTS

Despite the continued reporting of the frequency and severity of turbulence encounters, understanding of the nature and genesis of this complex atmospheric phenomenon remains limited. Research to better understand the nature and causes of free atmosphere aviation-scale turbulence has been limited in part by a lack of reliable data. Verbal pilot reports (PIREPs) have typically been the only source of information about the location and severity of turbulence at flight levels. These reports are, unfortunately, incomplete (reporting is voluntary), and highly subjective (what one pilot views as "moderate" might be perceived as "light" or "severe" by another). Further, recent investigations into the accuracy of PIREPs have

indicated an average position error of about 50 km, or several grid points with current operational numerical weather prediction (NWP) model grid spacings. While NWP models are very useful in forecasting other atmospheric hazards, they are of limited value for turbulence given that turbulence exists for short periods of time and in small geographical areas. In order to improve the detection and forecasting of turbulence, it is clearly essential to upgrade the turbulence observation and reporting system and to create empirical means for obtaining more abundant, reliable data. In pursuit of this goal, we are in the process of augmenting, and eventually replacing, the PIREPs with *in situ* observations from selected commercial aircraft. These observations and dissemination of them are completely automated, and provide a measure of atmospheric turbulence intensity levels (EDR). The *in situ* EDR system developed by NCAR scientists and engineers consists of a simple software upgrade to the aircraft's ACMS (Aircraft Condition and Monitoring System), and no hardware changes are required.

**FY2015 Accomplishments**

Currently the *in situ* EDR software package is implemented on about 22 United Airlines (UAL) 757-200 aircraft, 168 Delta Air Lines (DAL) 737 and 767 aircraft, and 100 Southwest Airlines (SWA) 737-700 and -800 aircraft, providing roughly 18,000 reports per month. An example of the coverage by these aircraft is given in Fig. 1. This algorithm is expected to be implemented on other aircraft in the coming years; the highest priority is implementation on international aircraft to enhance global coverage. Commercial vendors are also beginning to provide automated *in situ* EDR estimates, and one work area this year was to develop EDR estimation standards to insure that all EDR estimation methods provide similar results, at least within the operational needs.

**FY2016 Plans**

Discussions will be conducted with Air France, British Airways, Lufthansa, Korean Airlines, Xiamen Airlines, and DAL to implement the *in situ* EDR algorithm on all or parts of their fleets. Modifications to the algorithm will be made to accommodate B777 aircraft which has a 10-Hz sampling rate, compared to the others which are 8-Hz.

**REMOTE SENSING MEASUREMENTS**

In order to give pilots better information about potentially hazardous regions of turbulence in thunderstorms before they encounter them, RAL scientists developed the NEXRAD Turbulence Detection Algorithm (NTDA) to use ground-based Doppler radar data to remotely detect turbulence within clouds. The algorithm runs on data from each radar, processing each "tilt" or "sweep" independently to obtain estimates of EDR. The results are merged with measurements from other radars and mapped to chosen flight altitudes. The initial version of the NTDA was adopted by the National Weather Service and implemented on all of its radar systems in 2007 and 2008. Since then, a number of advancements have been made to the NTDA to increase its coverage, accuracy, speed and maintainability, and to accommodate NEXRAD changes like the adoption of dual-pol and the implementation of a new spectrum width estimator (also developed by RAL staff). Recently, the NTDA has been modified to run on radars in Taiwan, as well.

**FY2015 Accomplishments**

NTDA data were used to analyze the development of turbulence inside thunderstorms and relate turbulence intensity and volume to the occurrence of lightning. The correlation between these quantities may be used in conjunction with future geostationary satellite lightning mapping data to help diagnose likely regions of turbulence in regions not served by Doppler radar.

**FY2016 Plans**

RAL scientists plan to investigate the possibility of using the newly-available NEXRAD dual-polarization data to further improve the NTDA's data quality. NTDA will continue to run as a real-time prototype over the CONUS, Alaska, Hawaii and Puerto Rico, providing data used for the development of turbulence nowcast products and scientific investigations of the development of convective storms. It will be adapted as needed to accommodate changes to the NEXRAD radars.

**NOWCASTING/FORECASTING TURBULENCE**

RAL has been developing and testing aviation-scale turbulence forecast algorithms that provide forecasts out to 18 hours, updated hourly. The version that is used over the CONUS is termed the GTG (Graphical Turbulence Guidance product). It

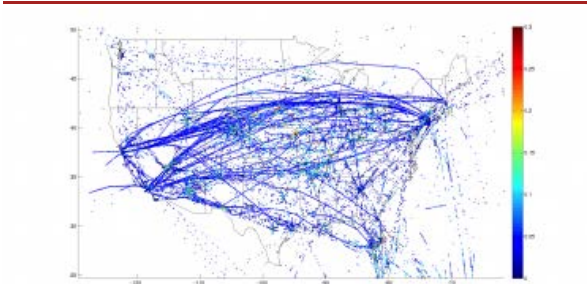


Figure 1. In situ EDR observations of turbulence automatically reported by UAL 757, DAL737, DAL767, and SWA737 aircraft for the 24hr period on 5 June 2015. The color scale is the EDR intensity (m<sup>2</sup>/3 s<sup>-1</sup>). EDRs > ~0.3 indicate areas of at least "moderate" turbulence intensity for a mid-sized commercial aircraft.



relies on the WRF RAP NWP model (<http://rapidrefresh.noaa.gov/>) output and provides what amounts to an ensemble weighted mean of various turbulence diagnostics output as EDR ( $\text{m}^{2/3} \text{s}^{-1}$ ) on designated flight levels. The output is available to interested users on NOAA's ADDS web site (<http://www.aviationweather.gov/adds/>).

In addition to the GTG *forecast* system (forecasts updated hourly), RAL is currently developing a *nowcast* system, GTG-N, which provides rapid (every 15 min) updates and make heavy use of the latest available turbulence observations from the *in situ* EDR estimates, PIREPs, NTDA, and other sources (e.g., satellite-based inferences) on a GTG background. This product is intended to provide enhanced pilot situational awareness, especially for turbulence associated with thunderstorms (convectively-induced turbulence or CIT). Special diagnostics (Diagnose Convectively-Induce Turbulence or "DCIT") have been developed to predict areas of likely near-cloud turbulence. DCIT employs statistical learning techniques in conjunction with a large database of *in situ* EDR reports and collocated radar, satellite, lightning, and NWP model-derived data fields.

**FY2015 Accomplishments**

A major upgrade to the GTG product (GTG3) was released in October 2015, following FAA's independent verifications and safety reviews conducted earlier in the year. The upgrades include (1) the inclusion of specific mountain-wave turbulence (MWT) predictive algorithms to better forecast this source of turbulence over mountainous regions of the U. S.; and (2) the prediction of turbulence at low levels, i.e., below 10,000 ft MSL (the previous GTG2.5 version provided predictions only at or above 10,000 ft MSL). The product now also produces separate forecasts for clear-air turbulence (CAT) and mountain wave turbulence (MWT). Although the displays are for EDR, an atmospheric turbulence metric, users may also be able to get some idea of the expected aircraft response to turbulence by choosing light, medium, or heavy aircraft for the displays.

Work also began on a turbulence prediction system, for the Alaska region, as well as on the development of a global forecast system.

**FY2016 Plans**

An update to the GTG forecast component will include a nowcast component (GTGN), which uses observations merged with short-term forecasts to provide EDR maps updated at 15 min intervals. GTGN will be independently evaluated by NOAA's GSD verification group. This new version of GTG will become operational in late 2016. Testing and evaluation of the Alaska and global products will continue. Research on developing algorithms for forecasting convectively-induced turbulence (CIT) will also continue. These CIT forecast algorithms will become part of GTG4.

**CHARACTERIZATION EFFORTS**

Substantial effort has been invested in developing a better physical understanding of the mechanisms responsible for convectively induced turbulence (CIT) and clear air turbulence (CAT) with the long-term goal of providing better operational turbulence forecasts. These studies make use of high-resolution nested (WRF) numerical simulations that have outer computational domains large enough to capture the relevant large-scale forcing processes and inner domains fine enough to capture the turbulence generating mechanisms. An example turbulence case related to banded structures in anvil cirrus associated with a winter-time storm over the N. Atlantic is shown in Fig. 3. In this case there were many reports of turbulence in the vicinity of the bands.

**FY2015 Accomplishments**

By careful examination of observations (PIREPs and *in situ* EDR reports) compared to satellite imagery, RAL scientists have isolated several cases where banded structures in the anvil cirrus of convective storms seem to

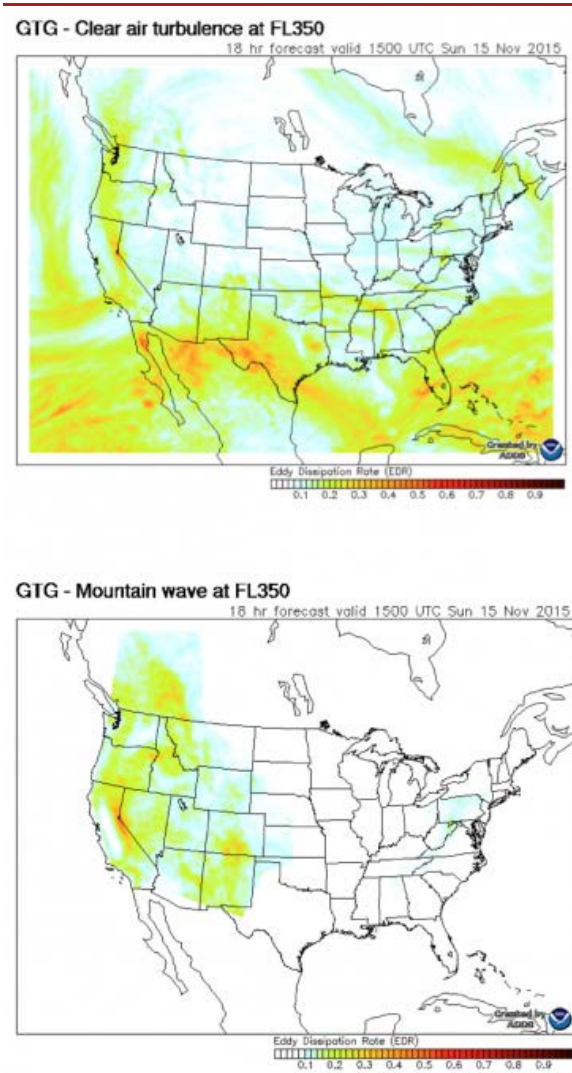


Figure 2. Example GTG3 output as it appears on NOAA's Experimental ADDS website for an 18-hr forecast at flight level (FL) 350, i.e., about 35,000 ft of (a) clear-air turbulence and (b) mountain wave turbulence.

be highly correlated to regions of elevated turbulence. The relation of the bands to the turbulence has been investigated for summertime storms revealing that the bands seem to have the character of planetary boundary layer rolls. Other cases involving banded structures in winter-time storms are being investigated (see Fig. 3). Preliminary results indicate the same mechanism is at play, but regions of negative absolute vorticity are also present, so this makes the turbulence generation processes more difficult to isolate. These cases are extremely complex, with convection playing a major role in the production of turbulence, even when the turbulence occurs outside the storm boundaries. Case studies such as these are ongoing.

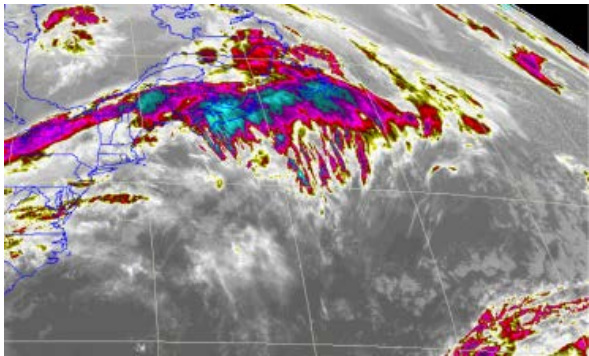


Figure 3. Example (16 UTC 15 Nov 2011) of turbulence associated with banded structures in a N. Atlantic storm.

FY2016 Plans

Efforts to isolate cases and resolve turbulence sources will continue. This will lead to a better understanding of turbulence in the free atmosphere which in turn should suggest improved forecasting strategies. Since this work is unique and original, we anticipate several publications to be forthcoming on the results.

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# INTEGRATION OF WEATHER INFORMATION INTO AIR TRAFFIC MANAGEMENT

## BACKGROUND

Since weather conditions can seriously restrict aircraft operations and levels of service available to system users, the manner in which weather is observed, forecast, disseminated, and used in making air traffic management (ATM) decisions is of critical importance to the operation of the United States' National Airspace System (NAS) and international airspaces, especially oceanic domains. As the United States moves toward significantly increasing the capacity of the NAS through implementation of the Next Generation Air Transportation System (NextGen), integrating weather information (and associated uncertainty) into ATM decision-making processes is critical. Moreover, harmonization around the globe with partners such as the Single European Sky ATM Research (SESAR) plays an important role as well. NCAR/RAL contributes in various ways to these efforts by developing aviation weather hazard guidance products and means for their dissemination, collaboration with users of such products, including assistance with integration into decision support tools. In addition, RAL participates in many outreach and education activities.

## WEATHER INTEGRATION ACTIVITIES WITH FAA

Under sponsorship of the FAA's Aviation Weather Research Program, RAL continues to develop weather hazard guidance products based on utilizing observations, diagnosing model output, and making use of data fusion and mining technologies. Probabilistic prediction methodologies are developed that build on ensemble models and translate atmospheric conditions into aviation impacts. These research and development efforts are discussed in the convective storms, turbulence, icing, oceanic weather and dissemination sections of this annual report.

## WEATHER INTEGRATION ACTIVITIES WITH NOAA

Under an Aviation Weather Cooperative Agreement (AWCA) with NOAA, RAL continued efforts to transition weather prediction capabilities from research to operations across federal agency lines for NextGen interim capabilities. The support for advancing technology transfer of icing and turbulence hazard guidance products to global forecast models in support of the World Area Forecast Centers (WAFCs) has ended. The primary focus this past year was on finishing the comparison of two radar-based convective storm products.

## FY2015 Accomplishments

Comparison of two key convective storms products: It is important to understand the similarities and differences between the radar analysis products and associated forecasts, which are used for operations at the NWS and those used at the FAA. The focus of this effort has been on objectively comparing the Multi-radar Multi-sensor (MRMS) convective storm analysis and forecast products generated by the National Severe Storms Laboratory (NSSL) to the Corridor Integrated Weather System (CIWS) products developed by the Massachusetts Institute of Technology (MIT) Lincoln Laboratories (LL). Notable differences have been identified (Figure 1) that also vary by time of day, season, and geographical location, as detailed in a

substantial report to NOAA. Understanding these differences and recognizing which solution may better represent the truth remains to be accomplished should additional funding for this work become available in the future.

FY2016 Plans

The period of performance for the NOAA Aviation Weather Cooperative Agreement is ending, and at this time no additional funding has been identified.

WEATHER INTEGRATION OUTREACH ACTIVITIES

RAL continues to participate in many outreach venues to further weather R&D, harmonization, and integration into ATM decision support tools. Notable events this past year included workshops sponsored by the FAA and the Air Traffic Control Association (ATCA). Moreover, the Friends and Partners in Aviation Weather (FPAW) meetings organized by RAL and hosted by the National Business Aviation Association (NBAA) at its Annual Convention & Exhibit and the National Transportation Safety Board (NTSB), respectively, continue to serve as an excellent venue to share and discuss latest developments with industry, government and research partners. RAL staff is represented on several ICAO, FAA and industry advisory committees such as the RTCA and SAE G-10 (weather displays on the flight deck), and professional organizations such as AMS and AIAA.

HALABY FELLOWSHIP

The Najeeb E. Halaby Graduate Student Fellowship was established by NCAR/RAL to shape the next generation of researchers in aviation weather, honoring the late Najeeb Elias Halaby, an eminent aviator and administrator, for his vision and more than five decades of extraordinary contributions to aviation (<http://www.ral.ucar.edu/halabyfellowship.pdf>). The recipient of the Halaby Fellowship will spend three months in residence with NCAR’s Aviation Weather Research Program, which Mr. Halaby was instrumental in establishing in the 1980s.

The Fellow will conduct research broadly aimed at improving the integration of weather into decision support tools for improved weather avoidance and air traffic management. The first fellowship holder, Manuel Sauer of the University of Hannover, Germany, will begin her stay in Boulder in November 2015.

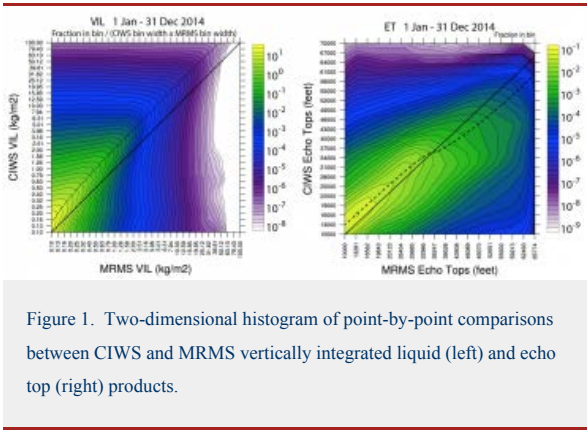


Figure 1. Two-dimensional histogram of point-by-point comparisons between CIWS and MRMS vertically integrated liquid (left) and echo top (right) products.

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## DISSEMINATION OF AVIATION WEATHER INFORMATION

### BACKGROUND

Development of the Next Generation Air Transportation System (NextGen), a national program designed to meet the expanding air transportation needs of the US in the 21<sup>st</sup> century, is well underway, with member agencies defining their needs for R&D and acquisitions. Defining the weather information needs of NextGen and providing common weather-related decision information to all stakeholders within the system is an important element of the overarching program. Since weather conditions can seriously restrict aircraft operations and levels of service available to system users, the manner by which weather is observed, forecast, disseminated, and used in decision-making is of critical importance.

RAL's activity in dissemination of aviation weather information is concentrated in three areas:

1. Common Support Services – Weather (CSS-Wx), developing next generation technology and infrastructure for dissemination of weather data to US Government and other users;
2. Aviation Digital Data Service (ADDS), delivering weather data and support services to the aviation community using the Internet; and
3. Weather Technology in the Cockpit (WTIC), developing methods for making the best weather information available to pilots for decision-making in the cockpit.

### COMMON SUPPORT SERVICES – WEATHER (CSS-WX) PROGRAM

RAL has been one of the key contributors in developing standards and technology for the FAA research and acquisition programs focused on weather in the NextGen. This work, part of the FAA's Common Support Services (CSS) Program, is aimed at developing next generation technology and infrastructure for dissemination of weather data to FAA and other aviation users. It focuses on enabling ubiquitous access to aviation weather data anywhere an appropriate network connection is available.

CSS-Wx achieves its goal by using a service-oriented architecture (SOA) approach in which existing Internet technology is leveraged to build weather data directory and delivery services that conform to international standards. CSS-Wx is combining a data directory service using OASIS ebXML Registry/Repository (Reg/Rep) standards with data servers based on the Open Geospatial Consortium (OGC) Web Feature Service (WFS) and Web Coverage Service (WCS) standards. Using these technologies, it is possible to build complex, dynamic weather systems in which data sources and clients can be developed

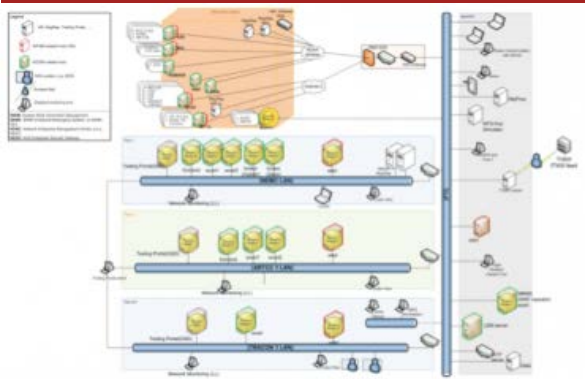


Figure 1. Diagram of Capability Evaluation with tiered data distribution.

and modified independently but remain compatible while optimizing data latency and network bandwidth. RAL's participation in this program is sponsored by the FAA CSS-Wx Program Office and work is conducted collaboratively with the FAA's William J. Hughes Technical Center, MIT/Lincoln Laboratories, and NOAA.

**FY2015 Accomplishments**

In FY2015, the FAA CSS-Wx program awarded a contract to a commercial vendor for implementation and operational deployment of the CSS-Wx system in the FAA National Airspace System. RAL made final updates to the Web Coverage Service Reference Implementation (WCSRI) capabilities to address needs identified by a FAA program that is acting as a pre-production user of the weather data dissemination technologies of NextGen. A final version of the WCSRI reference implementation software was delivered to the FAA in May. In addition, RAL acted as the FAA's technical expert and worked with experts from the International Civil Aviation Organization (ICAO) and the World Meteorological Organization (WMO) to establish new XML-based weather data standards.

**FY2016 Plans**

The focus for FY16 is supporting the FAA's acquisition process for CSS-Wx, including providing technical guidance to the FAA and the CSS-Wx commercial vendor. RAL will also continue its work on XML-based weather data standards in concert with ICAO and the WMO.

**AVIATION DIGITAL DATA SERVICE (ADDS) PROGRAM**

ADDS is a dissemination program that uses web pages to distribute aviation weather data. There are two instances of ADDS web pages: Experimental ADDS which is run at NCAR and Operational ADDS which runs at the NWS Aviation Weather Center in Kansas City. RAL uses Experimental ADDS to expose new prototype weather products to aviation users and gather feedback on the products' utility. Operational ADDS provides weather products that have been through the full review and approval process for operational use in aviation.

**FY2015 Accomplishments**

For the first 6 months of FY2015 Experimental ADDS continued to provide critical weather information to a broad cross-section of the aviation community, 24 hours a day, 7 days a week. NCAR's ADDS web site delivered real time aviation weather information to 500,000 different users every month. June marked a huge milestone in the ADDS Program. Technology transfer from NCAR to NOAA was completed and going forward the NOAA Aviation Weather Center will be operating ADDS.

**FY2016 Plans**

The Experimental ADDS Program is now completed.

**WEATHER DISSEMINATION TO THE FLIGHT DECK - WEATHER TECHNOLOGY IN THE COCKPIT (WTIC) PROGRAM**

One of the programs led by the FAA's Aviation Weather Office (AWO) is Weather Technology in the Cockpit (WTIC). RAL engaged in an effort for WTIC to study the requirements and technologies that would enable pilots to gain the advantages inherent in the rapidly emerging world of mobile technologies, including both tablets and phones. In this project, referred to as MobileMet, RAL provided a comprehensive technology assessment of mobile devices for use in delivery of weather information to the cockpit. RAL also conducted a broad survey of the needs and expectations of users in relation to mobile devices for aviation weather delivery. In addition, RAL developed and delivered prototype application based on the user needs survey.

**FY2015 Accomplishments**

Based on the results of the previous year's cognitive walkthrough evaluation, RAL enhanced the Mobile Met application to prepare for a

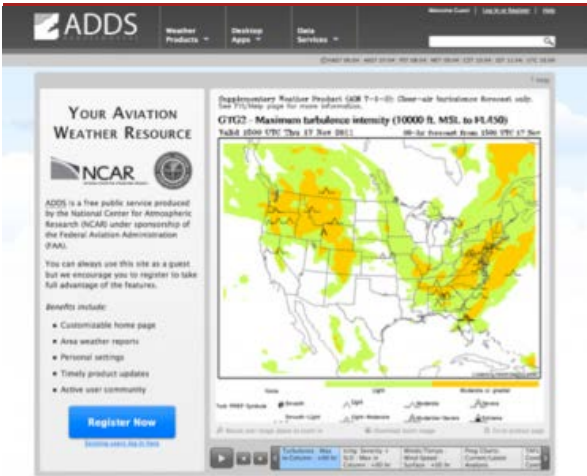


Figure 2. The Experimental ADDS Web site.



Figure 3. WTIC MobileMet Application Prototype screen

task simulation evaluation by the FAA Technical Center. These changes included modifications to the user interface and improved data display techniques.

FY2016 Plans

Based on previous research and evaluations, RAL will develop a draft of minimum weather service recommendations for mobile device use in general aviation aircraft. Also, RAL will make modifications to the Mobile Met Application to implement a phase of flight-oriented user interface and display. These modifications will be considered for evaluation by the FAA Technical Center.

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# OCEANIC WEATHER

## BACKGROUND

Weather conditions can seriously restrict aircraft operations and levels of service available to system users. Thus, the manner by which weather is observed, forecasted, disseminated, and used in decision-making is of critical importance. Aviation users operating within oceanic and remote regions have limited access to high-resolution (temporal and spatial) weather products that depict the current and future locations of deep convection and turbulence.

To address these needs, RAL scientists develop weather products related to the oceanic/remote occurrence of deep convection. Global ensemble forecasts are being utilized to provide probabilistic guidance of convective storm hazards for long term flight planning purposes as needed for transoceanic flights (24-36 hr). The Oceanic Convection Diagnosis and Nowcasting system is being developed to detect and forecast deep convection using satellite-based methodologies, global lightning data and numerical model results. Two products in the system, the Cloud Top Height (CTH) and the Convective Diagnosis Oceanic (CDO), are being displayed within the flight deck of Lufthansa Aircraft. The CTH has been tested for domestic use by the FAA Weather Technology in the Cockpit (WTIC) program. Accomplishments and plans related to the ongoing research and development of convection weather products are discussed below.

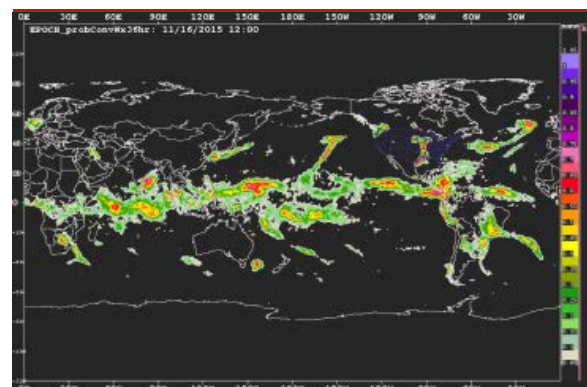
## PROBABILISTIC GUIDANCE OF CONVECTIVE HAZARDS

Use of ensemble probabalistic forecasts is one way of addressing uncertainty in convective hazard forecasting. NCAR/RAL has been developing such a forecast product to provide probabilistic guidance on convective storm hazards for transoceanic flights at lead times of 24 – 36 hours. RAL's approach of fusing ensemble forecasts provided by several global prediction centers is being utilized to facilitate global harmonization of World Area Forecast System (WAFS) products.

## FY2015 Accomplishments

This past year efforts went into refining the methodology of fusing data from multiple global numerical prediction centers and calibration of the resulting probabilistic guidance product. Moreover, the domain was significantly expanded from previously limited Pacific and Caribbean regions to nearly-global coverage (Figure 1). In addition, a cloud top height guidance product has been added. The current real-time prototype utilizes global ensemble forecasts from the United States and Canada's numerical prediction centers; ensemble data from two European and one Chinese prediction centers are also being explored in an offline mode.

Significant effort continues to go into development of a "truth field"





based on satellite and global lightning data to enable assessment and calibration of the probabilistic guidance on convective storm hazards. The truth field development is largely based on previous NASA-funded efforts for the detection and nowcasting of oceanic convection that can be viewed at [http://www.rap.ucar.edu/projects/ocn/realtime\\_sys](http://www.rap.ucar.edu/projects/ocn/realtime_sys).

This effort is in close collaboration with the NWS Aviation Weather Center (AWC) which currently receives first-generation products from RAL's prototype system and provides feedback based on evaluations it conducts for its Aviation Weather Testbed.

### FY2016 Plans

During the coming year, the prototype capability will be further enhanced and hardened based on performance assessment and feedback received from AWC forecasters. In addition, the cloud/echo top product will undergo further fine-tuning and calibration. The truth field will also be improved, as the performance assessment hinges on that. The collaboration with AWC is essential and will continue.

### CONVECTIVE HAZARDS DISPLAY WITH LUFTHANSA AIRLINES

Inflight display of products depicting convective hazards are needed by pilots of transoceanic aircraft to assist with strategic route planning and hazard avoidance. Using satellite-based algorithms augmented with global lightning data and global numerical model results, two convective products are being displayed on the Electronic Flight Bags (EFB) of Lufthansa Airlines aircraft. These products are called the Cloud Top Height (CTH) product and the Convective Diagnosis Oceanic (CDO) product. The CTH converts the infrared brightness temperatures from geostationary satellites to heights. The CDO uses a data fusion of three satellite-based detection algorithms (including CTH) along with global lightning data to produce a convection likelihood (or interest) product. A near-global domain is covered.

### FY2015 Accomplishments

Lufthansa Airlines, Basic Commerce & Industries, Inc. (BCI), and NCAR completed a feasibility study in late 2014 to display the CTH product on a tablet used in the flight deck of selected Lufthansa aircraft (Figure 2). The CTH product assisted pilots in identifying and strategically avoiding convective storms that were beyond the range of the airplane's onboard radar.

In early 2015, Lufthansa began implementing an operational, near-global display of the CTH and CDO products on the EFB's within their fleet with approval currently granted for their B747-8 fleet. For this effort, a fourth partner was added, the Weather Solutions Division of the Sutron Corporation, where the Oceanic Convection Diagnosis and Nowcasting operational system is housed. For the EFB display, the CTH and CDO products are defined by polygons (Figure 3) and served to the aircraft via an Open Geospatial Consortium (OGC) interface, called the Web Feature Service (WFS). The polygons are displayed over the navigational charts giving the pilot situational awareness of convective hazards over the planned flight route.

### FY2016 Plans

Operational display of the CDO and CTH products will continue.

### WEATHER TECHNOLOGY IN THE COCKPIT FOR OCEANIC REGIONS

The FAA Weather Technology in the Cockpit (WTIC) program for Oceanic and Remote Meteorology is working to analyze oceanic aviation inefficiencies in current operations or in future NextGen operations that are caused by gaps in either meteorological information or in the technology utilized in the cockpit. This effort had the purpose of designing an operational demonstration to uplink convective weather products into the cockpit of domestic airlines for the purpose of analyzing operational gaps.

See "Dissemination of Aviation Weather Information" for more

Figure 1. Probabilistic guidance for encountering convection (in colors) within  $\pm 60$  deg latitude based on a 36-hour forecast.



Figure 2. Display of CTH product on Lufthansa Airlines tablet.





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WEATHER IMPACTS ON UNMANNED AERIAL SYSTEMS

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BACKGROUND

Over the last few years the use of Unmanned Aerial Systems (UAS) has grown exponentially, and is expected to continue to grow. This development has occurred with little planning regarding the impact weather will likely have on these vehicles or on issues relating to managing airspace that UAS must share with general and commercial aviation air traffic. Last year NASA, recognizing the importance of air traffic management for UAS, announced its intention to plan, develop, and test an UAS Traffic Management (UTM) system. NCAR was selected as one of the suppliers of weather information, including low-level turbulence, to support the proposed UTM. The low-level turbulence work has two foci: (1) providing low-level turbulence forecasts of an atmospheric measure of turbulence, e.g., energy dissipation rate (EDR); and (2) investigating the effect of this atmospheric turbulence on the UAS response (pitch, roll, trajectory changes).

ACCOMPLISHMENTS IN FY2015

Work began to modify and enhance RAL’s automated turbulence nowcast (GTG3) to provide greater spatial detail in the lowest 1500 ft AGL (GTG-LLT). This work is intended to support the NASA Ames Research Center Systems Modeling and Optimization Branch in the development of their UTM product. To address the needs of the UAV community, research began to adapt the automated turbulence prediction algorithms and output displays to provide high resolution (vertically) maps of low-level turbulence. In addition, effort began to provide vehicle-specific guidance on expected effects on aircraft control for a fixed winged UASs.

PLANS FOR FY2016

Work with NASA to provide low-level forecasts as required for their UTM system will continue. RAL will also work to develop UAS turbulence/winds hazard metrics for other fixed-wing UAS, and start to develop hazard metrics for quadcopters.

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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
- Weather Prediction Statistical Optimization
- International Aviation
- Use and Value of Weather Information

< Weather Impacts on Unmanned Aerial Systems	up	Surface Transportation Weather >
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# SURFACE TRANSPORTATION WEATHER

## BACKGROUND

RAL is a key contributor to the research and development of the weather component of the Federal Highway Administration's wireless Connected Vehicle program. RAL also continues to support the adoption of the winter Maintenance Decision Support System (MDSS) technology across the nation and to enhance transportation decision support systems in preparation for the United States Department.

## FY2015 ACCOMPLISHMENTS

### Pikalert®

The Connected Vehicle program is focused on improving safety, mobility, and environmental efficiency. This program will ultimately provide vehicle probe data (including weather data) from millions of vehicles that will be available to the weather community to support the diagnosis and short-term prediction of weather and road conditions (Figure 1). With funding and support from the USDOT Research and Innovative Technology Administration (RITA) and direction from the Federal Highway Administration's (FHWA) Road Weather Management Program, RAL conducts research to further develop the prototype Pikalert® system including the Vehicle Data Translator (VDT). The Pikalert® system 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.



Figure 1. Schematic of the connected vehicle concept.

The Pikalert® Enhanced Maintenance Decision Support System (EMDSS) represents the latest innovations in snow control. Building on years of MDSS development, the Pikalert® EMDSS incorporates Connected Vehicle data into the forecast and decision process. As a result, end users can obtain information along the entire stretch of roadway, and not just at Road Weather Information System (RWIS) sites. This enables maintenance providers to better monitor and react to changing road conditions. They will be better equipped to make spot treatments on the road, improve safety, mobility, and reduce the environmental impact of de-icing chemicals.

The Pikalert® Motorist Advisory and Warning (MAW) is a revolutionary approach for providing hyper-local, near real-time road weather information for the travelling public. Incorporating Connected Vehicle data, the MAW provides current inferences for visibility, road condition, and road precipitation. It also blends the Connected Vehicle data with a forecast engine to provide 24-hour forecasts of road weather conditions. Using the MAW, drivers will be able to plan routes in advance of their travel, including knowing which way to go and whether to delay travel. While on the road, a phone application keeps drivers abreast of changing road weather conditions via audio alerts of hazardous weather on the road ahead.

In FY2015 RAL added the Canadian Global Environmental Multiscale Model (GEM) and the High Resolution Rapid Refresh (HRRR) model generated by the US National Center for Environmental Prediction to the underlying Pikalert® road weather

forecast system to improve overall road weather forecast accuracy, especially for near term forecasts out to 12 hours in the U.S. A variety of improvements were made to the Pikalert® precipitation and fog prediction algorithms in order to reduce the number of false alarms. The Pikalert® EMDSS display was enhanced significantly. In particular, National Oceanographic and Atmospheric Administration (NOAA) Weather Watches and Warnings were added to the Pikalert® EMDSS display providing the user with a new source of hazardous weather guidance. The National Severe Storms Laboratory (NSSL) radar mosaic was added as an overlay to allow users to view current reflectivity associated with rain and snow. Finally, modifications were made to improve the look and feel of the display as well as its overall efficiency.

**Assessing the Value of Connected Vehicle Data in the Weather Research and Forecasting (WRF) Model Assimilation**

FHWA funding supported an investigation into the value of assimilating Connected Vehicle data in the Weather Research and Forecasting (WRF) model. Since there is a significant lack of Connected Vehicle data, RAL simulated Connected Vehicle data by building a vehicle data simulator. This simulator produced output based on using Real-time Mesoscale Analysis (RTMA) model input as guidance. No significant benefit was found in utilizing the simulated data in this initial study, however, RAL expects the situation will change as models improve and Connected Vehicle data becomes more prevalent. RAL also worked with universities to provide new ideas for next steps in connected vehicle research.

**Pikalert® and the Colorado Department of Transportation**

The Colorado Department of Transportation (CDOT) is particularly interested in implementing Connected Vehicle technology in order to improve the assessment of current weather conditions on I-70, especially during the winter, as well as to understand the impact of hazardous weather on travel times between locations along the I-70 corridor. To address these needs, RAL is deploying the Pikalert® system in Colorado and developing a database connecting weather with traffic and travel time information.

**FY2016 PLANS**

**Pikalert®**

RAL will work with state partners in Minnesota, Michigan, Colorado, Nevada, and Alaska to create enhanced functionality in the Pikalert® System. New functionality will include expanding the road network to include areas beyond interstates and major state highways, incorporating additional Connected Vehicle data, improving the road weather hazard algorithms, and implementing more features into the Pikalert® display, including RWIS camera imagery.

**Travel Time Prediction**

RAL scientists will work for CDOT to predict travel times in the I-70 corridor. This project will utilize a database associating travel time, weather, road condition, and traffic data. The travel time forecast will be updated on an hourly basis and will be presented to CDOT users by means of a web interface.

**Forecasting Blow-Over Events**

RAL will be participating in a FHWA-funded project to begin providing Pikalert coverage in Wyoming. The I-80 highway in Wyoming has significant winds causing truck blow-over events. RAL will be investigating forecasting techniques that can be used to predict such events as well as ways to effectively communicate blow-over forecast information to motorists.

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RENEWABLE ENERGY

BACKGROUND

Since 2009 RAL has collaborated with university researchers, DOE labs, commercial partners, and other NCAR laboratories to develop methods to more accurately analyze and predict wind and solar power in support of the renewable energy industry. Projects have focused on resource assessment, analysis of the interaction between atmosphere and operating wind turbines, and real time wind, solar, and load forecasting to improve operations and economics of incorporating renewable energy into the power mix, and characterization and quantification of variability in wind and solar energy.

FY2015 ACCOMPLISHMENTS

Xcel Energy Variable Energy Forecasting System Project

In FY2013, RAL commenced a two-year collaborative project with Xcel Energy Services, Inc. with the goal to extend existing wind power forecasting capability developed in the previous phase of the collaborative effort. The comprehensive renewable power forecasting system summarized in Figure 1 helps operators make critical decisions about powering down traditional coal- and natural gas-powered plants when sufficient winds are predicted. The renewable power forecasting system enables more economical utilization of resources and more reliable grid operation while still meeting the needs of customers. Operational implementation of the initial day-ahead forecasting system resulted in significant savings for the utility and the rate payer (Mahoney et al. 2012, Haupt et al. 2013, Haupt and Mahoney 2015, Kosovic et al. 2015). NCAR has now extended the original capabilities to address a wide range of forecasting needs by developing a comprehensive renewable energy forecasting system. This system will enable more efficient wind power integration by: enhancing the short-term forecasting for energy dispatching, providing probabilistic estimates of wind power via an analog ensemble approach, forecasting extreme events, potential power, wind ramping, and load. To better forecast electrical loads distributed solar energy production forecast system has also been developed (Williams et al. 2014).

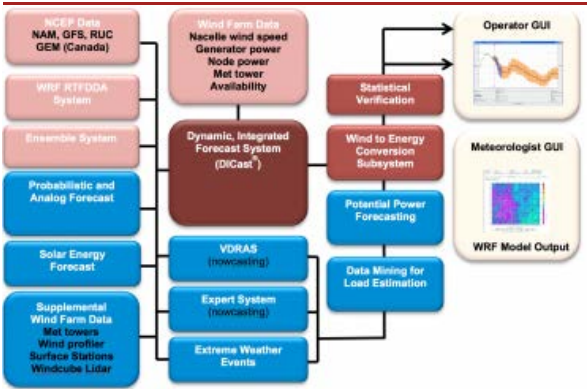


Figure 1. Schematic diagram of the comprehensive wind power forecasting system.

The numerical weather prediction portion of the forecasting system incorporates observations of current atmospheric conditions from satellites, aircraft, weather radars, ground-based weather stations, and even sensors on the wind turbines. The information is then utilized by the Real-Time Four-Dimensional Data Assimilation System (RTFDDA), which continuously updates the WRF model simulations with the most recent observations.

Initial forecasting capabilities developed by RAL focused on day-ahead forecasting. The goal was to minimize root square error in wind power forecast for energy trading purposes. This was accomplished using our own Dynamic Integrated Forecasting System (DIFCast®). DIFCast® statistically optimizes the forecasts based on current

observations, climatological data, and real-time validation of the model predictions while customized displays provide grid operators with a best forecast that includes error estimates as well as meteorological plots to visualize the weather graphics.

One aspect of the new forecasting system is a focus on development of a short-term forecasting capability to improve forecasts of wind ramps. The short-term forecasting system is based on NCAR’s Variational Doppler Radar Analysis System (VDRAS, Sun and Crook, 1997; Sun and Zhang, 2008; Sun et al., 2010). VDRAS is designed to use all available weather data: surface and upper observations, NEXRAD data, and aircraft observations, as well as any supplemental weather observations including meteorological tower data, wind profilers and surface stations in proximity to wind parks. We have applied VDRAS to analyze and forecast wind fields at wind plants in North-Eastern Colorado (Figure 2). The short-term forecasting system based on VDRAS provides wind forecasts within the first two hours, and thus, it is particularly useful for wind ramp forecasting. In addition to VDRAS system the high-resolution WRF-RTFDDA based has also been applied to short-term forecasting. This system is configured to provide more accurate short-term forecasts of turbine hub-height wind speed through assimilation of wind plant hub-height wind speed data (Figure 3).

Another novel capability recently added to Xcel Energy’s forecasting system is icing prediction. In cold climates icing can significantly reduce wind power production even when wind resource is abundant. Ice accretion on turbine blades reduces the effective lift and therefore reduces the rotor torque, resulting in significantly reduced performance that can lead to cut-outs. Freezing precipitation including snow, freezing drizzle and ice accretion is poorly observed by standard surface observation systems and by radar. Building on existing expertise in aircraft anti-icing projects at NCAR (Politovich et al, 2010), developed with Federal Aviation Administration sponsorship for over a decade, icing forecasting algorithms were adapted for application to wind turbine operations. The new wind turbine icing prediction algorithm is used to produce more accurate wind power forecasts under such adverse weather conditions. The icing prediction is based DICAST® forecast of temperature and wet bulb temperature system as well as high-resolution WRF model supercooled liquid water and temperature output to produce icing potential forecast. An example of an icing forecast using the WRF model is shown in Figure 4.

RAL also collaborated with Pennsylvania State University scientists who are conducting laboratory and numerical experiments on ice accretion on turbine blades. These experiments are designed to determine the effect of blade rotation speed and pitch angle on ice accretion and consequently the effect of ice accretion on power output. This study will enable improved wind power forecasts in icing conditions.

Another new capability that is being provided is advanced diagnosis and warning of high speed cut-outs, which will enhance overall forecast system performance. High-speed cut-outs are predicted through analysis of standard practices at wind parks of interest and development of a diagnostic algorithm to determine when high speed cut-outs occur.

An ongoing challenge in wind power prediction is the quantification of uncertainty in any given forecast. The accuracy of wind power forecasts

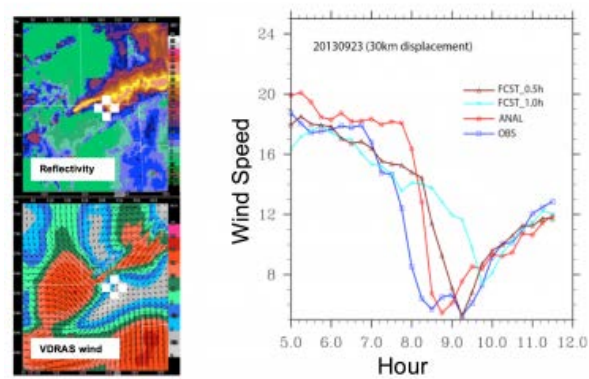


Figure 2. Radar reflectivity (top left panel), VDRAS analysis (bottom left panel) and VDRAS forecasts and analysis compared to observations (right panel).

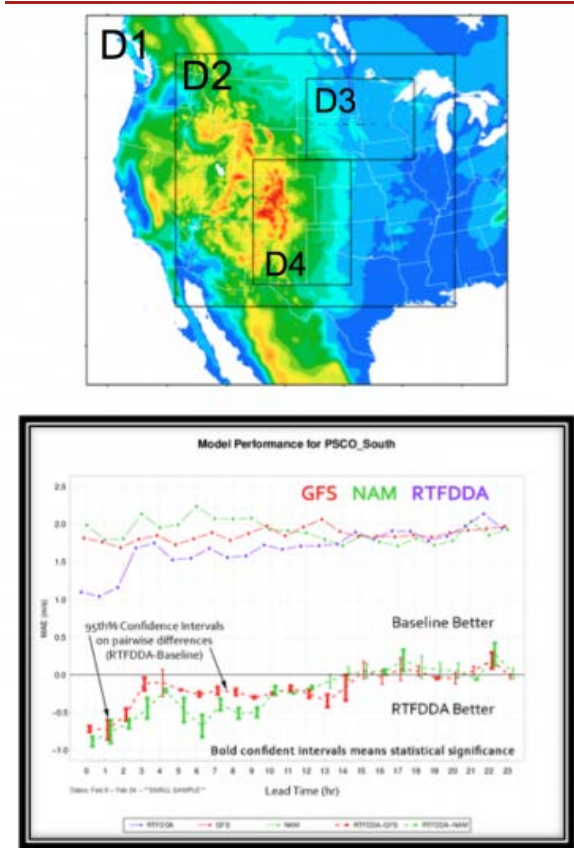


Figure 3. WRF-RTFDDA domains with high-resolution, 3.3km grid-cell size, domains (D3 and D4) include areas where wind plants are located (top panel). Comparison of Mean Absolute Error in hub-height wind speed from global model (GFS), regional model (NAM), and WRF-RTFDDA is shown in the bottom panel.

depends on a number of factors, including boundary and initial conditions, accuracy of parameterizations of physical processes, as well as inherent limits to predictability (Haupt and Delle Monache 2014). For that purpose we use a novel technique based on the analog ensemble described by Delle Monache et al. (2011, 2013). The analog ensemble approach combines real-time and historical data from state-of-the-art numerical weather prediction models and extensive records of wind power observations to provide reliable quantification of the forecast uncertainty and accurate power forecast of day-ahead lead times (Figure 5). The analog method has shown great value for improving both the best prediction and in quantifying its uncertainty.

During 2015 significant effort was focused on development and improvement of the new component of the comprehensive forecasting capability for electrical and gas load prediction. This system combined DICAST® forecast with meteorological and load observations using machine learning algorithms based on rule-based regression tree methodology.

Development of the comprehensive forecasting system presented numerous challenges related to data acquisition, quality control, data management, utilization, and archiving and it was truly a “big data” problem. This development provided opportunity to address some aspect of the “big data” problem and build experience and expertise that will be essential for the success of future efforts.

Solar Power Forecasting

In 2013, RAL embarked on a major DOE-funded effort to advance the state-of-the-science of solar power forecasting. This work is in partnership with the National Renewable Energy Laboratory, Brookhaven National Laboratory, National Oceanographic and Atmospheric Administration; universities – Penn State, Colorado State, Hawaii, Washington, and University of Buffalo; utilities – Long Island Power and Light, Public Service of Colorado, Sacramento Municipal Utility District, Southern California Edison, and the Hawaiian Electric System; independent system operators (ISOs) – New York Power Authority, Xcel Energy, California ISO, and Hawaiian Electric; and commercial forecast providers – Schneider Electric, Atmospheric and Environmental Research, Global Weather Corporation, and MDA Information Systems.

The primary objective of this project is to develop a solar power forecasting system that advances the state-of-the-science through cutting edge research, tests it in several high penetration solar utilities and ISOs, and disseminates the research results widely to raise the bar on solar power forecasting technology. This is a Big Data problem (Haupt and Kosovic 2015). To reach this goal requires basic and use-inspired research in targeted core areas. Metrics have been developed in collaboration with DOE, the other DOE-funded team led by IBM, and thoroughly vetted by the stakeholders. These metrics measure improvements in solar forecasts, the resulting power predictions, and value to the utility or ISO. The value chain is depicted in Figure 6.

Advances are also being made in solar radiation measurement and cloud observation and tracking techniques, as well as in their use for short-range prediction. This includes working with BNL on total sky imaging (TSI) technology. Three TSIs have been deployed in Xcel Energy’s solar farms in the San Luis Valley of Colorado. NCAR is also working with NOAA and CSU to advance the use of satellite data in models. A new method for integrating multiple satellite inputs and using that information to project cloud shadows onto the earth’s surface and advect the clouds using cloud vectors has been developed. A second new technology has been developed to fully assimilate these multiple sources of cloud data (satellite data and TSI images) into a rapid update version

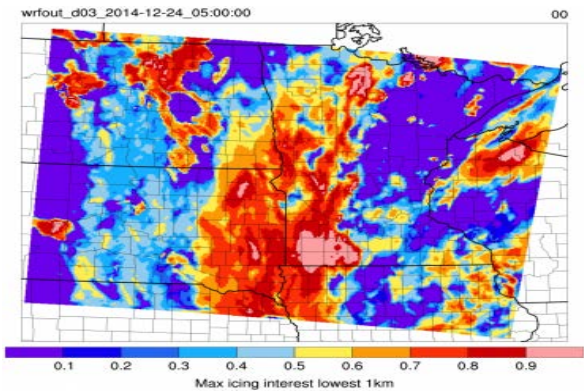


Figure 4. Icing potential forecasted by high-resolution simulation with WRF.

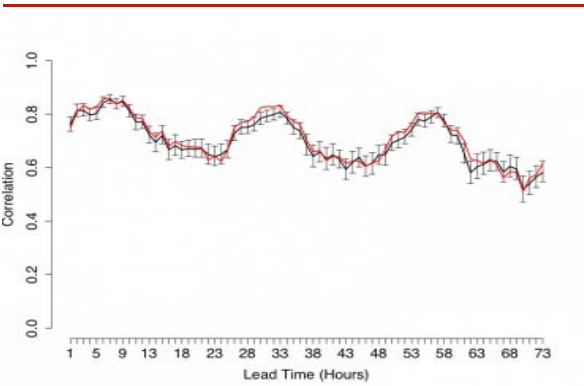
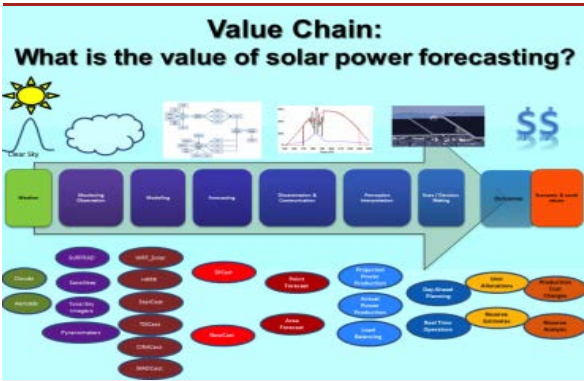


Figure 5. Comparison of correlations between observations and DICAST (red line) as well as Analog Ensemble forecasts (black line). While mean power prediction by Analog Ensemble is as accurate as that produced by DICAST, Analog Ensemble approach also provides quantitative estimate of forecast uncertainty (error bars).





of WRF that advects the diagnosed clouds using the WRF dynamical core and computes the resulting irradiance. Finally, new methods are being devised to statistically predict irradiance that includes identifying regimes, training Artificial Neural Networks for each regime separately, and also predicting variability (Figure 7) (McCandless et al. 2015a, b, c).

Methods to quantify and track aerosols that affect cloud formation and radiative transfer, including the prediction of aerosols, haze, and contrails, are being investigated. Radiative transfer through distinct types of clouds and aerosols, NWP modeling capabilities tuned for solar radiation at specific locales, and a new shallow convective scheme are resulting in a new version of the Weather Research and Forecasting (WRF) model tuned to solar irradiance prediction – WRF-Solar (Jimenez et al. 2015).. WRF-Solar is being run in two test modes: a rapid-update 6 hr forecast run hourly at 9 km resolution, and a “next day” forecast run twice a day out to 48 hours at 3 km resolution with 1 km nested domains over the target solar farms. It is also blending in the multi-sensor satellite cloud data assimilation capabilities. Recent work has used an ensemble approach to assess the new shallow convection scheme effectiveness for improving irradiance prediction and demonstrated a substantial improvement.

These new technologies must be blended seamlessly and delivered to the utilities and ISOs. Thus, statistical learning methods are used to blend the disparate forecast models, and real-time learning techniques are needed to optimize irradiance forecasts under dynamic conditions. Irradiance-to-power conversion methods provide the users with the power information that they require. Finally, economic analysis is assessing the value of the forecast improvements.

The research in FY15 is has focused on deploying a prototype solar forecasting system that is being tested for a full year in collaboration with utilities and ISOs in geographically diverse areas, including Long Island, Colorado, and coastal California. Each component of the system is in the process of being verified and validated using evaluation techniques developed specifically for the project through in-depth interactions with stakeholders. The results are being widely disseminated through publications, workshops, and software. The impact of this effort includes enhanced solar forecasting that is integrated into utility operations, advancing the potential capacity of renewable energy.

Off-Shore Wind Energy Projects

RAL staff have been working on several DOE-funded projects aimed at advancing offshore wind energy. These projects are focused on enhanced understanding and characterization of the interactions between the ocean and the atmosphere in order to better predict winds over rotor disks for both locating wind plants and for forecasting power for plant operations. Analysis of available offshore observations is combined with modeling efforts to develop improved marine boundary layer parameterizations, as well as improved ocean-atmospheric coupling techniques, with a goal to reduce market barriers to offshore wind energy. One of the projects, in collaboration with Penn State University, focused on developing a "Cyber Wind Facility", a computational facility akin to a field wind turbine test facility that blends models across scales. NCAR collaborated with PSU to integrate time varying mesoscale forecasts with large eddy simulations (LES) of the atmosphere in the vicinity of a wind farm. A second project combines the efforts of staff in RAL and MMM to characterize the coupling between wind, wave states and stratification to reduce errors and uncertainties in hub-height wind speed and rotor-plane shear prediction. A third project seeks to improve understanding of the complex interactions between the atmosphere and the ocean surface. This knowledge will be used to develop improved marine boundary layer (MBL) parameterizations, as well as improved ocean-atmospheric coupling techniques. These projects will lead to better modeling capability to reduce market barriers to developing offshore wind energy.

Lidar Support for Wind Energy

RAL researchers worked closely with faculty and students from the University of Colorado and the National Renewable Energy Laboratory’s National Wind Technology Center to deploy lidars in field studies relevant for boundary layer meteorology and wind energy applications. In 2015, RAL’s lidar was deployed at the Boulder Atmospheric Observatory (BAO) during the XPiA field study. The focus of XPiA was to quantify the uncertainty of the new types of measurements using Ka-band radars and scanning lidars. RAL’s vertically profiling lidar was deployed at the lidar super-site, 100 m south of the BAO tower, from mid-February - 8 June. It provided measurements of wind speed and wind direction for comparison with multi-Doppler lidar and radar measurements.

Figure 6. Value chain of implementing a weather decision support system for solar power. At the bottom are the components of the NCAR team’s system that build toward providing an economic impact of this system.

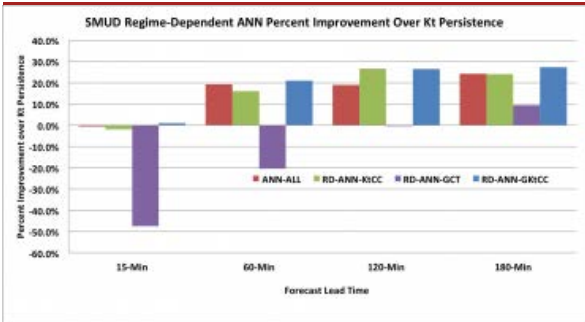


Figure 7. Percent improvement over the clearness index persistence forecasts for artificial intelligence methods for cloudy instances.

Validation of Large Eddy Simulation with Weather Research and Forecasting Model

Using Data from Askervein Hill Experiment

Numerous applications, including atmospheric dispersion and wind energy, require high-resolution numerical simulations of flows in atmospheric boundary layers. Increasing computational capabilities make multiscale simulations possible. Two main approaches to developing multiscale modeling simulation capabilities for simulation of atmospheric flows include developing turbulence resolving capabilities within numerical weather prediction models (NWP) or coupling NWP models to standalone large-eddy simulation (LES) models. Current development in NWP models enable multiscale simulations bridging the gap between mesoscale and microscale simulations. However, before such simulations can be carried out with confidence LES with NWP models must be validated. During 2015 RAL scientists have worked with colleagues from the Lawrence Livermore National Laboratory on validation of the Weather Research and Forecasting model for LES of flows in complex terrain using data from Askervein Hill experiment. This study represents another step toward seamless multiscale simulations using an NWP model.

Wind Forecast Improvement Project in Complex Terrain Near the Columbia River Gorge

RAL is collaborating with Vaisala Inc. in developing improved planetary boundary layer parameterizations for high-resolution mesoscale simulations of flows in complex terrain with application to wind forecasting. In general physics parameterizations in mesoscale models including parameterizations of turbulent stresses and fluxes are based on the assumption of horizontal homogeneity and therefore essentially one-dimensional parameterization. Computational resources now enable mesoscale simulations with grid cell sizes of 1 km or less. While such simulations resolve well large scale features, the effects of atmospheric boundary layer turbulence on the mesoscale flow must be parameterized. Accurate parameterization of turbulent stresses and fluxes is essential for accurate wind forecasting. However, as grid cell size decreases over heterogeneous surfaces including complex terrain the homogeneity assumption is violated. Therefore the goal is to develop fully three-dimensional PBL parameterization that will account for the effects of surface heterogeneities and enable more seamless coupling between mesoscale and microscale simulations.

Mesoscale to Microscale Coupling for Renewable Energy

A new collaboration with DOE commenced in FY15 that focuses on blending information from mesoscale model simulations into microscale simulations in order to provide a capability to more accurately model details of flow that impacts a wind plant (Figure 8). RAL is leading a collaboration of six DOE national laboratories (Argonne, Los Alamos, Lawrence Livermore, National Renewable Energy Lab, Pacific Northwest, and Sandia) to accomplish mesoscale and microscale simulations of carefully selected cases that are representative of wind farm conditions. The mesoscale modelers studied the sensitivity to boundary layer schemes, boundary and initial conditions, and use and type of data assimilation for nearby data. The microscale modelers focused the initial sensitivity studies on the convective and neutral cases, studying sensitivity to grid spacing, the geostrophic wind speed, roughness height, aspect ratio, order of the advection scheme, and the subgrid scale turbulence model employed. NCAR performed formal statistical assessment tailored to the needs of wind farm production. A major finding is that when tuned for the cases, the models performed similarly and the differences between models was smaller than the uncertainty in the observation data that was being used for comparison. The team held a first year workshop at NCAR on Sept. 23-24, 2015 that was attended by all team members, plus representatives from the community (universities and industry). In addition to presenting results, the team sought feedback from the external community. The impact of this project is expected to include improved wind plant operation and control.

Wind Resource Assessment in the Developing World

In 2014, NCAR embarked on a project with the National Renewable Energy Laboratory (NREL) to assess and quantify the wind resource in Bangladesh. NREL deployed sodars on site as well as several meteorological observation towers (Figure 9). NCAR's role is to use modeling capabilities to assess the resource and to assimilate data from the new observational network to calibrate the models. The first step was to compare the wind resource from three separate historical reanalyses, which blend information from historical observations with models. The next step involved working closely with NREL to downscale and assimilate the observations using the Real Time Four Dimensional Data Assimilation (RTFDDA) of RAL.

PLANS FOR FY2016

FY2016 will continue to be an exciting time for renewable energy research at RAL. New collaborations with national laboratories, university

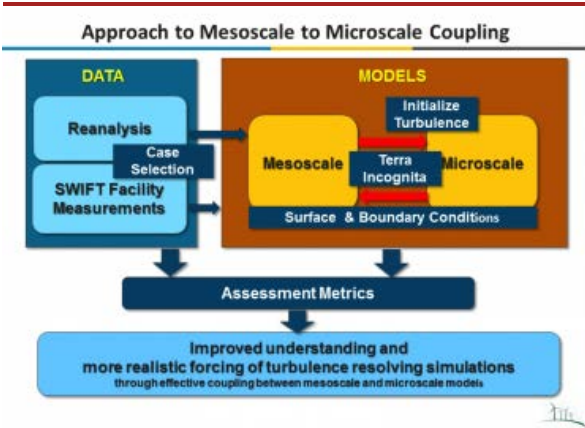


Figure 8: Process for coupling mesoscale to microscale simulations for wind plant management.

scientists, private companies, and foreign research institutions and companies will advance the state-of-the-science necessary to make a large penetration of renewable energy capacity feasible. In FY2016 significant efforts will include advancing comprehensive renewable power forecasting capabilities. An emphasis will be on porting the research to other regions of the world. RAL and its partners will also continue implementing a new solar forecasting system for both utility scale and distributed solar facilities. In addition, the analog ensemble methodology will be further advanced and applied to a range of renewable energy related projects to quantify uncertainty.

Other plans include:

- Continued collaboration with many partners under DOE funds to iteratively improve and assess a solar power forecasting system and report results widely.
- Collaboration with NREL and the University of Colorado to deploy a vertically pointing lidar to study wind turbine wakes and to model those wakes using LES techniques.
- Continuing to work with NREL with resource assessment and developing measurement programs in developing countries, including Bangladesh.
- Expansion of the wind forecasting capability into new areas, including international, complex terrain and desert sites.
- Continued collaboration with DOE laboratories to discover best practices for coupling mesoscale with microscale simulations.
  - Collaborate with Vaisala Inc. and DOE laboratories to improve mesoscale simulations of flows in complex terrain as part of the DOE-funded WFIP2 project.



Figure 9. Partners deploying a sodar in Bangladesh.

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# WEATHER PREDICTION STATISTICAL OPTIMIZATION

## BACKGROUND

RAL is a leader in the development of intelligent weather prediction systems that blend data from numerical weather prediction models, statistical datasets, real time observations, and human intelligence to optimize forecasts at user-defined locations. The Dynamic Integrated Forecast System (DlCast®) and the GRidded Atmospheric Forecast System (GRAFS) are examples of such technology (Figure 1). DlCast® is currently being used by three of the nation's largest commercial weather service companies. Applications of this technology continue to expand as 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.

## FY 2015 ACCOMPLISHMENTS

During this year the statistical improvements in DlCast's short-term precipitation forecasting have been significant with the addition of data from the High Resolution Rapid Refresh (HRRR) model. The addition of this data allows users in all sectors to react to rapid weather changes in a more tactical sense. Another major addition to the system has been the development of a probabilistic forecast capability for temperature fields based on Bayesian Model Averaging (BMA). This sub-system uses a recent history of DlCast forecast modules to develop the forecast uncertainty at specific locations.

DlCast's impact on wind energy forecasting has led to its use in other renewable energy arenas. In particular, it is currently being used as the core forecast integration module for a DOE-funded solar energy forecasting project, using freely available NWP models and a version of the WRF optimized for solar forecasting (WRF-Solar). In this project DlCast has been modified to make forecasts of Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and diffuse irradiance at locations where partnering utilities are providing observational data. Additionally, a separate short-term Nowcasting blending system brings together forecasts from statistical models (StatCast), from total sky imagers (TSICast), satellite cloud advection algorithms (CIRACast), the Multi-Advection Diffusive foreCast (MADCast) system, and a rapid update version of WRF (WRF-SolarNow). Progress has also been made on creating uncertainty forecasts for power using the RAL Analog Ensemble (AnEn) system.

RAL continued the effort to develop a new gridded forecast system (GRAFS) that is available to the university community for research (Figure 1). This system is modular in nature, allowing choices in base numerical weather prediction models to be used, as well as consensus forecasting techniques. This system was first applied to solar energy allowing utilities to assess production of distributed solar power, but has been extended to other weather variables as well.

RAL systems continue to push the envelope of advanced weather forecasting in the transportation arena as well. The Maintenance Decision Support System (MDSS) was adapted from its original focus on roadways to be used as a Runway Decision Support System for Denver International Airport (DIA). The system generates tuned weather forecasts and treatment recommendations for the runways at DIA. In addition, DlCast and a weather-tuned version of GRAFS forms the backend weather engine used in both the Federal Highway Administration and Colorado Pikalert Hazard Assessment forecast systems (Figure 2).

## FY 2016 PLANS

Areas of development for the next fiscal year include:

- Continued evaluation of DICAST's skill in solar energy forecasting
- Expansion of DICAST forecast modules to include other artificial intelligence techniques
- Extension of the BMA probabilistic forecast technique to other variables
- Expansion of GRAFS to other consensus blending methods and other variables
- Improvements related to road temperature and precipitation forecasts in the MDSS

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# INTERNATIONAL AVIATION

## 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, and capacity and safety at Taiwan's major hub airports. Since 2010, NCAR has partnered with a Taiwanese technology company, International Integrated Systems, Inc., to support the system.

Major components of the AOAWS include: Low-Level Wind Shear Alert Systems (LLWAS Phase III) at Songshun and Taoyuan International Airport; the WRF model which provides regularly-updated forecasts on two domains with grid spacing of 20km, and 4km; the Java-based Multi-dimensional Display System (JMDS), which integrates all available real-time observational data and displays the information automatically to aviation forecasters and flight planning specialists; a web-based display system (WMDS) that displays most of the data available on the MDS on a CAA website for users (e.g., pilots and dispatchers) to view the AOAWS weather products remotely; and an AOAWS System Monitor Display (SMD) that provides system and networking activity information and alerts to the operators if any one of the sub-systems is not running smoothly. Since 2010, the WRF modeling enhancements have been developed by NCAR/MMM under a separate research agreement with the Taiwan Central Weather Bureau (CWB).

## FY2015 ACCOMPLISHMENTS

The development of the Nexrad Turbulence Detection Algorithm (NTDA) and display application upgrades were completed, and the new capabilities were integrated, tested, and became operational in the AOAWS in late 2014. Verification and tuning of the Current Icing Product (CIP) and NTDA products were conducted through a series of case study analyses to ensure that the product performance skill was appropriate for the climate of Taiwan compared to North America. Enhancement of the ceiling and visibility product was performed by applying and testing a variety of artificial intelligence methods to the model and observational data. In addition, a real-time verification component was designed, developed, and implemented. A user-configurable external data server was developed that allows the Taipei Aeronautical Meteorological Center (TAMC) additional independence and control of sharing data products with its various aviation industry collaborators and partners. Collaboration with the TAMC to further develop the AOAWS was suspended after this delivery to give the TAMC forecasters time to gain experience with the new products and assess their future needs. It is anticipated that the research and development partnership with the TAMC will resume in one to two years.

## FY2015 PLANS

With NCAR/RAL's long experience in developing advanced aviation

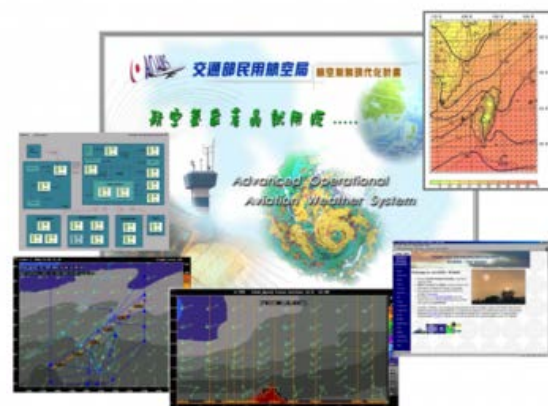


Figure 1 Composite image showing several AOAWS end-user display components



In addition, RAL supported the Sultanate of Brunei in its acquisition of an operational Low Level Wind Shear Alert System (LLWAS) for its International Airport at Bandar Seri Begawan. RAL scientists also assisted the Korea Aviation Meteorological Agency (KAMA) in modernizing and upgrading their aging LLWAS system on Jeju Island, a major tourist destination which is now the second busiest airport in South Korea.

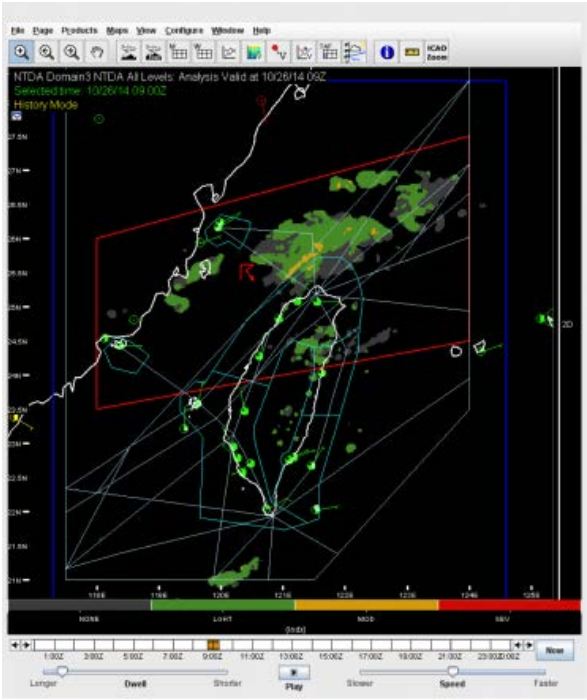


Figure 2 Image showing the NCAR Turbulence Detection Algorithm (NTDA) on the AOAWS end-user display screen.

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# USE AND VALUE OF WEATHER INFORMATION

## BACKGROUND

Weather and climate affect all economic sectors, regions, individuals and communities. Improved weather forecasts – and better use of current forecasts – could save lives and hundreds of millions of dollars annually. To realize the potential benefits associated with improved weather forecasts and stakeholder decision making, NCAR established the Collaborative Program on the Societal Impacts and Economic Benefits of Weather Information (aka Societal Impacts Program or SIP) to create a dedicated focal point for assembling, coordinating, developing, and synthesizing research and information on the societal impacts and economic benefits of weather information.

The SIP aims to improve the societal gains from weather information by infusing social science research, methods, and applications throughout the weather enterprise and to be the premiere focal point for integrating social science and societal impacts understanding into the weather enterprise through cutting-edge research and capacity building. The SIP endeavors to:

- Advance knowledge on the socio-economic impacts of weather and the communication, use, and value of current and improved weather information.
- Build a multi-disciplinary, multi-stakeholder community of researchers and practitioners engaged in developing and applying knowledge on societal aspects of weather information.
- Enhance social science aspects of policy-making, development, and use of related weather information

## FY2015 ACCOMPLISHMENTS

### Socio-Economic Benefit (SEB) Guidance Document

The USAID funded and World Meteorological Organization (WMO)/World Bank supported socio-economics benefits (SEB) guidance document entitled “Forecast Value: Economic Assessment of Meteorological and Hydrological Services” was published and released at a meeting of the WMO in May 2015. In addition to producing the document, RAL collaborated in developing and conducting week-long regional training sessions on economic analysis for national hydro-met services in Antigua and Barbuda (February 2015), the Seychelles (May 2015) and Croatia (June/July 2015).

### Assessing the Economic Value of Improving Weather, Water, and Climate Information in Mozambique

Building on work supported by the World Bank, analysis and reporting was completed on a survey of 576 members of the public in Mozambique on the sources, perceptions, uses, preferences, and values for current and improved weather, water, and climate information. Three non-market valuation methods for eliciting economic values were implemented to determine the current value of weather information as well as the potential value of improved forecast information. A report on this work was published on OpenSky.

### Assessment of Hurricane and Flash Flood Warnings

Efforts to examine decision processes employed by institutions, organizations, and individuals in analyzing, disseminating, and interpreting warnings of for hurricanes and flash floods continued in FY2015. This work was accomplished using balanced research teams representing the fields of meteorology, sociology, economics, public policy analysis, and decision sciences and represented an important step in evaluating warning processes and systems holistically. In-depth

interviews and observational sessions with NWS forecasters, emergency managers, and the media from the Greater Miami area with respect to hurricanes and from the Boulder-Denver, Colorado area with respect to flash floods were analyzed to examine roles, goals, and interactions, and to identify strengths and challenges in how key participants communicate with each other and with the public.

### **A Public-Private-Academic Partnership to Advance Solar Power Forecasting**

For this DOE-funded project, primary research continued with a focus on identifying methods for assessing the economic value of improved solar irradiance information. Working with utility partners and stakeholders, Production Cost Modeling was selected as the common valuation approach and will be undertaken by several of the utilities as a contribution to the project. Implementation will be coordinated by NCAR personnel and the feasibility aggregation of results to national benefit estimate will be assessed.

### **Socio-economic Value of Meteorological Satellites**

Work was initiated on the value of meteorological satellites including working with the Coordination Group on Meteorological Satellites (CGMS) and NOAA. Guidance and input is being provided to the design for a CGMS case study of the value of polar orbiting satellites as well as the general process of economic valuation of satellite information for hydro-meteorological observations and forecasts. Expert external review is being provided on a socio-economic benefits assessment of the proposed Joint Polar Satellite System (JPSS).

### **Effective Tropical Cyclone Forecast and Warning Communication: Recent Social Science Contributions**

Working with Betty Morrow, faculty emeritus at Florida International University, a review paper was written as a contribution to the WMO International Workshop on Tropical Cyclones. The paper was presented at the meeting in Seoul, Korea and published in the conference proceedings. A primary recommendation of the paper is to develop an ongoing socio-economic focus in conjunction with WMO tropical cyclone efforts. The manuscript is now under review for publication in *Tropical Cyclone Research and Review*.

### **FY2016 PLANS**

Work will continue on several projects on communication, understanding, use, and value of hydrometeorological information particularly with respect to hurricane forecasts and warnings. Analysis of primary survey data and in-depth interviews will continue to further develop an integrated understanding of warning systems and processes with a focus on hurricanes in Miami, Florida by assessing the relationship between factors affecting evacuation decision making and individuals' stated values for improved hurricane forecasts.

Follow-on work for the World Bank, WMO, and USAID supported guidance document for National Hydro-Meteorological Services on best practices for socio-economic benefit (SEB) assessment will involve providing guidance in the Seychelles and the Caribbean on development of SEB studies.

Analysis and reporting will be completed on the public survey and expert elicitations of the World Bank hydrometeorological improvement program efforts in Mozambique and Bangladesh. Analyses will compare results between the two countries and begin to develop best practices to facilitate implementation in other developing countries. In addition related projects are being pursued in several African and Central American countries.

Production Cost Modeling results from stakeholder partners will continue as part of the DOE funded project "A Public-Private-Academic Partnership to Advance Solar Power Forecasting." This analysis will estimate the value to improved solar irradiance forecasts in the day-ahead unit-commitment decision making of four partner utilities. If feasible this will be aggregated to a national benefit estimate based on considerations of the significant differences in utility institutional and physical structures.

Work will continue on development of a case study for the Coordination Group on Meteorological Satellites (CGMS) and review of the JPSS economic analysis. This effort will also involve working with the OECD Space Forum and the OECD/NASA/USGS funded 2015 workshop "Data to Decisions: Valuing the Societal Benefit of Geospatial Information."

The Societal Impacts Program will help coordinate and implement a March workshop for broadcast meteorologists with the George Mason University / Climate Central team on the NSF-Funded project "Taking to Scale a Proven Climate Education Method by TV Weathercasters: Climate Matters."

SIP staff will participate in the WMO World Weather Research Programme (WWRP) HIWeather Project – Human Impacts, Vulnerability and Risk (HIVR) Task Team. The HIWeather project is a ten year activity within the WMO WWRP to promote

cooperative international research to achieve a dramatic increase in resilience to high impact weather, worldwide, through improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications.

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*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.*

- Numerical Weather Prediction
- Data Assimilation
- Uncertainty Quantification and Probabilistic Forecasting
- Post-Processing
- Air Quality Forecasting
- Statistical and Dynamical Mesoscale Climate Downscaling
- Atmospheric Transport and Dispersion of Hazardous Materials Research and Development

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## NUMERICAL WEATHER PREDICTION

*Over the past several decades, RAL has developed and deployed complex computer-based operational systems for analyzing and forecasting climate and weather at high resolution worldwide. This development is built upon the Laboratory's deep foundation of applied scientific research and engineering. Systems and their products are tailored to each project to maximize the benefit to the sponsors and end-users. For example, improved analyses and forecasts at Army test ranges saves millions of tax dollars by identifying when weather suitable for testing will occur, and improves safety by predicting conditions that would be hazardous to personnel and materiel. Other domestic and international projects include forecasting for wind farms at resolutions that can approximate large eddies within the atmosphere's boundary layer; new, innovative ways to supply models with current observations from radar ; and exploring how urban development affects the weather, and how that weather in turn affects the health of people living in urban areas. In this section of the Annual Report, we describe our work in the following areas:*

- Four-Dimensional Weather System (4DWX)
- Real-Time Four-Dimensional Data Assimilation (RTFDDA) and Forecasting Advances
- Operational RTFDDA
- Fine-Scale Precision NWP: WRF-RTFDDA-LES
- High Performance Computing for Operational Modeling

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## FOUR-DIMENSIONAL WEATHER SYSTEM (4DWX)

### BACKGROUND

Since the middle 1990s, the U.S. Army Test and Evaluation Command (ATEC), then known as TECOM, has sponsored RAL to conduct research, development, and technology-transfer of the Four-Dimensional Weather (4DWX) system. 4DWX is an advanced numerical weather prediction (NWP) system that analyzes current weather and makes detailed predictions of weather over the next several days. 4DWX's NWP core is the Weather Research and Forecasting (WRF) Model, an industry standard. 4DWX ingests observations into the NWP core through NCAR's Real-Time Four-Dimensional Data Assimilation (RTFDDA) scheme. 4DWX is used by ATEC forecasters at seven test ranges across five major climate zones. RAL upgrades 4DWX software several times per year.

4DWX provides ATEC forecasters the technology and expertise they need to produce weather forecasts and analyses at the scales, and with the accuracy and utility, required to support safe and cost-effective testing by the Department of Defense (DOD). For NCAR one of the most attractive elements of the 4DWX project is that the ATEC test ranges serve as natural laboratories for atmospheric research, complete with dense observing networks and specialized data that permit study of mesoscale and microscale phenomena in complex terrain. Continual improvements to 4DWX and to community numerical weather prediction models, such as the WRF Model, are made possible through this collaboration.

## PRIMARY 4DWX TECHNOLOGY

### Weather Research and Forecasting (WRF) Model

The WRF Model is an industry standard for numerical weather prediction in operations and research. The model code is open source. It was developed by a group of partners including NCAR, the National Oceanic and Atmospheric Administration, the Air Force Weather Agency, the Federal Aviation Administration, and the university community. The model is designed for NWP across many scales, from global to microscale. 4DWX uses the WRF Model as its predictive core.

### Data assimilation through hybrid Real-Time Four-Dimensional Data Assimilation (RTFDAA)

The project continues to rely on Real-Time Four-Dimensional Data Assimilation (RTFDAA) as one way to ingest observations and define the atmosphere's current state for 4DWX's NWP core, the WRF Model. RTFDAA involves modifications to an NWP model's predictive equations so the model can be gently adjusted, or nudged, toward observed conditions during the model's analysis stage, before the forecast stage begins. The scheme is computationally efficient and preserves the precise timing of observations, which gives 4DWX a particularly accurate depiction of the weather at any instant. RTFDAA continues to show itself superior to, or the equal of, many alternative methods of data assimilation in operational systems. RTFDAA assigns quality flags to observations within the analysis and forecast cycling, rather than as a pre-processing step, providing more accurate and stable assessments of each observation's usefulness in data assimilation. RTFDAA also has an improved means of dealing with cases when an observing site's actual elevation differs significantly from the simulated terrain height in the model.

### Ensemble 4DWX

Since 2007, Dugway Proving Ground, UT has used an ensemble version of 4DWX (called E-4DWX) developed by RAL. E-4DWX provides a suite of 30 forecasts valid at the same place and time, each producing slightly different but similarly realistic forecasts. Differences among ensemble members are induced by varying initial conditions, boundary conditions, and model physics. All members are based on the WRF Model. The ensemble captures the forecasts' probability information that varies with changes in weather regime. In 2014, E-4DWX was expanded to include three additional ranges in the intermountain West: White Sands Missile Range, NM; Yuma Proving Ground, AZ; and the Electronic Proving Ground, AZ.

A subset of output from E-4DWX is calibrated—that is, made statistically consistent with observations so that the probability of E-4DWX's forecasts being realized represents the observed probability. By using a method known as quantile regression, the distribution of ensemble forecasts (i.e., quantified by the mean, spread, and higher moments) is adjusted toward the actual probability distribution of weather as determined through observations. The benefits of calibration include: 1) reducing forecast error and biases, producing a calibrated ensemble mean that has on average one half the error variance of any single ensemble member; 2) predicting accurate likelihoods of extreme and potentially devastating weather; and 3) providing a measure of forecast uncertainty through the dispersion among ensemble members. Calibration is performed on moments of the overall probability distribution function, no matter the size of the ensemble membership from which the distribution is created, as opposed to calibrating output from specific ensemble members. This makes E-4DWX particularly robust, even if individual members of the ensemble fail at some point during the forecast.

### Forecasts of severe weather

The 4DWX system has components that predict severe weather on two scales: the next few hours, based on both observations and model predictions blended via the AutoNowcaster, and the next few days, based on model predictions alone. The AutoNowcaster now employs the dual polarization data newly available from the nation's NEXRAD network.

Several Level 3 symbolic products have recently been added to the AutoNowcaster: hail index, tornado vortex signature, mesocyclone, and melting layer. Terminal Doppler Weather Radar (TDWR) data have also been added to the system. Finally, RAL continues to refine its algorithms for short-term and longer-term prediction of lightning at the ATEC ranges by sharpening the forecasts, accounting for lightning in the anvil cirrus clouds of storms, and refining displays.

### Coupled applications

Direct weather analyses and predictions from 4DWX and E-4DWX are the core of the weather information used by forecasters at the ATEC ranges, but that information can be made even more valuable when it is supplied to decision support systems (DSSs) that simulate how the weather affects other processes and conditions, such as sound propagation and the transport and dispersion of airborne hazards. Examples of DSSs that have been linked to 4DWX and/or E-4DWX include:

- Noise Assessment and Prediction System (NAPS)

- Second-order Closure Integrated Puff (SCIPUFF) model
- Lewis Rocket Trajectory Model
- Open Burn / Open Detonation Model (OBODM)

In 2015, RAL continued to collect observations and predictions for verifying the skill of a new version of the lab's Graphical Turbulence Guidance (GTG) product, another DSS which is being modified for application to unmanned aircraft systems. RAL intends to deploy to ATEC a prototypical version of the GTG in 2016.

### 4DWX Web Portal

The primary interface to the 4DWX system at all ATEC ranges continues to be the 4DWX Portal. The portal's flexibility, accessibility, modularity, and extensibility are ideally suited to the customized weather support that RAL provides to forecasters who have eagerly welcomed how the Portal improves their workflow. Weather maps and related graphics from 4DWX include optional color palettes that can be seen by the color-blind. By using web forms designed in RAL, forecasters can more efficiently customize their weather maps. The Portal's dashboard has a flexible, configurable layout, with streamlined access to portlets for coupled applications. The list of output formats that the Portal supports includes the third-party BUFKIT and RAOB applications.

### Integrated Data Viewer (IDV)

RAL collaborates with UCAR's Unidata program to include among 4DWX's display options the Integrated Data Viewer (IDV), which is a sophisticated, flexible, Java-based application for analyzing and displaying geophysical data. IDV is the primary means by which range forecasters explore in greater depth the weather analyses and forecasts from 4DWX. This more complex and flexible exploration complements the "virtual map wall" that is available through the 4DWX Web Portal, whose purpose is to provide the easiest and quickest interface to a standard suite of pre-generated weather maps. IDV is also a research tool and is employed by scientists and engineers during their testing, development, and refinement of 4DWX.

### Outreach and training

RAL continues to emphasize outreach and training as core components of the 4DWX project through on-site forecaster training conducted at each range, and through teleconferences and on-line documentation.

## FY15 ACCOMPLISHMENTS

### Improvements to 4DWX's NWP core and data assimilation

In FY2015 the data structures within 4DWX were restructured which reduced the system's demand for CPU memory, improved input/output speeds, and improved handling of cross-correlations for assimilating remotely sensed observations.

A prototype of a new hybrid data assimilation for 4DWX was upgraded for multi-variable analysis increments in RTFDDA. Kalman filtering is being used to assimilate radar radial velocity along with direct assimilation of wind speeds and directions using Kalman weights for heterogeneous observations.

### Explicit predictions of precipitation phase

4DWX was enhanced to produce explicit forecasts of the type of precipitation (snow, rain, hail, etc.). The approach combines model-predicted near-surface mixing ratios of snow and rain with model-predicted temperature to determine areas of snow, rain, and mixed-phase precipitation.

## FLASH FLOOD PREDICTIONS

Trident software was installed at YPG to help alert forecasters to conditions that could lead to flash flooding in dry washes. Predictions are at 10-min intervals to a lead time of 1 h. The algorithm currently uses a standard Z-R relationship to relate radar reflectivity to precipitation rate. An upgrade under development will allow dual-polarization data to be used in the relationship.

### Experimental very large-eddy-simulation (VLES) and large-eddy-simulation (LES) versions of 4DWX

At three ranges—Aberdeen Test Center, Dugway Proving Ground, and White Sands Missile Range—RAL is running VLES and LES experimental configurations of 4DWX as a step toward modifying the operational version of the system for use by forecasters.

### Advanced quality-control of range observations

RAL has finished developing an initial set of algorithms to evaluate the quality (often called-quality control or quality-assurance) of each observation in the long-term datasets collected at each of the ATEC ranges. This is a key step to enabling 4DWX and coupled applications to read and respond to quality-control (QC) flags so that observations can be used in the manner most appropriate for the model or application. Among the tests being applied are: general validity, climatic validity, temporal consistency, and spatial consistency.

### **Analog ensemble**

In our final code release of the calendar year, we included a beta version of a 4DWX Analog Ensemble (AnEn) forecasting tool for use at three test ranges. The tool uses a set of algorithms to calculate probabilistic predictions that rely on archives of observations and model output to collect an ensemble of prior forecasts made under analogous weather patterns. Predictions from analog-based methods are inherently calibrated, so an extra calibration step is not required.

### **Improvements to the 4DWX Portal**

The 4DWX Portal was upgraded to include 1) a suite of figures from the AnEn described above, including time series of ensemble spread in temperature and wind speed; quality-control flags from the QC algorithms described above; and alerts for severe weather parameters such as hail, tornado vortex signatures, and mesocyclones. The transfer of data from relational databases to the Portal has been streamlined.

### **Climatology of boundary-layer characteristics in 4DWX**

We recently explored the characteristics of 4DWX's simulated nocturnal atmospheric boundary layer (ABL) over northern Utah (Serafin et al. 2015). Results demonstrate that 4DWX realistically approximates the long-term, aggregate patterns of wind speed and direction in the area, and realistically depict the gradients of wind, pressure, and temperature one would expect from the complex arrangement of mountains and valleys in the area.

### **Importance of accurate analyses of soil moisture in mesoscale NWP**

Ongoing collaboration with scientists working on the MATERHORN field project has improved understanding of how inaccurate analyses of soil moisture can undermine the skill of mesoscale weather forecast systems such as 4DWX. Regional analyses that depict the soil to be erroneously moist were also determined to lead to morning warm biases and afternoon cold biases in the lower troposphere (Massey et al. 2015).

## **SELECTED KEY PLANS FOR FY2016**

### **4DWX workflow**

A new workflow manager will be tested for 4DWX. If tests are promising, the new manager will be incorporated into the next upgrade of the operational version of 4DWX.

### **E-4DWX**

RAL will continue to improve the skill, functionality, and reliability of E-4DWX. Improvements may include expansion to additional ranges, more optimal configurations, higher resolution, more realistic physical parameterizations, better use of observations, and additional diagnostic output that is not currently available.

### **4DWX-VLES**

A white paper will be written documenting best practices for applying mesoscale models, such as the WRF Model, at VLES scales. Some of the material for the paper will be drawn from comparisons of 4DWX-VLES with 4DWX-LES, which will illuminate the sensitivities of the system to progressive increases or decreases in resolution, and to any convergence of simulation properties (e.g., updraft width or updraft strength) at certain grid intervals.

### **4DWX Analog Ensemble (AnEn)**

AnEn will be extended to additional ranges, and will be applied to additional variables. AnEn will be explored as a method for predicting three specific phenomena that are problematic for the dynamical 4DWX and critical for testing at some ranges: chinooks, cold-air damming, and drainage flow.

### **MATERHORN field project**

In FY2016 project staff will continue to collaborate on work related to the MATERHORN field project. MATERHORN's datasets are on a scale well-suited for validating 4DWX-VLES. Field data will also be used for testing methods of filtering model output and observations so that both represent approximately the same scales of motion, which has implications for data assimilation and model validation.

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# REAL-TIME FOUR-DIMENSIONAL DATA ASSIMILATION (RTFDDA) AND FORECASTING ADVANCES

## BACKGROUND

Many applications, including military tests and operations, renewable energy assessment and prediction, weather-related emergency response etc., desire high-resolution, rapid-update, high-accuracy, and customized weather information for particular regions. RTFDDA (Real-time Four-Dimensional Data Assimilation and forecasting system) is a mesoscale numerical weather modeling system that has been developed for such diverse applications. RTFDDA is built upon the WRF (Weather Research and Forecasting) model and is designed to effectively and efficiently assimilate all available weather observations into the advanced full-physics WRF model and providing best possible weather information service to a target application and region. RTFDDA is optimized in its data assimilation strategies, dynamical configuration and physical parameterizations for each application. An important feature of RTFDDA is that it allows for smooth and uninterrupted assimilation of diverse weather observations and produces physically consistent and dynamically balanced 4D weather analyses and "cloud/precipitation "spun-up" predictions. In the past 15 years, RTFDDA has been applied to over 40 weather-critical applications across the US and the globe. The applications include military testing and operations, regional operational NWP (numerical weather prediction), dispersion and transportation emergency response, urban meteorology, renewable energy, water resource and flood prediction, etc.

Along with deployments of RTFDADA for operational application, significant effort has been made to advance the RTFDADA system itself and improve its accuracy and capabilities. In the last six years, RTFDADA has evolved from a single mesoscale deterministic analysis and forecasting system to a modeling capability suite that integrates ensemble prediction technology (Ensemble-RTFDADA), regional climate downscaling with four-dimensional data assimilation (Climate-FDDA) and microscale NWP with a refined LES model grid at 10s to 100s meters of grid intervals (RTFDADA-LES) (Fig. 1). As a result, RTFDADA is now able to produce customized high-resolution and ultra-high-resolution precision weather analysis and forecasts, probabilistic weather forecasts, and multi-year/multi-decadal microclimatology analyses for a given target region. In addition, the WRF-Chem model has been assessed and is being added to RTFDADA for forecasting sand and dust storms.

The data assimilation technologies of RTFDAA include Newtonian relaxation based “observation-nudging” and “analysis-nudging” FDDA schemes, the community WRFDA, GSI, DART-EnKF data assimilation modules, a four-dimensional relaxation ensemble Kalman filter (4D-REKF) FDDA scheme and a hydrometeor-latent-heat-nudging (HLHN) radar data assimilation schemes. For a specific application, these technologies are configured to formulate a hybrid data assimilation engine to provide optimal modeling to meet the application requirements.

## FY 2015 ACCOMPLISHMENTS

## Advances in Observation Quality Control and WRF Obs-Nudging

Observation quality control is a vital component of the RTFDFA model system. Because FDDA observations are ingested into the full physics WRF and interact directly with the model dynamics and physics, even a few bad observations can seriously affect the model's reliability and performance. An online QC scheme and an algorithm that corrects observation and model inconsistency due to the differences between model terrain heights and observation station elevations have been developed. These data processing and quality-control procedures significantly enhance RTFDFA data assimilation and forecasting accuracy and system operation reliability.

With an increasing number of observations and the addition of ensemble Kalman filter data assimilation strategies, the efficiency and memory requirements of the FDDA data assimilation scheme has become a bottleneck. Observation data structures in WRF have been refactored to overcome these problems. This significant change has been implemented successfully during 2015, permitting more efficient real RTFDDA operations and conducting Doppler radar radial velocity data assimilations with the advanced 4D-REKF technologies.

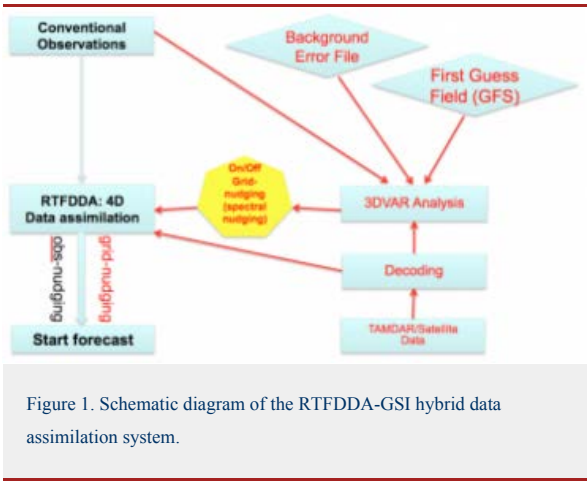
## RTFDDA-GSI Hybrid Data Assimilation

One of the challenges for numerical weather prediction in the regions where conventional weather data are excessively sparse, such as over oceans, the Middle East, Africa etc., is the limitation of the observations that can be used for properly initializing mesoscale models. An RTFDDA-GSI hybrid data assimilation scheme (Fig. 1) has been developed in order to incorporate unconventional observations, especially remote sensing measurements such as satellite radiance, for model initialization. RTFDDA-GSI hybrid data assimilation works also as an engine to assimilate Doppler radar radial velocity observations in RTFDDA. A major characteristic of the RTFDDA-GSI hybrid data assimilation technology is that it takes full advantage of the RTFDDA ability to generate 4-D dynamically consistent and physically spun-up analysis and forecasts.

Incorporating radar data assimilation (RDA) capability into the real-time operational framework of RTFDDA has been one of the major undertakings of the next-generation RTFDDA development. To assimilate radar radial winds and reflectivity into the WRF-based RTFDDA system, a hybrid approach that couples RTFDDA and GSI with a hydrometeor and latent heat nudging (HLHN) technique has been developed (Fig. 1). RTFDDA-GSI/HLHN hybrid radar data assimilation has been tested with retrospective case studies for convective systems in the Colorado Front Range, the Army Aberdeen Test Command (ATC) range and Redstone Test Command (RTC) range. A prototype RTFDDA-GSI-HLHN hybrid system was also run in real-time for the ATC domain.

## Sand and dust forecasting with WRF-Chem

Creating a dust forecast capability for Saudi Arabia based on the fully coupled WRF-Chem has been explored. Major steps taken thus far include (a) assessing available technologies for dust forecasting in Saudi Arabia, (b) designing proper algorithms and a system for implementation, and (c) producing sample dust forecasting results through a case study to demonstrate feasibility and capability. Fig. 2 shows an example of the dust forecast for a severe dust event over Saudi Arabia.



Improvements to RTFDDA Post-processing

Ensemble-RTFDDA has been run in real-time with several configurations (e.g., different domains, resolutions, members, etc.) over the USA (ATEC and Xcel-energy projects) and over China (CEPRI project). For the ATEC-4DWX project, a deterministic fine-scale forecasting system WRF-RTFDDA-LES has also been run in real-time over Utah, with a 300-m resolution. The post-processing of model data for visualization, bias correction and verification, has been improved for convenient configurations for different real-time forecast systems. Its efficiency has been improved with a new data flow, a better parallelization, and running different configurations on a single computing cluster. To meet special project needs, specific products have been added with an increased frequency (every 15 minutes) to visualize and verify wind energy and surface station forecasts. Also, a real-time bias correction (ANKF) and ensemble calibration (Quantile Regression) system has been implemented for wind farms and surface stations, with an updated web-page to access the new outputs.

PLANS FOR FY 2016

RTFDDA is an evolving modeling system. Research and development efforts are conducted continuously to improve all major system components, integrate community WRF achievements, and advance the nudging-based FDDA scheme. All operational RTFDDA systems will be upgraded to WRF Version 3.7.1 by the middle of FY2016, and then work will begin to upgrade the system for Version 3.8.x.

R&D will focus on the RTFDDA-GSI-HLHN hybrid radar data assimilation system, 4D-REKF four-dimensional data assimilation scheme, sand and dust simulation and prediction capability, and statistical model output processing techniques. For radar data assimilation, GSI and 4D-REKF data assimilation schemes will be assessed and tuned for assimilation of Doppler radar radial velocities. A sensitivity study will be conducted with the assimilation of radar reflectivity measurements with HLHN. Specifically, the impact of data frequencies between six minutes and one hour, relaxation strength, and algorithms for hydrometeor and latent heat derivation from the radar reflectivity will be studied. HLHN-based radar reflectivity data assimilation scheme will be studied for development of a high-resolution (2.5km grid) RTFDDA system that will span the contiguous US (CONUS) domain. In addition, assimilation of polarimetric radar products and lightning data in the hybrid RDA system will be assessed. 4D-REKF is an advanced FDDA capability that combines the advantages of Newtonian relaxation based “observation nudging” and the advanced ensemble Kalman filter. 4D-REKF using flow-dependent data assimilation weights generated with dynamical ensemble forecasts and historical forecast analogs will also be studied.

The RTFDDA forecast post-processing suite will be improved by adding two capabilities: a) ability to produce pin-point meteograms and profiles at 5-minute time intervals with development of corresponding calibration and verifications, and b) development of bias correction and calibration algorithms for station variables based on weather-pattern clustering classifications. Furthermore, wavelet analysis technology will be employed to separate the scales of the high-frequent observation and model forecast time series and the model forecast bias will be analyzed and corrected for individual wavelet components.

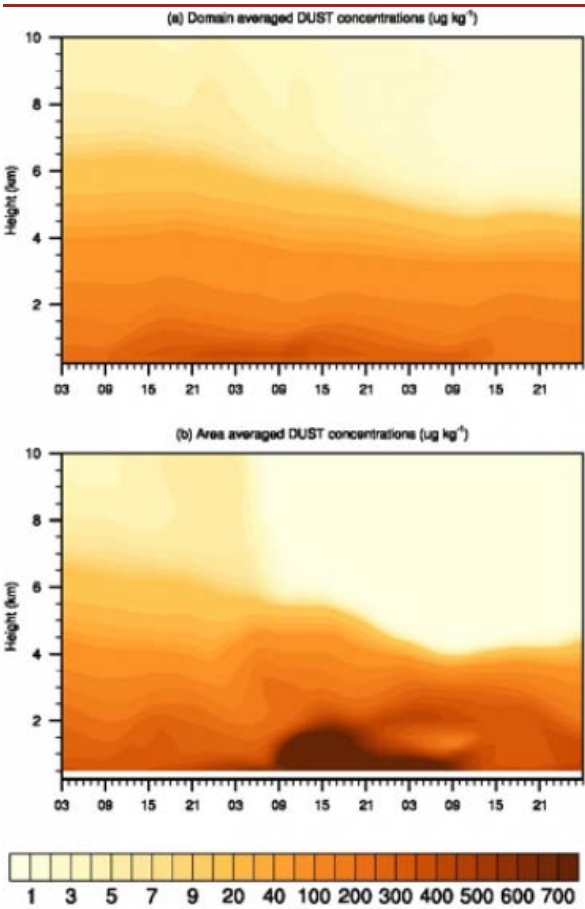


Figure 2. Height-time cross section of the WRF-Chem simulated (a) Domain 2 averaged and (b) an area centered around Solar Village averaged dust concentrations ( $\mu\text{g kg}^{-1}$ ) during the period of 03 LST March 9 through 03 LST March 12, 2009.

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## OPERATIONAL RTFDDA

### BACKGROUND

To meet the need for high-resolution, accurate, and rapidly updated weather information for weather-critical applications directed at national defense and security, energy, and health, RAL continues to advance and deploy its Real-Time Four-Dimensional Data Assimilation (RTFDDA) and forecasting system. RTFDDA has been deployed to provide real-time operational weather services for over 50 weather-critical applications by US government agencies and international organizations over the US and other global regions. This section reviews the following operational RTFDDA NWP projects:

1. US Army Test and Evaluation Commands (ATEC) test ranges
2. MAGEN for the Government of Israel
3. Ensemble wind prediction for State Grid Corporation of China (SGCC)
4. WRF-RTFDDA for wind power prediction of Xcel Energy
5. CONUS-scale RTFDDA operation for Panasonic Weather Solutions
6. RTFDDA high-resolution reanalysis and nowcasting for Shenzhen, China

### FY2015 ACCOMPLISHMENTS

#### US Army Test and Evaluation Commands (ATEC)



RTFDAA system serves eight Army test ranges located in the US and also supports on-demand test missions of ATEC in other regions over the globe. One ensemble-RTFDAA system and a deterministic RTFDAA-LES system have been set up for operational forecasts at the Army Dugway Proving Ground, Utah. More detail on specific advances made in ATEC modeling systems can be found at the 4DWX section of this report.

MAGEN for Israeli Government

MAGEN (Model for Advanced GENERation of 4D Weather) employs RTFDAA and WRFDA-3DVAR hybrid data assimilation technologies to provide high-resolution weather guidance over the eastern Mediterranean region. The second and final MAGEN system was enhanced and delivered to the Israeli Air Force; the system passed the on-site acceptance test and is now running in its own operational environment. The technology transfer was conducted through on-site training and updates to the MAGEN system technical manual. A new research topic will be initiated in FY2016 to extend the capabilities of the existing MAGEN hybrid system to assimilate data from dust models to improve dust forecasting capability. Plans for further enhancements to the MAGEN models also include increasing model resolution, cloud analysis and assimilation, ensemble data assimilation and probabilistic prediction, adaptive observation, and improvement of integration with the European Centre for Middle-range Weather Forecasts (ECMWF) model output.

Ensemble Wind Prediction for State Grid Corporation of China (SGCC)

To support wind power integration into the SGCC electric grids, NCAR collaborates with Chinese Electric Power Research Institute (CEPRI) and applies Ensemble-RTFDAA (E-RTFDAA) technologies for wind power prediction at SGCC. In 2014, NCAR accomplished a real-time E-RTFDAA system for wind prediction at wind farms over northwest provinces of China. One year reforecasts for Year 2012 with 20 ensemble members have been produced. The reforecasts are used for calibrating real-time ensemble forecasts and performing training of the CEPRI ANN (Artificial Neuron Network) wind power forecasting system. To assess the E-RTFDAA system for wind prediction at wind farm, the one year ensemble reforecasts are compared with the observations of 18 met-towers and turbine hub-height wind reports at 4 wind farms. Figure 1 shows a sample for forecast verification for a week period in September, 2012.

WRF-RTFDAA for Xcel Energy Wind-Power Prediction

Deterministic WRF enhancements

The NCAR-Xcel wind power prediction collaboration has moved into its third phase in which enhancements are being made to the WRF-RTFDAA system. The goal is to further improve WRF-RTFDAA’s hub-height wind prediction at wind farms by improving the model’s boundary layer and land surface schemes, and refining the algorithms for assimilation of turbine Nacelle wind speed (Fig. 2), wind direction, and temperature. An algorithm to assimilate wind-speed-only wind farm observations (no direction observation) has been developed, and WRF has been modified to perform the data assimilation. A next-generation RTFDAA data assimilation technology called Four-Dimensional Relaxation Ensemble Kalman Filter (4D-REKF), recently developed at NCAR, will be applied in the Xcel WRF-RTFDAA system, which is expected to improve the impact of wind farm and other data on model wind forecasts.

Another major research area is the simulation and prediction of microphysical hydrometeors, including supercooled liquid water and wet snow in the lowest 100 – 200m layer, to support wind-turbine icing prediction. Turbine blade icing can impede power production of turbines and/or potentially damage the turbines themselves.

PWS CONUS-scale RTFDAA Operation

NCAR and PWS (Panasonic Weather Solutions; formerly AirDat LLC) have been long-term partners in developing RTFDAA technology for TAMDAR (Tropospheric Airborne Meteorological Data Reporting) data quality-control, optimization of TAMDAR impact in regional NWP, and in developing operational RTFDAA forecasting systems. A CONUS-scale operational WRF-based RTFDAA data assimilation and forecasting system at 12/4-km resolution was deployed at PWS in 2009, and has been continuously running since then. A major task now underway focuses on enhancing the PWS-NCAR 12/4km CONUS RTFDAA system

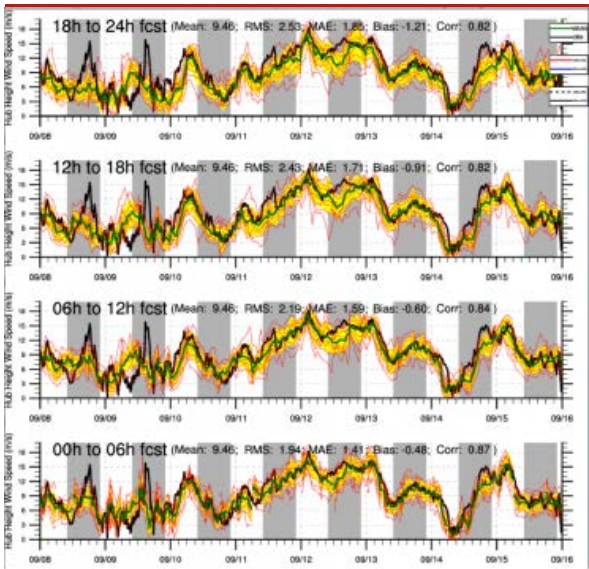


Figure 1. Sample verification of CEPRI-NCAR Ensemble-RTFDAA forecasts of wind speed at 70m AGL at a major wind farm in Gansu Province, China. Black : Observation, Green : Calibrated 50 percentile forecasts ; Red : quantiles; and Yellow : one standard deviation.



with radar data assimilation. More recent land cover data are used to better specify the RTFDAA model land use types, which significantly improves the representation of the current land surface properties, especially urbanization over the last 30 years (Fig. 3). The RAL hydrometeor-latent-heat-nudging (HLHN) radar data assimilation scheme has been employed. In case studies for two convective storms the impact of the radar data assimilation has been assessed. Pseudo-real-time tests are also being conducted. The system will be implemented on a super-computing cluster, newly purchased by PWS for real-time operational forecasting. Future work includes optimization of radar data assimilation in different regions with complex terrain.

### RTFDAA High-resolution Reanalysis and Nowcasting for Shenzhen, China

Shenzhen is a major city located in the Pearl River Delta in southern China; the municipality, which includes both urban and rural areas, spans 2,050 square kilometers. NCAR is collaborating with Shenzhen Meteorological Bureau to develop a RTFDAA modeling system for improved predictions over the city. The specific goal is to effectively integrate a high-density observation network with advanced remote sensing instruments, including ultra-dense surface Automatic Weather Station (AWS), wind profilers, radiometers, met-towers, Doppler radars, the Global Positioning System (GPS), lightning, and other platforms, into the RTFDAA system to provide continuous weather analysis and forecasts, and generate a five-year microclimatology for the Shenzhen area. The modeling system was configured with four nested domains with horizontal grid sizes at 27km, 9km, 3km and 1 km, respectively (Fig. 7a). The 1-km domain covers Shenzhen municipality, Hong Kong, and the neighboring area.

The main accomplishments in FY2015 include: 1) installation of RTFDAA technologies at Shenzhen Meteorological Bureau, and optimization of the model configuration including local land-surface characteristics presentation and surface-layer momentum flux computation; 2) completion of the last 5.5 year of climate-FDDA runs and verification; and 3) maintenance and continuous tuning of the real-time, rapid-updated RTFDAA microscale weather analysis and nowcasting system.

### PLANS FOR FY2016

Research and development efforts will focus on continuous deployment and improvements of the RTFDAA technologies for providing weather-critical applications with high-fidelity, high-resolution 4-D weather information, including microclimatology, current weather and short-term forecasting. This will include advancing the core model sciences and technologies as well as enhancing the capabilities of on-going and new operational systems. Proposals are under development to build RTFDAA systems for UAE, Thailand and other countries. Plans for several other on-going RTFDAA projects include:

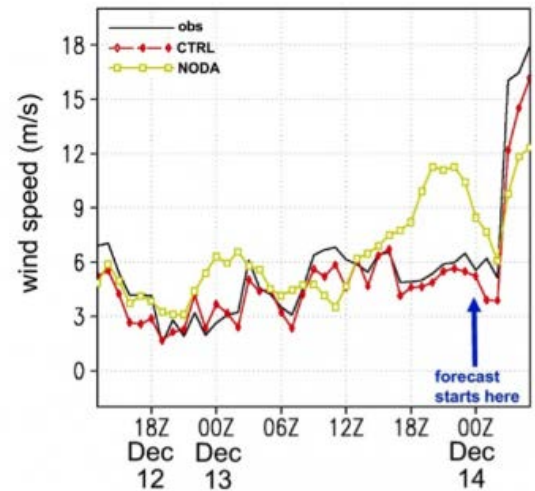


Figure 2. Time series of farm-averaged hub-height wind speed for a wind farm in Northern Colorado from observations (black), WRF control experiment assimilating turbine observations with enhanced nudging coefficients, and WRF experiment without wind farm data assimilation (yellow). In this “idealized” experiment, the only data assimilated were the wind farm data (from 1200 UTC 12 December to 0000 UTC 14 December) with enhanced nudging coefficients to study its maximum impact with enhanced nudging coefficients. The wind farm data helped to remove the spurious wind ramp and improved on the magnitude on the actual wind ramp.

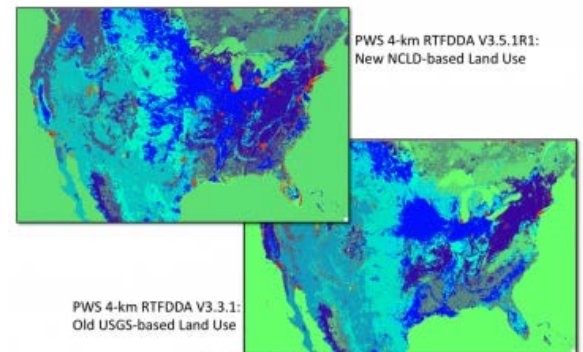
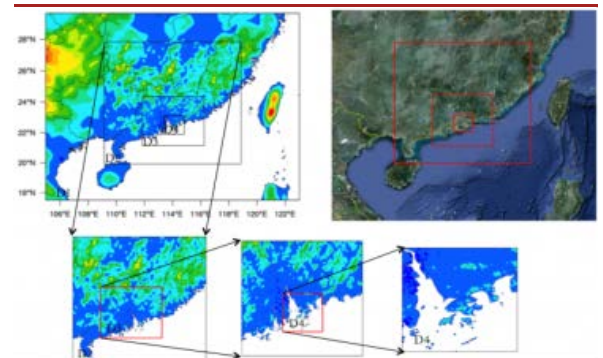


Figure 3. Update of land uses for the PWS-NCAR CONUS 4-km grid RTFDAA land use using the new land cover-based datasets. Many differences can be seen, especially the improved representation of the urbanization in the recent decades (red areas).



China Electric Power Research Institute

RAL will collect and process the SGCC wind farm data for assimilation into the E-RTFDADA system and for use in E-RTFDADA forecast calibrations. The ensemble perturbation approaches will be enhanced with SKEP, EnkF and usage of more global models. Currently a proposal is under development to expand the collaboration with CEPRI to develop general NWP capabilities for broader use in solar energy, electric-grid load, and power grid safety operations in severe weather conditions. RAL will also likely propose a plan to support the development of SGCC intelligent grid systems.

Figure 7a. The model domain configuration for real-time high-resolution weather analysis and production of 5-year microclimatology for Shenzhen metropolitan areas. The terrain height is shown in color shades.

Xcel Energy

Research will be conducted to enhance the Xcel Energy WRF-RTFDADA system by optimizing the wind farm data assimilation, including assimilating new data (wind direction and temperature measured directly by wind turbines) and refining the data assimilation weight functions. Special attention will be placed on improving WRF-RTFDADA capabilities with respect to wind ramp and turbine icing prediction.

Panasonic Weather Solutions

A major task has been defined to examine and optimize the NCAR-PWS CONUS-scale 2.5-km operational RTFDADA system with assimilation of radar reflectivity.

Shenzhen Meteorological Bureau

RAL will continue to optimize the WRF-RTFDADA setting for SZMB area to reduce the simulated wind bias, especially over the ocean. A new collaborative project has been established to implement and improve radar data assimilation for the real-time system at Shenzhen area and to develop local quantitative precipitation estimates based on SZMB’s radar, a rain-gage network, and a disdrometer network.

< Real-Time Four-Dimensional Data Assimilation (RTFDADA) and Forecasting Advances	up	Fine-Scale Precision NWP: WRF-RTFDADA-LES >
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FINE-SCALE PRECISION NWP: WRF-RTFDDA-LES

BACKGROUND

Demands on fine-scale precision weather forecasts from weather-sensitive organizations are rapidly increasing. To meet their needs, NCAR-RAL takes advantage of its advanced real-time four-dimensional data assimilation (RTFDDA) weather forecasting system and increased computing power to study the feasibility of using its numerical weather prediction (NWP) capability to model at the sub-kilometer Very-Large-Eddy Simulation (VLES) scale down to the Large Eddy Simulation (LES) scale. To accomplish this, the newly developed WRF-RTFDDA-LES system can be directly nested inside a parent mesoscale system. This fine-scale forecasting system provides detailed weather information that can be integrated to improve operational and logistic effectiveness of a multi-faceted prediction system. In the course of developing this system, RAL has conducted fundamental research on various fine-scale weather scenarios including tornado storm and wind farm turbulence. This work

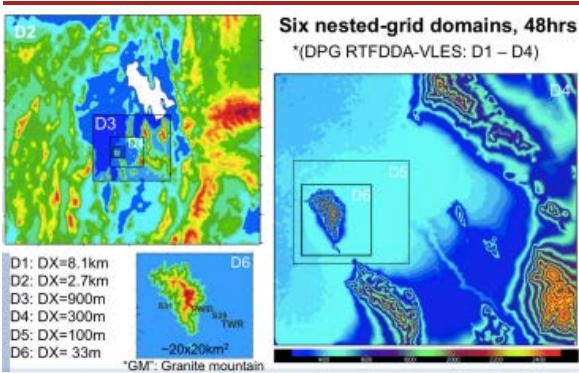


Fig. 1. Simultaneous multi-scale WRF-RTFDDA-LES simulations with six-nested-grid domains with model grid intervals varying from



is currently being adapted for research and operational use by several meteorological agencies.

FY2015 ACCOMPLISHMENTS

Research on WRF-RTFDDA-LES during this year was mainly focused on an evaluation study of a real-time modeling system for the US Army’s Dugway Proving Ground (DPG) in Utah, and a real-time modeling system for the US Army’s Aberdeen Test Center in Maryland. A WRF-RTFDDA-LES model has also been set up to simulate fine scale weather flows and mountain convections over the White Sand Missile Range in New Mexico.

To study the impact of WRF model grid resolution on the multi-scale flow interactions at Granite Mountain in DPG with a LES-scale system, RTFDDA-LES was implemented for DPG. It was configured for four nested-grid domains, with grid sizes of 8.1, 2.7, 0.9 and 0.3 km, respectively (Fig.1). The system assimilates all available observations, including the dense network of observations at DPG. Verification of the real-time analyses and forecasts shows the benefits of the ultra-high-resolution NWP system in resolving realistic sub-mesoscale flows; it also exposes artificially amplified turbulence over broad spatiotemporal scales. To study the VLES potential with regard to true LES modeling, a simulation was conducted with six nested-grid domains (two extra nested domains with grid sizes of 100m and 33m, respectively [Fig. 1]) were added to the DPG RTFDDA-VLES. The study focused on the Granite Mountain (~60 km<sup>2</sup>) and neighboring areas at DPG, the site of the MATERHORN field campaign. The modeling results show increasing ability of the VLES and LES model over the mesoscale model in resolving the fine-scale flow features, especially wind ramps (e.g. Fig. 2), and confirm the validity and value of VLES-scale NWP.

Two approaches are being developed to contain the artificially amplified turbulence in the VLES model. One approach is to add a TKE-based boundary layer scheme on the top of the LES sub-grid-filter and the other is to adjust the sub-grid-filter mixing parameters. Both approaches mitigate, but do not remove, the artificially amplified turbulence. For the end user’s benefit, a wavelet-based scale separation strategy is being developed to post-process the VLES meteograms and remove the artificially amplified turbulence.

In addition to the modeling work at DPG, RTFDDA-VLES/LES is also being implemented for the ATC region. In contrast to the terrain at DPG, ATC is characterized by bay-land contrast and complex coastlines Military test activities strongly rely on the fine scale flows and other weather variables over the test range which extends over a 10x15 km<sup>2</sup> peninsula and surrounding areas in the upstream of Chesapeake Bay. The area presents very complex coastlines, hills and heavily man-modified landscapes.

In FY2015 RAL scientists RTFDDA-LES to study the multiple-scale flow interaction of synoptic, local land-surface forcing, and thermally driven land-sea flows. Six nested-grid domains, with grid sizes of 8100, 2700, 900, 300, 100, and 33m, respectively, were configured and a 48h simulation was carried out simultaneously on the six nested grids for a two-day period during summer 2013. The data assimilation of RTFDDA was turned on for the mesoscale domains (1, 2 and 3), while the LES domains (4, 5 and 6) were run with “free forecasting”. The mesoscale data assimilation on the coarse meshes provide realistic mesoscale forcing for the LES simulation, so that the model outputs of the LES domains can be reasonably verified using high-resolution (every 1 – 5 minutes) measurements of APG surface weather stations and the remote-sensing systems.

The model results were analyzed to evaluate the feature, value, and feasibility of LES-scale precision weather forecasts for applications over

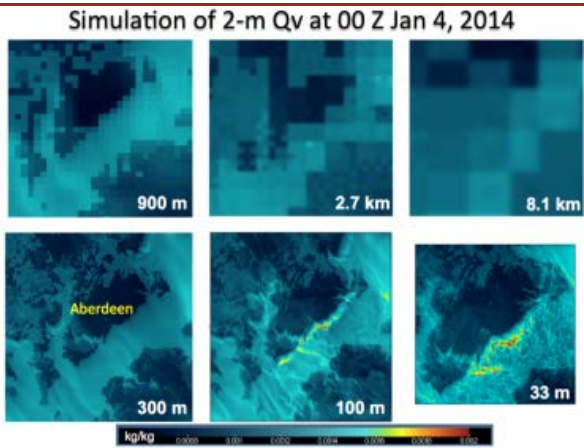
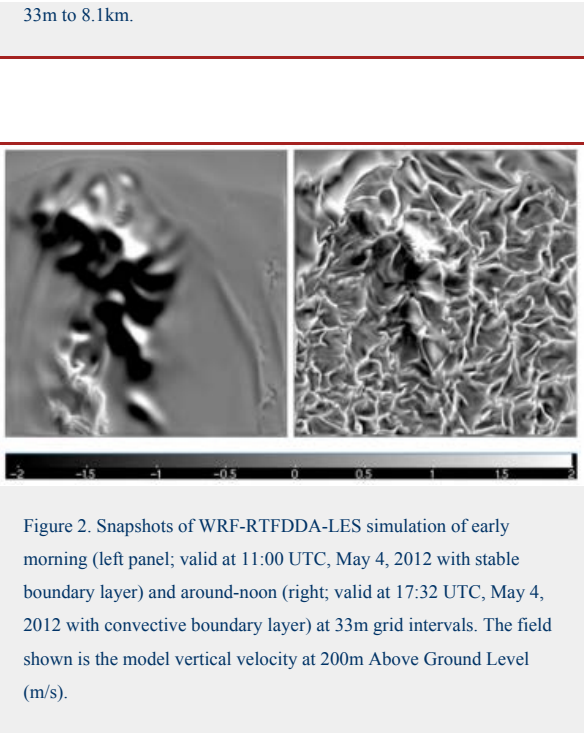


Figure 3. A snapshot view of surface moisture (water vapor mixing ratio) structures over the Aberdeen area, simulated with models with

complex coastal regions. Through an inter-comparison of the mesoscale, VLES and LES scale model output, the validity and value of running VLES NWP for real-time forecasting with the currently available computing capability was assessed. A snapshot showing impact of model resolutions on wind flows and surface moisture fluxes are given in Fig.3. RTFDDA-VLES simulated much more accurate wind flow than the corresponding mesoscale models at ATC, just as it had at DPG.

grid sizes of 8100, 2700, 900, 300, 100, and 33m respectively.

FY2016 PLANS

In the coming year, RAL will continue to study and evaluate the WRF-RTFDDA-LES modeling system by focusing on refinement of the fine-scale forecasting capability, and development of tools to improve the use and visualization of VLES forecasts by end users. Research will also focus on developing VLES forecast verification strategies, as well as investigating LES-scale data assimilation algorithms. In particular, RTFDDA-LES will be employed to study the orographic convection over the mountain ranges surrounding the Army’s White Sand Missile Range, as well as to study a severe wind event. Observations from advanced instruments fielded by the Army Research laboratory will be used to validate and aid the modeling research.

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## HIGH PERFORMANCE COMPUTING FOR OPERATIONAL MODELING

### BACKGROUND

RAL's research and development in advanced, small-footprint computing is focused on providing scalable solutions to high-resolution numerical modeling with demanding data storage requirements. By keeping abreast of the increasing speed and density of rack-mounted cluster computing, RAL delivers climate analyses and real-time weather predictions that fit into an ever-decreasing footprint. As hardware vendors continue to provide higher density computing, RAL is able to move toward more green computing, with lower power and cooling requirements.

An important feature of RAL/NSAP's computing design is its ability to provide solutions across scales. Given the need to deploy systems that range in size from 32 cores to 832 cores, and applications that range from global climatology to large eddy simulations, the flexibility and extensibility of the computing architecture becomes a critical component for success. Cumulative number of computing cores presently exceeds 3000, across 475+ nodes in use by NSAP projects.

### COMPUTING

In order to effectively utilize core-dense compute resources (nodes) for parallel codes (e.g., the WRF model) as well as serial based post-processing, various software layers have been under examination to improve performance across differing

job sizes. During FY2015 the testing, analysis and impact measurements have included everything from Intel compilers, differing versions of openmpi, Linux kernel power features, as well as combinations of Infiniband OFED software stacks and FDR IB equipment. Through the evaluation of these tools, technical staff can help assess specific efficiencies that can be gained when sizing hardware architectures to varied job-type and runtime requirements, or to assess how non-local, hosted HPC centers might benefit NSAP projects by utilizing shared computing resources in the future.

STORAGE

RAL continues to utilize improvements in data storage management through the deployment of NAS (network attached storage) systems that are simultaneously accessible by a variety of project clusters. The transition away from RAID disks that were directly attached to a single computing cluster to NAS data repositories that are accessible across the local area network has been accompanied by greater reliability, increased data accessibility, and less time spent on storage maintenance by system administrators and users. In addition to the increased reliability, the NAS solution provides a growth path that allows for incremental additions to data storage, while maintaining consistent, logical namespace. The end result is that data users no longer have to spend time juggling datasets across individual disks, leaving it to the NAS architecture to manage the mapping between logical and physical space.

Further enhancing the scalability of application to storage performance are parallel IO access methods, which each server uses to access file systems over a dedicated gigabit to 10Gigbit network. The parallel NFS standard minimizes hot-spot contention for data sets and provides a topology where high demand IO requests are balanced over dozens of disk spindles and network ports to provide streaming of data in both write or read modes.

At the end of FY2015 NSAP had approximately 228TB of highly fault-tolerant, parallel, network attached object-based storage, with the capability to increase by 100s of TB in FY16 and beyond. Cumulative storage across various project clusters now exceeds 550TB. In addition to available storage, as a result of commensurate networking upgrades, the data throughput potential to backend storage has grown to 60 Gbps, providing bandwidth for the increasing demands of higher resolution weather and climate forecasting.

MONITORING

In addition to continued expansion into smaller and more efficient use of computing and storage resources, accomplishments include an expansion in the use of network-enabled system monitoring and performance analysis tools at the data management layer. Through the deployment of these tools, technical staff receive real-time alerts and are able to evaluate a historical record of metrics graphically to help diagnose both system and application scalability. The extensible community-supported, plug-in architecture allows developers to easily adapt existing monitoring examples to varied applications across different computing architecture without the need to write code from the ground up.

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SATELLITE PRECIPITATION DATA ASSIMILATION

BACKGROUND

An accurate description of the wind at the surface and in the planetary boundary layer is critical to Transport and Dispersion studies. Current fine scale reanalyses, such as those obtained through dynamical downscaling with the Weather Research and Forecasting model, are primarily driven by conventional observations. However, most of the regions of the world that strategic for our security are usually void of conventional observations. The use of satellite data is therefore critical, and studies (Zou and Kuo 1996, Fillion and Errico 1997) suggest that satellite precipitation observations may have the strongest impact in the model boundary layer when assimilated.

ACCOMPLISHMENTS IN 2015

RAL’s approach builds on Fillion and Belair’s (2004) work, in which precipitation is assimilated within a variational framework. The method, which makes use of the Kain-Fritsch cumulus parameterization, has been ported to the WRF model. Practically, it acts as a one-dimensional variational (1D-VAR) data assimilation of precipitation estimates through the KF scheme and its Jacobian to produce increments to the model temperature and moisture profiles, including those in the boundary layer. An initial WRF integration is performed with assimilation of conventional observations and the 1D-VAR is performed grid point by grid point using precipitation estimates from the Climate Prediction

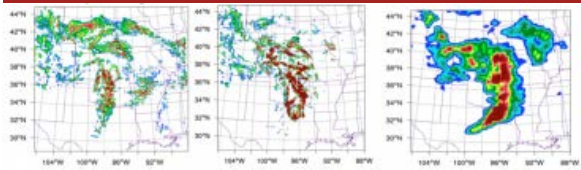


Figure 1: 3-hour accumulated precipitation: WRF without assimilation (left), WRF with assimilation (center) and NOAA CMORPH analysis (right), valid at 00z on May 25, 2011 (7pm local time). The WRF grid increment is 9km. The CMORPH grid increment is 0.25°.

Center MORPHing (CMORPH) as observations and the WRF integration as first guess. A second integration is then conducted in which the WRF model is nudged toward the gridded solutions of the 1D-VAR precipitation assimilation. Figure 1 shows WRF precipitation with (middle) and without (left) assimilation of precipitation for an event that occurred over the Southern Great Plains (SGP) in the evening of May 24, 2011, compared to the precipitation estimate from the CMORPH analysis (right). CMORPH blends precipitation estimates that have been derived from low orbiter satellite microwave observations exclusively.

PLANS FOR FY2016

The method described above will be validated on the comprehensive observational data set collected during the Midlatitude Continental Convective Cloud Experiment (M3CE) over the Atmospheric Radiation Measurement region in the SGP. By assimilating the radio-soundings as well as the precipitation measurements collected during M3CE data sets, we will also seek to refine the thresholds of important parameters such as convective available potential energy (CAPE) and vertical velocity, which are key to the initiation and triggering of convection in the KF cumulus scheme. Once validated, the method will be operationally implemented into the Global Climatology Analysis Tool.

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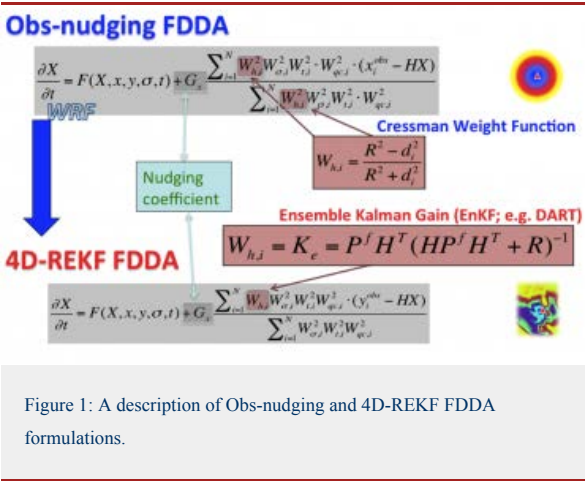
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MESOSCALE ENSEMBLE DATA ASSIMILATION AND PREDICTION SYSTEM

BACKGROUND

A Four-Dimensional Relaxation Ensemble Kalman Filter (4D-REKF) mesoscale analysis and forecasting system has been developed by RAL’s numerical weather prediction (NWP) modeling group. 4D-REKF is built upon the multi-model (MM5 and WRF), multi-approach (perturbations), and multi-scale (nested-grid) E-RTFDAA (Ensemble Real-Time Four-Dimensional Data Assimilation and forecasting system). E-RTFDAA was developed at RAL and has been deployed for real-time operational weather forecasting at the Army Dugway Proving Ground and in wind energy forecast applications. E-RTFDAA model members employ Newtonian-relaxation 4D data assimilation algorithms to achieve rapid cycling of continuous 4D analysis and forecasting. To take advantage of E-RTFDAA ensemble prediction, 4D-REKF uses Kalman gains that can be computed using the multi-model E-RTFDAA forecasts. The Kalman gains are ingested into E-RTFDAA models to replace the simple distance-dependent observation weighting functions in the original nudging model. A Local Ensemble Kalman Filter (LEKF) approach is employed to take account of multi-observations.

4D-REKF retains and leverages the advantages of both traditional Newtonian-relaxation and Ensemble Kalman Filter data assimilation schemes. It eliminates the shortcoming of empirical specification of spatial weight functions in the current



station-nudging FDDA formulation. On the other hand, it extends the traditional (intermittent) EnKF data assimilation method to a 4D continuous data assimilation paradigm that greatly mitigates the dynamic shocks associated with the intermittent EnKF processes. Furthermore, 4D-REKF also greatly reduces the critical dependency on the background error covariance inflation with the traditional EnKF and permits effective assimilation of all observations that may be available at irregular locations and times. Figure 1 describes the general formulation of the 4D-REKF FDDA scheme. 4D-REKF enhances both the accuracy of model initial conditions and also the initial condition perturbation approach, and thus improves the overall capabilities of E-RTFDDA ensemble prediction.

FY2015 ACCOMPLISHMENTS

Major work done on 4D-REKF in FY2015 includes testing and optimizing the 4D-REKF code and algorithms in preparation for real-time operational runs. Several approaches have been tested and implemented for computing the Kalman gain accurately and efficiently. The schemes tested include a 2D mathematical fitting function, a ray-tracing method and a "nearest-point" approach. It was found that the "nearest-point" method presents the best trade-off between accuracy and efficiency for the Kalman gain computation. In order to deal with diverse observation types, two kinds of Kalman gain computation have been designed. For fixed stations, the Kalman gains are calculated at the exact station locations. For time-space changing observations such as aircraft weather reports, the Kalman gains are computed at regular grid points and then interpolated to the observation locations.

To validate the 4D-REKF data assimilation system, OSSE experiments based on the "perfect-model-perfect-observations" approach have been conducted. For comparison, WRF 3DVAR, 4DVAR, GSI, and NCAR DART-EnKF have also been tested with the same OSSE framework and the data. The verification results of this OSSE study indicate that 4D-REKF outperforms other existing WRF data assimilation technologies. Figure 1 presents an example showing the bias and RMSE of various meteorological variables in 4D-REKF at the end of 6-hour data assimilation in comparison to those of WRF 3DVAR, 4DVAR, NCAR DART-EnKF, and GSI. The bias and RMSE in the standard Station-Nudging FDDA are also shown in the figure.

The 4D-REKF FDDA scheme has been deployed as a component of the operational E-RTFDDA system running at the US Army Dugway Proving Ground, Utah. Assessment of the impact of 4D-REKF is on-going, but the preliminary results suggest that the "raw" Kalman gains computed from the ensemble forecasts are not sufficiently accurate. Further refinements to the Kalman gains estimation and new hybrid Kalman gain schemes that combine real-time ensemble-based background error covariance and historical regime-based background error covariance were formulated. Figure 2 shows impact of changing weights (a) between Cressman weighting and ensemble Kalman gains.

Surface weather observations are very important for local and regional (meso- beta and gamma) scale weather analysis and 0 - 12hr forecast. In fact, many weather-critical businesses, such as the Army test ranges, deploy and maintain surface weather station network to support their applications. Effective assimilation of surface observations into high-resolution mesoscale models has also been one of the high-interest scientific topics for improving regional and local-scale weather analysis and prediction. The 4D-REKF data assimilation scheme enables the use of flow-dependent background error covariance to spread the observation information in the state space of the WRF model. In order to take advantage of 4D-REKF when an ensemble is too expensive to run, an approach to use climatological weather-regime based spatial correlation ( $K_c$ ) in the place of ensemble-based Kalman gain ( $K_e$ ) to improve the surface data assimilation has been developed. With this approach, the weather day/times that are similar to the weather regime of the current weather are identified from the recent and/or historical high-resolution model forecasts, and these forecasts are collected and used to form a "climate" ensemble. Kalman gains are computed with this ensemble (so-called "climate-ensemble Kalman gains":  $K_c$ ) and ingested in 4D-REKF to enhance the surface data assimilation in WRF. Case studies have been conducted to test this algorithm and the result shows obvious improvements from RTFDDA which is based on the Cressman-type weight function for surface data assimilation.

FY2016 PLANS

4D-REKF is currently at an early stage of initial operating capability. Further evaluation and enhancement are necessary to fully exploit the power of the technology. FY2016 plans include work to:

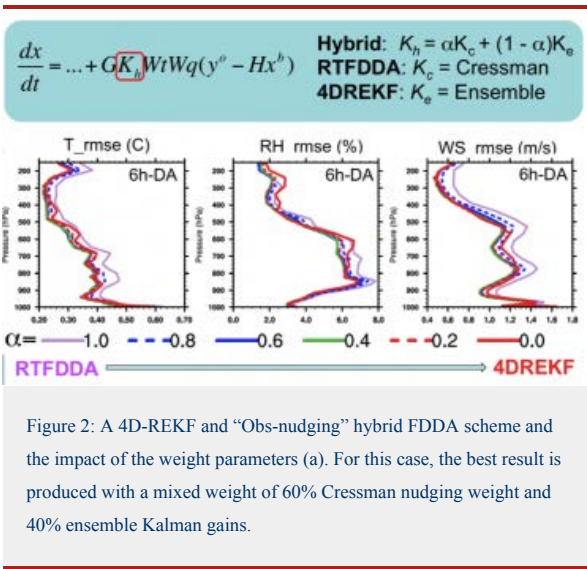


Figure 2: A 4D-REKF and "Obs-nudging" hybrid FDDA scheme and the impact of the weight parameters (a). For this case, the best result is produced with a mixed weight of 60% Cressman nudging weight and 40% ensemble Kalman gains.

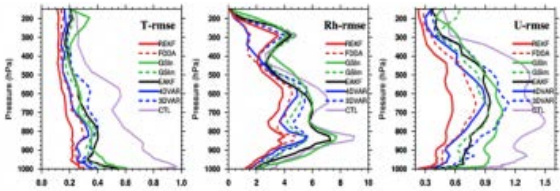


Figure 3. Comparison of the RMSE of 12hr forecasts of temperatures (T), relative humidity (Rh), and zonal wind component (U) of WRF that are initialized from 12h data assimilation using Cressman-type observation-nudging (FDDA), 4DREKF (REKF), WRFDA 3DVAR and 4 DVAR, DART-EnKF (EAKF), and two flavor of GSI (GSIm and GSIn) for an OSSE study. The WRF Forecast without data assimilation is denoted as CTL.

- Evaluate and enhance the representativeness of Kalman gains computed from meoscale ensemble forecasts that typically subjects to rank-deficiency issues (excessively small number of ensemble members than needed to describe the realistic probability distribution of the background states).
- Study empirical algorithms to improve 4D-REKF analysis and prediction. This work will address the fact that ensemble mesoscale forecasts often lead to formation of sporadic, unrepresentative local structures in the Kalman gains that introduce noise and lessen the effectiveness of data assimilation.
- Continue to refine ensemble Kalman gain computation for 4D-REKF and enhance 4D-REKF with cross-variable (covariance) “observation-nudging” capabilities. In particular, this new capability will be applied to assimilate Doppler radar radial velocities.
- Implement 4D-REKF for real-time semi-operational use at the US Army Dugway Proving Ground; verify performance, and extend this capability to other real-time E-RTFDDA systems.

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ENSEMBLE DATA ASSIMILATION FOR WIND PREDICTION AND MODEL ERROR

BACKGROUND

This project was funded as part of the Department of Energy effort “U.S. Offshore Wind: Removing Market Barriers” and completed in 2015. The outcome has been improved understanding of the complex interactions between the atmosphere and the ocean surface. This knowledge will be used to develop improved marine boundary layer (MBL) parameterizations, as well as improved ocean-atmospheric coupling techniques, significantly reducing market barriers to offshore wind energy, delivering the Department of Energy’s goals. These goals include more accurate predictions of turbine hub-height winds in marine environments, resulting in improved power prediction and potentially saving millions of dollars for the wind energy industry, and improved wind resource assessment techniques in marine environments.

FY2015 ACCOMPLISHMENTS

The project started in late April 2013 and was focused on: (1) collecting observational data sets, quality control, formatting, and analysis for 1D experiments, (2) implementating 2-way coupling between WRF Single Column Model (SCM) and the wave model WaveWatch III, and (3)

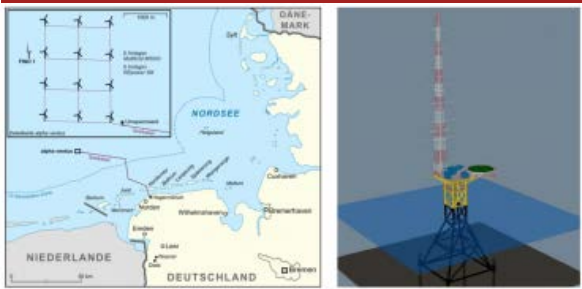


Figure 1. Location and configuration of the FINO 1 platform. Images are from [www.fino1.de](http://www.fino1.de).

performing state estimation (SE) experiments with WRF SCM/Data Assimilation Research Testbed (DART). All work on these tasks was completed in FY2015.

FY2016 PLANS

Should additional funding be identified, state estimation, i.e., unknown parameter estimation within a data assimilation framework, will be explored for boundary layer parameterizations over land, and microphysics schemes.

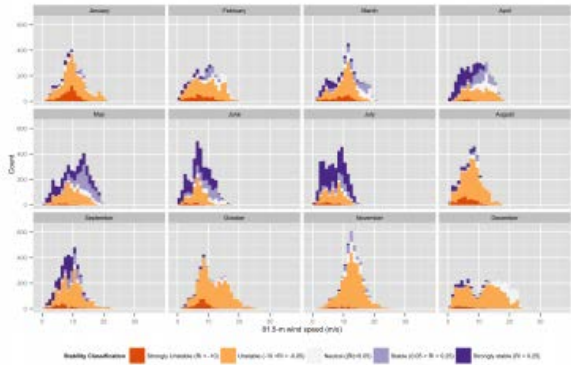


Figure 2. Monthly distributions of wind speed and stability. Stability data are plotted as a function of the 81.5 m wind speed

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RTFDDBA-3DVAR HYBRID SYSTEM

BACKGROUND

RTFDDBA (Real-Time Four-Dimensional Data Assimilation and forecasting system) is a mesoscale numerical weather modeling technology that has been developed for applications that desire high-resolution, rapid-update, high-accuracy, and customized weather information for specific regions. An important feature of RTFDDBA is that it allows for smooth and uninterrupted assimilation of diverse weather observations and produces physically consistent and dynamically balanced 4D weather analyses and cloud/precipitation “spun-up” predictions.

RTFDDBA integrates different community WRF data assimilation tools that can be activated and configured to provide the best data assimilation strategies for a given application scenario. For data sparse regions, an RTFDDBA and 3DVAR (WRFDA and GSI) hybrid data assimilation approach has been developed, with RTFDDBA taking a greater roles on fine-grid simulation of meso-beta and meso-gamma scale processes and 3DVAR on coarse grids for synoptic scale simulation. 3DVAR is able to assimilate satellite radiance measurements that provide important weather information in regions where conventional observations are sparse.

FY 2015 ACCOMPLISHMENTS

RTFDDBA-GSI-HLHN Hybrid Data Assimilation

One of the challenges for numerical weather prediction in the regions where conventional weather data are excessively sparse, such as over oceans, the Middle East, Africa etc., is the limitation of the observations

that can be used for properly initializing mesoscale models. An RTFDAA-GSI hybrid data assimilation scheme (Fig. 1) has been developed in order to incorporate unconventional observations, especially remote sensing measurements such as satellite radiance, for model initialization. RTFDAA-GSI hybrid data assimilation approach is also employed to assimilate Doppler radar radial velocity observations in RTFDAA. A major benefit of the RTFDAA-GSI hybrid data assimilation technology over the typical GSI-only model initialization scheme is that it keeps the advantage of the RTFDAA in generating 4-D dynamically consistent and physically spun-up analysis and forecasts

Another important utilization of GSI/WRFDA 3DVAR is to assimilate Doppler radar radial velocity. In this situation, Doppler radar reflectivity measurements are assimilated with a hydrometeor-latent-heat-nudging (HLHN) scheme where radar reflectivity is used to retrieve precipitation particles (snow, rain drops and graupel) which are then nudged into WRF along with adjustments of latent heat releases. Figure 2 shows a diagram of the RTFDAA-GSI-HLHN radar data assimilation (RDA) capability

Incorporating radar data into the real-time operational framework of RTFDAA has been one of the major undertakings of the next-generation RTFDAA development. RTFDAA-GSI/HLHN hybrid radar data assimilation has been tested with retrospective case studies for convective systems in the Colorado Front Range, the Army Aberdeen Test Command (ATC) range and Redstone Test Command (RTC) range. A prototype RTFDAA-GSI-HLHN hybrid system was also run in real-time for the ATC domain.

Plans for FY 2016

Research and development efforts relating to RTFDAA-GSI-HLHN will be focused on enhancement of radar data assimilation (RDA). GSI and 4D-REKF data assimilation schemes will be assessed and tuned for assimilating Doppler radar radial velocities. Sensitivity study will be conducted with the assimilation of radar reflectivity measurements with HLHN. Specifically, impact of data frequencies between six minutes and one hour, relaxation strength, and strategies for hydrometeors (rain, snow, and graupel mixing ratios) and the corresponding latent heat derivation from radar reflectivity observations will be studied. HLHN-based radar reflectivity data assimilation scheme will be employed in a development of a high-resolution (2.5km grid) RTFDAA system that span over the contiguous US (CONUS) domain. In addition, work to assimilate polarimetric radar products and lightning data into the hybrid RDA system will begin.

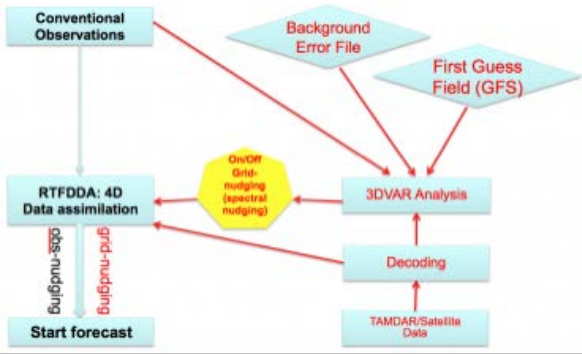


Figure 1. Schematic diagram of the RTFDAA-GSI hybrid data assimilation system.

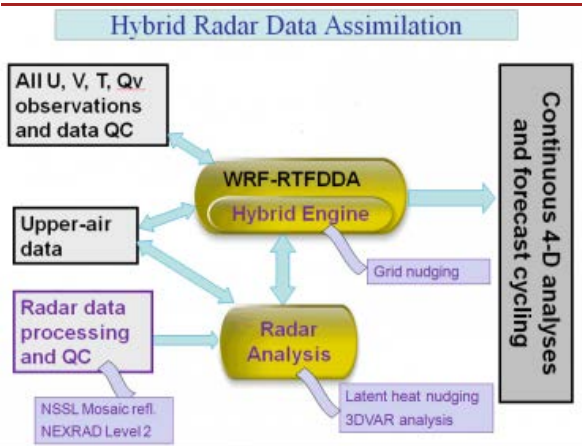


Figure. 2 Schematics of the RTFDAA, GSI and HLHN hybrid for radar data assimilation.



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# UNCERTAINTY QUANTIFICATION AND PROBABILISTIC FORECASTING

## DYNAMICAL ENSEMBLE PREDICTION

### Background

Given the chaotic nature of the atmosphere and the imperfections of numerical weather prediction (NWP) models, probabilistic forecasts are imperative for applications. To address this need, RAL has been developing an Ensemble Real-Time Four-Dimensional Data Assimilation (E-RTFDDA) and forecasting system. This WRF-based mesoscale ensemble has been deployed to support US Army test range operation and real-time wind energy prediction. Unlike most other mesoscale ensemble systems, E-RTFDDA is a multi-model, multi-scale, and rapidly cycling data assimilation and prediction system with multiple perturbation approaches. The continuous cycling mechanism of E-RTFDDA allows the model to produce accurate nowcasts and short-term forecasts. E-RTFDDA also contains an innovative ensemble data assimilation algorithm known as four-dimensional relaxation ensemble Kalman filter (4D-REKF). It replaces the simpler Cressman-type "observation-nudging" FDDA in E-RTFDDA with a flow-dependent weighting. The research and development of E-RTFDDA is currently conducted under the sponsorship of the Army Test and Evaluation Command, Xcel Energy and China State Grid projects, whose broad objectives and progress are also discussed in this annual report.

### FY2015 Accomplishments

The R&D of Ensemble RTFDDA (E-RTFDDA) during FY2015 was mainly focused in three areas: 1) enhancements to the ensemble perturbation, 2) development of 4D-REKF, and 3) Ensemble system deployment/operation and advances in post-processing and calibration.

### FY2016 Plans

E-RTFDDA will be further enhanced in the following areas:

- Implement more global model forecasts as drivers for E-RTFDDA perturbations.
- Continue to evaluate and optimize the SKEP scheme for WRF dynamical ensemble perturbation and DART-EnKF for WRF initial condition perturbation strategies for mesoscale applications.
- Implement 4D-REKF for real-time semi-operation at US Army Dugway Proving Ground and verify the advantages.
- Continue to improve the ensemble forecast verification and calibration algorithms. The Quantile Regression (QR) calibration approach will be reformulated to train the correction according to weather regimes. Improvement of the definition and determination of "Analog" in the ANKF scheme will also be considered.

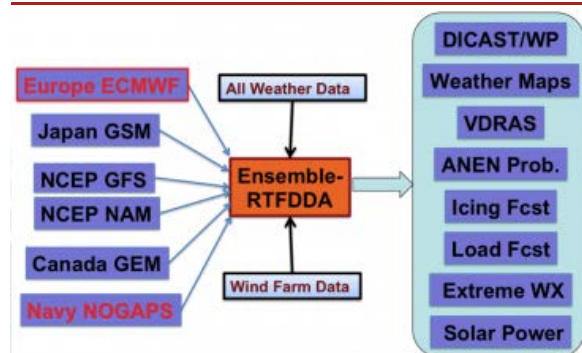


Figure 1: A diagram showing E-RTFDDA downscaling global model

- Continue the E-RTFDFA technology transfer through developing new collaborations with existing and new U.S. and international agencies.

ANALOG ENSEMBLE

FY2015 Accomplishments

The analog ensemble has been applied with success to the following applications:

- Solar wind power predictions (Alessandrini et al., 2015). When compared to state-of-the-art solar power prediction systems such as quantile regression or neural networks, the AnEn exhibited better performances especially for those forecast lead times concurrent to a low solar elevation (early morning and late afternoon, see Figure 1).
- Wind power forecasting. The benefit of the predictor weights optimization for wind power forecasting has been tested. This test regards a new data-set (Junk et al. 2014) including four wind farms located in Italy, Denmark and Colorado (USA).
- To generate probabilistic weather predictions over a 2/3D grid, the AnEn has been applied on a 500x500 km<sup>2</sup> grid, using ECMWF analysis field as the ground truth. Preliminary results show superior skill for forecast lead times between 0-72 hours ahead than ECMWF Ensemble Prediction System (EPS).
- Prediction of tropical cyclones intensity. AnEn has been applied on a dataset covering the period 2008-2013. This dataset includes 78 hurricanes on western Atlantic basin. Preliminary results show that AnEn can improve the mean absolute error of HWRF maximum wind speed forecasts of about 8%.
- An analog-based ensemble model output statistics (EMOS) has been applied to improve EMOS for the calibration of ensemble forecasts (Junk et al., 2015).

FY2016 Plans

In FY16 the potential of the analog ensemble technique will be further explored for several application: forecasting of precipitation, the generation of probabilistic weather predictions over a 2/3D grid, the prediction of tropical cyclones intensity in the eastern Pacific basin, and air quality forecasts to improve deterministic predictions of O<sub>3</sub> and PM<sub>2.5</sub> concentrations by the Community Multi-scale Air Quality (CMAQ) model over 564 sites of AIRNow Environmental Protection Agency (EPA) network across the US.

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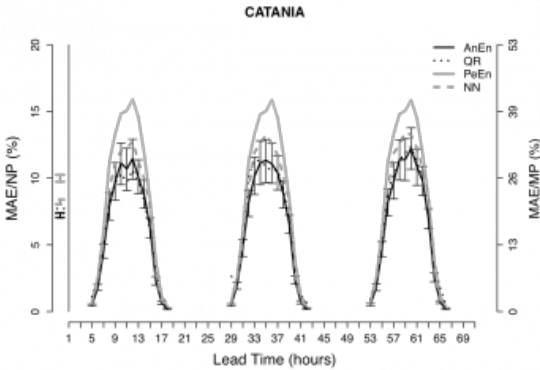


Figure 1 Percentage mean absolute error normalized by nominal power (MAE/NP %, left y axis) and by mean power (MAE/MP %, right y axis) of analog ensemble (AnEn), quantile regression (QR), Neural Network (NN) and persistence ensemble (PeEn) as function of forecast lead time. Bootstrap 5-95% confidence intervals are plotted for AnEn only to reduce clutter. Next to the left y-axis the metric confidence interval is computed by pulling all the lead times together for the hours with a positive average solar elevation.

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## BACKGROUND

Post-processing ensemble forecasts is generally a necessary requirement to provide meaningful probabilistic guidance to users. One approach that has been used for a variety of applications is quantile regression (QR). RAL scientists are applying a novel statistical correction approach by combining QR with other post-processing approaches (e.g. analog, logistic regression) to calibrate at the specific probability intervals required by the user. Some of the benefits of this approach are that no assumptions are required on the form of the forecast probability distribution function to attain optimality; the resultant forecast skill is no worse than a forecast of either climatology or persistence; and the generated ensembles have dispersive properties directly related to the uncertainty in the forecast that one would expect.

## ACCOMPLISHMENTS IN FY2015

- QR was merged with the analog approach to post-process numerical weather prediction ensembles of wind prediction of wind turbines within China
- QR was similarly merged with the analog approach to post-process weather station forecasts for the Army Test and Evaluation Command at the Dugway Testing Range in Utah

## PLANS FOR FY2016

- Utilize QR to generate ensemble predictions at hydrologic stations in the Ganges and Brahmaputra rivers within India
- Apply QR to medium-, monthly-, and seasonal-range ensemble prediction of river discharge flowing into hydro-electric reservoirs within East Africa to provide probabilistic guidance on water release decision-making

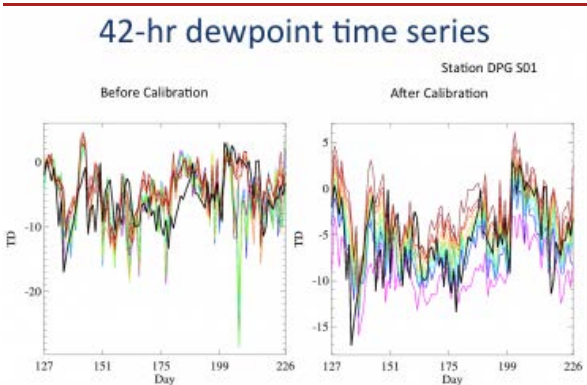


Figure 1: Quantile regression applied to dewpoint temperature at one station at the Army Test and Evaluation Command at the Dugway Testing Range in Utah, providing a probabilistic range that the dew point may fall within at a lead-time of 42-hr.

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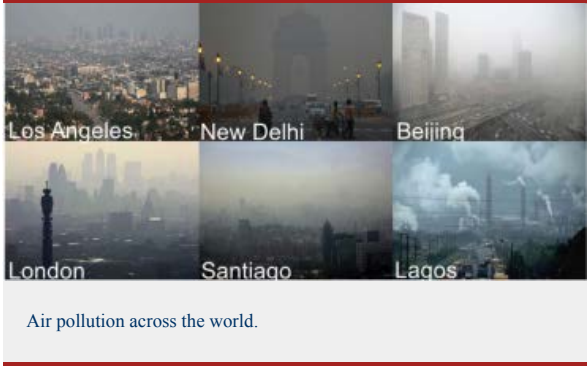
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AIR QUALITY FORECASTING

BACKGROUND

Air pollution is estimated to cause about 3.7 million premature deaths worldwide and destroy enough crops to feed millions of people every year, and is thus a major global environmental risk to both our health and food security.

NCAR has more than two decades of experience in developing advanced community models that are widely used for both air quality prediction and research. Scientists are working in collaboration with other agencies to develop new technologies to:



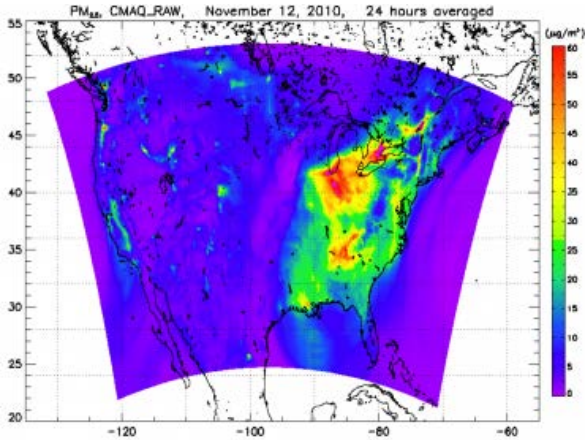
- Forecast air quality for cities and rural areas days in advance.
- Project impact of future changes in human activities and climate on air quality.
- Quantify cross-border transport of air pollution.
- Quantify regional transport of air pollutants within a country.
- Assess societal impacts of air pollution
- Improve emission estimates.

FY2015 ACCOMPLISHMENTS

In an effort funded by NASA, RAL and its partners are developing a new capability to produce 48-hour detailed forecasts of ground level ozone and fine particulate matter. The new forecasting capability combines satellite and in-situ observations with state-of-the-art modeling capabilities. It will generate more detailed, probabilistic air quality forecasts compared to the current forecasts, which provide just a single-value prediction and do not specify the uncertainty associated with the prediction. Just as a weather forecast, for example, might warn of a 80% chance of rain in the afternoon, new air quality forecasts might warn of a 80% chance of high ozone levels during certain times of the day while the current forecasts only tell whether ozone will be high or low. Such detailed forecasts will significantly enhance decision making in air quality management. The system is being set up over the USA but can be easily applied to any part of the world.

The first objective of the ongoing project is to improve the initialization of the National Oceanic and Atmospheric Administration (NOAA) / National Centers for Environmental Prediction (NCEP) operational air quality system, which is based on the Community Multiscale Air Quality (CMAQ) model, through chemical data assimilation of satellite retrieval products with the Community Gridpoint Statistical Interpolation (GSI) system (Fig. 1). GSI is used to assimilate retrievals of aerosol optical

depth from the NASA Aqua/Terra Moderate Resolution Imaging Spectroradiometer (MODIS) satellite instruments and possibly retrieval of carbon monoxide from the NASA/Terra Measurements Of Pollution In The Troposphere (MOPITT) and the EUMETSAT/MetOp Infrared Atmospheric Sounding Interferometer (IASI). Surface observations of PM<sub>2.5</sub> (and possibly of ground-level ozone) from the AIRNow network, the Interagency Monitoring of Protected Visual Environments (IMPROVE) stations, and the Clean Air Status and Trends Network (CASTNET) will also be assimilated. The second objective is to improve the CMAQ deterministic predictions and reliably quantify their uncertainty with analog-based post-processing methods applied to the CMAQ deterministic predictions. The third objective is the extrapolation of deterministic and probabilistic point-based predictions to a two-dimensional grid over the U.S. with a Barnes-type iterative objective analysis scheme. This effort is led by NCAR, in collaboration with NOAA, CU Boulder, and the University of Maryland.



Fine particulate matter predictions over the US.

FY2016 PLANS

A first prototype of the GSI/CMAQ system, analog ensemble probabilistic predictions of ground-level zone and surface PM<sub>2.5</sub>, and the corresponding gridded predictions will be implemented and tested with the NSF/NCAR/State of Colorado Front Range Air Pollution and Photochemistry Experiment (FRAPPÉ) and the NASA Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ). Both field campaigns took place in the summer of 2014. The comprehensive suite of measurements will be used to assess the accuracy of the proposed forecasting product.

< Post-Processing	up	Statistical and Dynamical Mesoscale Climate Downscaling >
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# WIND RESOURCE ASSESSMENT AND DYNAMICAL DOWNSCALING COST REDUCTION VIA THE ANALOG ENSEMBLE

## FY2015 ACCOMPLISHMENTS

### Analog Ensemble for Wind Resource Assessment

As part of NASA and NREL-funded projects, a new method has been proposed and demonstrated for the long-term estimation of wind speeds at a target site, a key step in wind resource assessments (Vavyve et al. 2013, Zhang et al. 2015). This method uses analog ensemble (AnEn) techniques which have been successfully for short-term weather predictions (e.g., Delle Monache et al. 2013). In the context of the wind resource assessment, the analog-ensemble method draws on the information contained in the historical data of multiple physical quantities over the period these data overlap with the observations (known as *training period*; typically 365 days) of the quantity of interest (known as *predictand*; the wind speed in this study). The relationships derived within the training period are then applied to reconstruct the on-site wind speed over the period for which there are no observations (hereafter referred to as *reconstructed period*, e.g., the past 20 years before the measurement campaign started).

More precisely, this is a three-stage process that is executed independently at every target site for every hour  $t$  of the reconstructed period, as sketched in Fig.1. First, the historical value of multiple physical quantities (known as *analog predictors*; e.g. wind speed itself, wind direction, pressure, etc.) is retrieved for a time window (known as an *analog trend*)

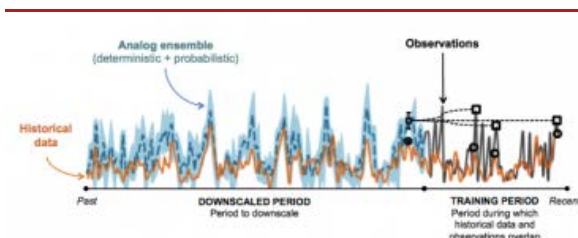


Figure 1. Sketch of the functioning of the analog ensemble method for one analog predictor, the analog trend reduced to one time step, and when retaining the best three analogs.



centered around time  $t$  (black dot in Fig. 1). The analog predictors are selected beforehand based on their known or anticipated correlations to the predictand. Second, other historical cases with conditions similar to those in the target window are identified (known as *analog*s) by looking at a time window (known as *analog search window*) centered around the same hour of the day for every day in the training period, and ranked by closeness of match. Analogues may therefore come from any day the training period. Using multiple predictors helps distinguish the analogs by identifying specific weather regimes relevant to the predictand. Third, the  $K$  best analogs ( $K$  the *number of analogs*; black circles) are selected, and the corresponding observed values of the predictand are retrieved (black squares). The latter constitute the *ensemble members* for hour  $t$ .

The final result is the *analog ensemble*, i.e., a set of  $K$  wind speed values for every hour  $t$  of the reconstructed period. The assumption is that if analogs are found, their errors will likely be similar to the error of the historical time step to reconstruct, error that can then be inferred from them. As shown by Vavyve et al. (2013) and Zhang et al. (2015), it can now be concluded that the AnEn:

- Can be used effectively for wind resource applications;
- Provides an accurate long-term wind resource estimate at target sites;
- Reliably quantifies the uncertainty allowing for cost-effective decision making;
- Represents a computationally inexpensive method for wind resource assessments.

**Dynamical Downscaling Computational Cost Reduction via the Analog Ensemble**

The AnEn technique has been tested for the first time as a way to reduce the computational cost of dynamical downscaling over a 3-dimensional grid. The AnEn algorithm has been implemented to extend a high-resolution model estimate from one to several years. A coarser model run is assumed to be available over several years (e.g., 10), while a finer resolution model estimate is assumed to be available over only a subset (e.g., 1 year) of that period. The period over which both coarse and fine model runs are available is called *training period*, whereas the period over which only the coarse run is available is called the *downscaling period*. For a given grid point and time of the downscaling period, the coarse run is downscaled as follows: first the best matches (i.e., similar coarse runs) are sought over the training period. Then, the fine resolution runs corresponding to the best coarse run matches are selected as analogs. This set of best analogs forms AnEn, and they can be seen as samples of the probability density function that downscales the time considered over the downscaling period. This procedure is then repeated independently (and possibly in parallel) for every grid point and time of the downscaling period. Preliminary tests indicate the ability of this approach of reducing the cost of dynamical downscaling by a factor between 5-10, depending on the location and the required accuracy. Tests are ongoing to assess in-depth the accuracy and reliability of this approach, as well as the ability of AnEn to preserve the 3-dimensional physical structure of the atmospheric flow.

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# FUTURE CLIMATE DYNAMICAL DOWNSCALING

## BACKGROUND

Global seasonal climate predictions at about 100~200 km resolution issued by national climate centers provide reliable perspectives of the general circulation about six months in advance. Such forecasts, however, lack the fine scale details that are critical to regional and local climate-sensitive business and decision-makers. To fill that need, RAL is developing a fine-scale seasonal climate prediction capability through dynamical downscaling. A framework for fine-scale seasonal climate prediction has been set up to apply the global large-scale seasonal forecasts issued by the Weather Service's Climate Forecast System (CFS) for use in forcing the Weather Research and Forecasting (WRF) model. (The version of the WRF model used has been specially customized and configured for climate purposes.) Both deterministic and ensemble predictions can be performed. Techniques from Artificial Intelligence such as Principal Component Analysis and Self Organizing Map analysis are used to extract the relevant climate information.

## ACCOMPLISHMENTS IN 2015

The fine-scale seasonal climate prediction framework has been applied to the Jack Rabbit II field Campaign at Dugway Proving Ground in Utah. A 3-month global climate forecast was downscaled down to one-kilometer and subsequently verified with the local

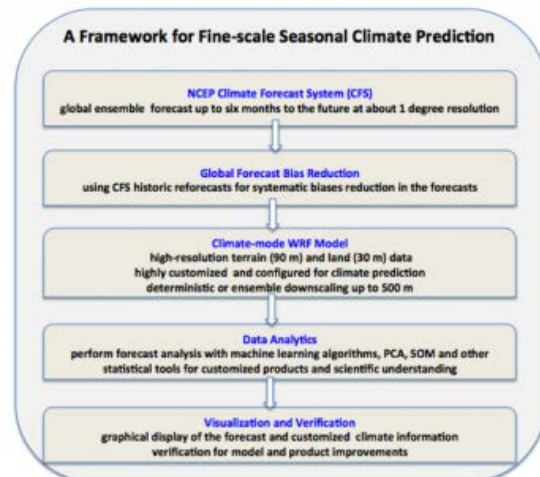


Figure 1. The framework for fine-scale seasonal climate prediction

observations collected during the field campaign. The verification results show some predictive skills in the method.

PLANS FOR 2016

An algorithm to correct biases in the global climate forecasts will be devised. Bias-reduced global forecasts are expected to dramatically improve the fine-scale prediction. In addition, we plan to evaluate the benefit of downscaling the other 8 members of the CFS ensemble system. The downscaled ensemble has the potential to provide probabilistic prediction and, thus, a characterization of the uncertainty associated with the produced fine scale climate information.

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GLOBAL CLIMATOLOGICAL ANALYSIS TOOLKIT

BACKGROUND

RAL scientists continue to support the DoD’s National Ground Intelligence Center (NGIC) in its mission of assessing the consequences of the transport and dispersion of accidental and intentional releases of hazardous materials into the atmosphere. This is done by providing the agency with access to the RAL-developed GCAT (Global Climate Analysis Toolkit) system. GCAT is a fully-automated dynamical downscaling system that allows NGIC scientists to remotely generate a high-resolution 30-year climatology for any region on the Earth. GCAT is based upon Climate Four-Dimensional Data Assimilation (CFDDA) technologies and can run with four domains, reaching a grid increment of 1.1-km. This enables NGIC to conduct transport and dispersion analyses at very fine scale. GCAT has the capability to automatically classify WRF output fields into climatological regimes. The method is based on the Self Organizing Map (SOM) [1] artificial neural network pattern recognition technique. Figure 1 shows the results of a SOM classification, in which 30 months (May 1981-2010) of WRF 1.1km hourly outputs were used to estimate the main six regimes of the wind flow over the Energetic Materials Research and Testing Center in Socorro, NM. The six regimes that have been identified are given with their frequency of occurrence and their most representative days, which are chosen based on their Euclidian distance to each SOM node. Weather data valid for the representative days provides better forcing to NGIC’s transport and dispersion climatological studies, as they didn’t

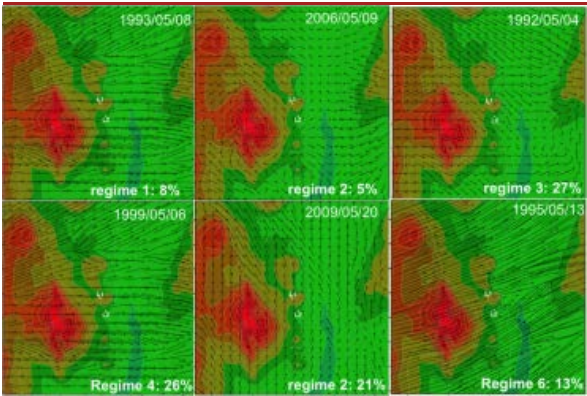


Figure 1. Typical days based on SOM classifications for downscaled historical flow during May over Socorro, NM.



undergo averaging which can destroy important model physical properties (balance etc.) available with dynamical downscaling.

The Second-order Closure Integrated PUFF (SCIPUFF) transport and dispersion model is implemented for execution for each dynamical downscaling simulation upon user request. This way, SOMs can be built based on plume dosage, in addition to weather variables, when analyzing the past climate. The system makes use of the Climate Forecast System Reanalysis (CFSR) data set available on a 0.5-degree grid for initial and lateral boundary conditions.

### FY2015 ACCOMPLISHMENTS

Updates to GCAT developed in 2015 will be released in December. This new version of the toolkit includes:

- **Case Study capability:** This functionality will generate WRF model output, available for the download, for any events that occurred between Jan. 1, 1981 and yesterday, including a "last week event". GCAT automatically uses real-time forecasts from the NCEP Global Forecasting System (GFS) to initialize WRF runs when a "case study" job is selected.
- **Ensemble intra-seasonal forecasting.** Climate Forecast System (CFS) are downloaded every day for the 6 months ahead period and can be used as initial and boundary conditions for WRF high-resolution simulations. The user can select any period between today and 6 months ahead to perform WRF simulations to downscale CFS forecasts in any part of the world.
- **New SOMs implementation:** SOMs classification libraries used in the previous GCAT version have been replaced with new R libraries [2]. The new R classification allows a new initialization of the SOMs node arrays. Previously the arrays were randomly initialized. In the current implementation they are chosen on a regular grid built on the first 2 components Eigen vectors resulting from Principal Component Analysis (PCA). The PCA analysis is performed using all the arrays of the input data-set. The novel initialization approach guarantees the repeatability of the classifications (not possible with the random initialization) and a better convergence (lower quantization error, QR) than the random initialization. The new feature generates plots that will help assessing the quality of each SOMs classification. The plots include maps of nodes colored by their frequency, spatial maps of meteorological variables corresponding to the first 5 selected days and wind roses [3]. These wind roses are built by using wind data at the center of the domain from all the input data-set and from the selected typical days, weighted by their frequencies. The comparison between the two plots allows understanding if the selected typical days are able to preserve the statistical properties of the complete input data.

### FY2016 PLANS

**Bias correction for intra- seasonal forecasts:** Forecasts from the Climate Forecast System are biased and contribute to biases in the WRF dynamically downscaled forecasts. An archived reforecast data set is available, and can be used to calculate biases. Once known, large-scale intra-seasonal forecasts can be corrected for bias. The WRF downscaled forecasts should also have less bias.

**SOM Classifier extension to 3D winds and stability parameters:** Testing additional meteorological variables for the SOMs classification such as: higher-level (100m - 200m above the ground) wind speed and wind direction fields, and the Monin-Obukhov length used to describe the effects of buoyancy and shear on turbulent flows. They both have a significant impact on the transport and dispersion in the lower troposphere and should be accounted for, especially because dosage is not extensible to all scenarios and cannot be counted on as a key classifier going into the future.

**Improve background and observation error estimates for precipitation assimilation:** Assimilation of ground-based precipitation, to provide information about the thermal structure of the atmosphere (and consequently winds), can be improved by using self-consistent background error estimates from the WRF, rather than the default errors from an older model currently in use. Observation errors can also be adjusted to help control the observation increments and consequently the adjustment to the atmospheric profile.

**Migration to HPCMP super computers:** Transition of GCAT system to the DoD HPCMP system will be accomplished.

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HAZARDOUS MATERIAL SOURCE TERM ESTIMATION

BACKGROUND

Atmospheric releases of hazardous materials, either accidental or intentional, continue to pose a viable threat to both United States citizens, as well as troops abroad and at home. To counter this threat, RAL is actively supporting research and the development of novel techniques and systems which can be used to more accurately simulate the atmospheric state and evolution of the released material in both time and space, for planning, real-time response, and forensic purposes.

Hazardous Material Source Term Estimation

In addition to needing a representative description of the atmospheric state (past, present, and future), Atmospheric Transport and Dispersion (AT&D) modeling systems also require precise specifications of the material release characteristics (e.g. location, time, quantity). For most real-time response scenarios, the specifics of the material release will be unknown, with only ancillary concentration sensor measurements available.

Algorithms and techniques to characterize the source and material are actively being developed at RAL to quickly reconstruct and estimate the source release using these limited sensor observations. In particular, RAL is actively developing a tailored Source Term Estimation (STE) and hazard refinement system, called the Variational Iterative Refinement

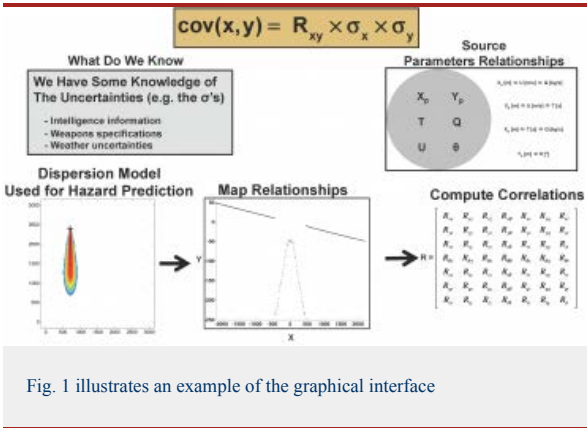


Fig. 1 illustrates an example of the graphical interface



STE Algorithm (VIRSA). VIRSA is a combination of models that include: the Second-order Closure Integrated PUFF model (SCIPUFF), its corresponding STE model, a hybrid Lagrangian-Eulerian Plume Model (LEPM), its formal numerical adjoint, and the software infrastructure necessary to link them. SCIPUFF and its internal STE model are used to calculate a "first guess" source estimate based on available hazardous material sensor observations and meteorological observations. The LEPM and corresponding adjoint are then used to iteratively refine the "first guess" source and wind estimate using variational minimization techniques.

Version 1.0 of this system was successfully integrated into the US Department of Defense (DoD) emergency response modeling systems—HPAC (Hazard Prediction and Assessment Capability) and JEM (Joint Effects Model) in FY2012 (Fig. 1 illustrates an example of the graphical interface). This version of VIRSA includes the capability to refine the "first guess" source location, mass, and release time utilizing material sensor observations and meteorological observations provided in the North Atlantic Treaty Organization (NATO) Nuclear Biological and Chemical (NBC) messaging format. A stand-alone version that refines the first guess using the LEPM and its formal numerical adjoint was delivered to DTRA in FY2014.

FY2015 ACCOMPLISHMENTS

RAL scientists:

- Verified and validated VIRSA after an Institute of Defense Analysis DTRA report concluded that the performance IDA observed was due to the concentration information degradation from the NBC messaging system.
- Added visualization to VIRSA stand-alone and delivered the stand-alone version of VIRSA v.2 to DTRA Reachback.
- Began testing the background error covariance methodology described in Fig. 1

FY2016 PLANS

- Create a full stand-alone version of VIRSA (VIRSA v.3) that includes the latest versions of SCIPUFF and reverse SCIPUFF. After verification and validation, VIRSA v.3 to DTRA Reachback will be delivered.
- Add urban capability to VIRSA. The Urban Dispersion Model (UDM) and the reverse UDM developed at the Defence Science and Technology Laboratory (Dstl) to upgrade our current VIRSA capabilities will be used.
- Enhance VIRSA by initiating gradient normalization testing and resume background error covariance testing.

< Atmospheric Transport and Dispersion of Hazardous Materials Research and Development	up	Virtual Atmospheric Dispersion Field Testing >
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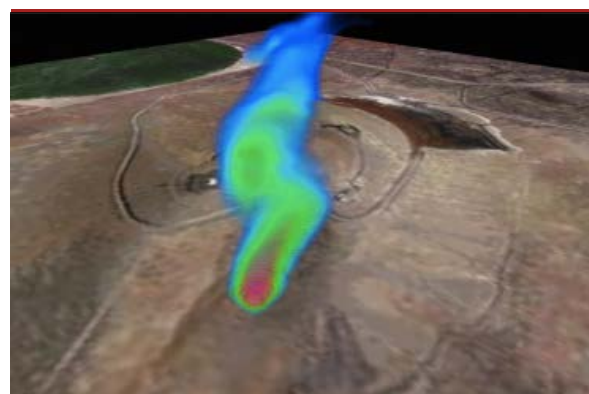
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## VIRTUAL ATMOSPHERIC DISPERSION FIELD TESTING

In order to more robustly test and evaluate the evolving Variational Iterative Refinement STE Algorithm (VIRSA) system, RAL has developed the Virtual Threat Response Emulation and Analysis Testbed (VTHREAT), enabling simulation of physically realistic hazardous release scenarios, placement of material and meteorological sensors, and extraction of the resulting synthetic sensor readings (Fig. 1). VTHREAT utilizes research grade numerical weather prediction (NWP) and atmospheric transport and dispersion (AT&D) models to generate high-resolution realizations of the turbulent atmospheric boundary layer and the resulting turbulent transport of materials released in the synthetic environment. More specifically, VTHREAT is currently leveraging the Large Eddy Simulation (LES) capabilities provided by the Weather and Research Forecast (WRF) NWP model, combined with continued advancements being made with the NCAR Lagrangian Particle Dispersion Model (LPDM).

The resulting environmental simulations can then be sampled utilizing a variety of material and meteorological sensor models, which emulate the operating characteristics of the sensing modality. These tools have been incorporated into a consolidated desktop software application, which allows a user to load virtual test simulations, visualize the 4-dimensional environment, place material and meteorological sensors within that environment, and save the sensor readings for later analysis or as input

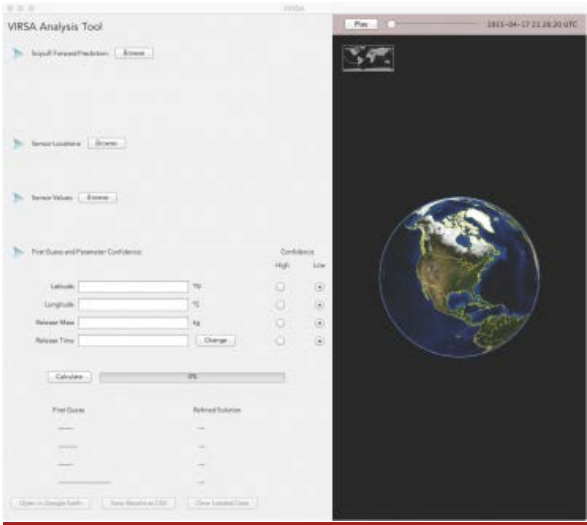


Virtual Threat Response Emulation and Analysis Testbed  
(VTHREAT)

to downstream sensor information systems. The GUI architecture is currently based on the National Aeronautics and Space Administration (NASA) World Wind Java Geospatial Visualization Platform, which provides access to a variety of external web map server (WMS) services and datasets, and an immersive display environment for data.

FY2016 PLANS

- Continue validation of the WRF LES capability.
- Utilize the VTHREAT display capability within a physical sand table augmented reality system.
- Expand the VTHREAT synthetic environment and release scenario library to include urban environments/scenarios.
- Complete the testing and integration of the latest 2-particle version of LPDM, into the VTHREAT application.
- Port the LPDM to GPUs so that transport and dispersion solutions can be efficiently computed.
- Link VTHREAT with other analysis models such as health-effects models.



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DENSE GAS MODELING

BACKGROUND

Accidental releases of a toxic, dense gas from a truck or railcar pose a significant health threat to a population in a neighboring community and risk assessments are required. Dispersion models are used for such assessments, i.e., for predicting the cloud behavior and downwind concentration field. One troubling issue from previous accidents was that the dispersion models predicted very high concentrations with significant impacts – severe injury and death – for distances out to a few kilometers from the source. In contrast, “on-the-ground” results showed that the high impact region was much smaller, closer to the source, and limited to only a few deaths. As a result of these differences, the Defense Threat Reduction Agency (DTRA) initiated a series of “Jack Rabbit (JR)” experiments to investigate the behavior of a dense gas cloud from a full-scale chlorine ( $\text{Cl}_2$ ) release and the downstream concentration field. The experiments were intended to assess the dispersion model formulations, assumptions, and predictions using the  $\text{Cl}_2$  measurements. The JRI experiment was conducted in 2010 with 1- or 2-ton chlorine releases and JR II in 2015 with 5- to 9-ton releases, both experiments being conducted at the Dugway Proving Ground. A third experiment is planned for 2016.

In support of the DTRA activity, RAL/NSAP initiated a dense gas modeling effort in 2015 aimed at predicting  $\text{Cl}_2$

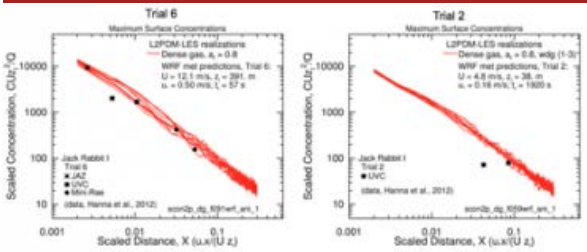


Figure 1. Comparison between predictions (red lines) and observations (points) of scaled maximum surface  $\text{Cl}_2$  concentrations in Jack Rabbit I experiments as a function of scaled downwind distance for two trials; Trial 6 and Trial 2 correspond to 2- and 1-ton  $\text{Cl}_2$  releases. Rationale and variables used in scaling described in text.

concentrations in the vicinity of an accidental release and used the JRI data for assessment. Our effort was aimed at worst-case scenarios – stable atmospheric conditions and slow dispersion – that would result in the highest Cl<sub>2</sub> concentrations.

ACCOMPLISHMENTS IN 2015

A Lagrangian two-particle dispersion model (L2PDM) driven by large-eddy simulations (LESs) of a stable boundary layer (SBL) was developed and used to make concentration estimates for a dense gas (DG) release. A relatively simple dense gas model with "slumping" or rapid initial descent of the cloud/plume top, gravitational spreading, and upper boundary or plume-top entrainment have been included. The DG model has been formulated in both: 1) integral form, which gives the correct plume spread versus distance and initial buoyancy as verified with laboratory data, and 2) a "particle" form for compatibility and coupling with the L2PDM. The buoyancy-generated velocity from the model pertains to "relative dispersion" of the DG plume, i.e., about its meandering centerline, and has been superposed on the velocities from the L2PDM. The SBL flow fields were obtained using the NCAR LES model (Sullivan, Moeng, and Patton) and were generated using 200<sup>3</sup> grid points over the model domain; the SBL had a height of 207 m, a mean wind of 7 m/s, and a surface friction velocity of 0.28 m/s.

The randomness in the SBL turbulence field leads to broad variability in the concentration field downwind of a source. A key advantage of the coupled DG-LPDM-LES model is that one can generate individual "realizations" of the concentration field from which this variability can be determined. Here, 15 realizations of the concentration field have been computed with the maximum surface concentrations on crosswind transects found as a function of downwind distance. Figure 1 shows realizations of the maximum concentrations scaled using the mean SBL wind speed (U), SBL depth (z<sub>i</sub>), and the source strength (Q) as a function of the scaled downstream distance X based on the friction velocity, distance x, U, and z<sub>i</sub>. This scaling is useful when the meteorological conditions in the field are similar to but not identical to the modeled conditions even though both pertain to the SBL.

The ideal or best outcome is that the modeled concentration realizations capture the observations and spread, i.e., the field data fall within the range of the realizations. Figure 1 shows that this capture is mostly true for the two JRI releases or trials with two exceptions. Overall, the behavior and agreement found in Fig. 1 is considered good.

PLANS FOR 2016

Our plans for 2016 are to: 1) refine the coupled DG-L2PDM-LES model with a better entrainment formulation, detrainment model, and other features, 2) test the refined model with additional field trials from the Jack Rabbit I experiments, 3) extend the model to shorter-duration releases as conducted in Jack Rabbit II, where evolution from a continuous plume to an elongated "cloud" or "puff" occurred and test the model with the JRII data, and 4) possibly add a non-building-aware urban parameterization for dealing with releases in the near-surface, urban canopy layer. The Jack Rabbit II experiments included a Mock Urban array of low-height (container) "buildings."

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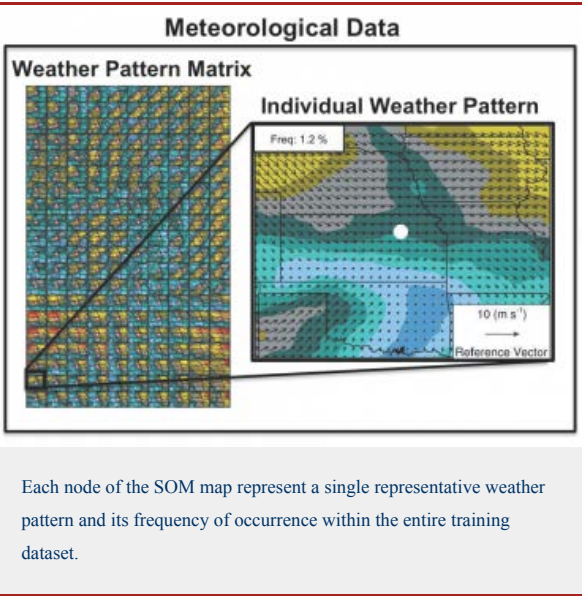
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CLIMATOLOGICAL DISPERSION PATTERNS WITH SELF-ORGANIZING MAPS

In order to characterize and manage large climate datasets, RAL has developed a methodology that utilizes the Self-Organizing Map (SOM) technique to identify “Representative Days” which typify the overarching meteorological patterns of the entire dataset using a significantly smaller subset. The SOM, also known as Kohonen Map or Self-Organizing Feature Map, is an unsupervised neural network based on competitive learning which maps high-dimensional data into a two-dimensional space. Using this method, recurring patterns can be distinguished and the frequency with which those patterns occur can be identified. These patterns can then serve as input to atmospheric transport and dispersion (AT&D) models to analyze an ensemble of statistically likely downwind contaminant exposures.

For disaster response, when rapid intelligence is of the essence, minimizing computational time for modeling a release incident is paramount and using this technique should result in the same high-quality results that a larger climate dataset would provide in just a fraction of the time. RAL has developed tools and expertise in the use of SOMs over the past few years and continues to improve and refine the analysis tools to produce increasingly better results.

FY2015 ACCOMPLISHMENTS



Developed an end-to-end toolset to analyze Climate Forecast System Reanalysis (CFSR) 30-year data to extract representative days and couple that input to the Second-order Closure Integrated Puff (SCIPUFF) atmospheric transport and dispersion model.

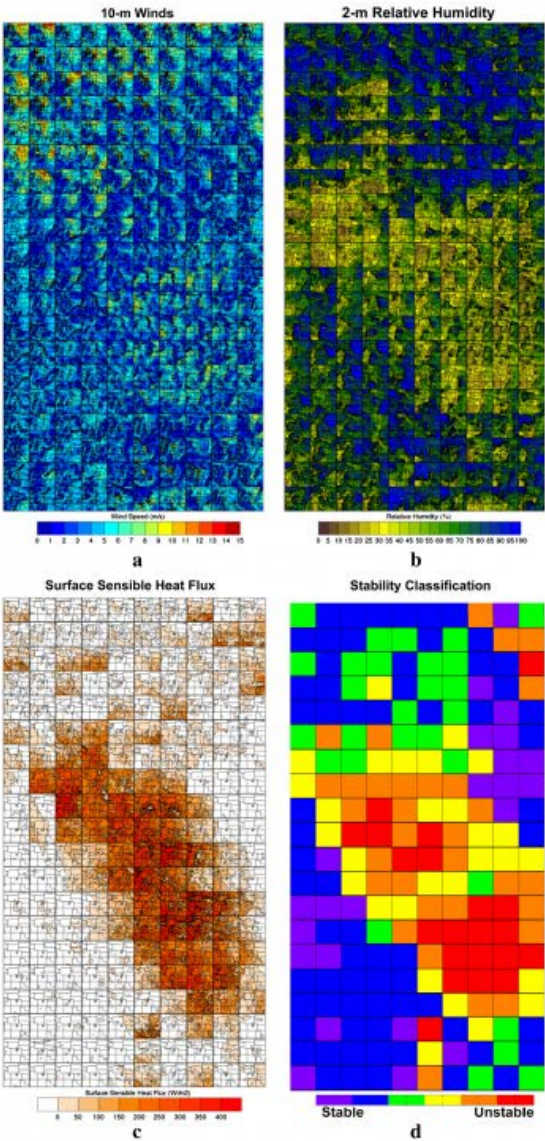
- Delivered a study to the United States Strategic Command demonstrating the utility of the SOM for reducing the necessary climate record length for incident characterization

## FY2016 PLANS

- Continue improvement of the NCAR-RAL Climate SOM algorithm to further reduce the amount of data necessary to produce statistically similar climatologies.
- Develop a turn-key Climate SOM capability that can be used by sponsors to produce their own reduced dataset climatologies

## < Dense Gas Modeling

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The SOM matrix maps for relative humidity (a), wind speed (b), surface sensible heat flux (c), Pasquill stability categories (d).”

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# MESOSCALE MODELING SYSTEMS

## BACKGROUND

The Developmental Testbed Center (DTC; <http://www.dtcenter.org>) – a distributed facility with components in the Joint Numerical Testbed (JNT; <http://www.ral.ucar.edu/jnt>) at NCAR's Research Applications Laboratory (RAL) and the Global Systems Division (GSD) of NOAA's Earth System Research Laboratory (ESRL) – facilitates the transfer of research results into operations and provides the research community with an easily accessible state-of-the-art Numerical Weather Prediction (NWP) system for research. One of the DTC's focal points is accelerating the rate at which new mesoscale modeling technology is infused into operational weather forecasting. The DTC meets its goals by maintaining and supporting community codes that represent the latest NWP technology, performing extensive testing and evaluation of new NWP technology, maintaining a state-of-the-art verification package, and connecting the NWP research and operational communities through its visitor program.

## FY2015 ACCOMPLISHMENTS

### Community Codes

Community code is a free and shared resource with distributed development and centralized support. The DTC's community code efforts are collaborative activities with developers at NCEP's Environmental Model Center (EMC), NCAR's Mesoscale and Microscale Meteorology (MMM) Division, NOAA/ESRL/GSD, NOAA's Geophysical Fluid Dynamics Laboratory, National Aeronautics and Space Administration's (NASA) Global Modeling and Assimilation Office (GMAO), the University of Rhode Island (URI), and NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division (HRD). During 2015, the DTC worked with the following software packages:

- Weather Research and Forecasting (WRF; <http://wrf-model.org>) – NWP model + pre-processors
- WRF for Hurricanes (<http://www.dtcenter.org/HurrWRF/users>) – Coupled model capabilities (atmosphere and ocean) in support of tropical cyclone forecasting
- NOAA Environmental Modeling System (NEMS) Nonhydrostatic Multiscale Model on the B-grid (NMMB; <http://www.dtcenter.org/nems-nmb/users>) – NWP model + pre-processor
- Ensemble Kalman Filter (EnKF) DA System
- Unified Post Processor (UPP; <http://www.dtcenter.org/upp/users>) – NWP model post-processor
- Gridpoint Statistical Interpolation (GSI; <http://www.dtcenter.org/com-GSI/users>) – Data Assimilation System
- Modular end-to-end ensemble system
- Model Evaluation Tools (MET; <http://www.dtcenter.org/met/users>) – Verification package including standard verification techniques, advanced techniques, and tools for use with tropical cyclone verification (MET-TC)

The DTC contributes to the software management of all of these systems and provides user support for the publicly released systems (WRF, HWRF, GSI, EnKF, UPP, and MET), which include the latest developments of new capabilities and techniques. Prior to each official release to the user community, the DTC ensures the integrity of all community code software components through a broad range of testing. The DTC also strives for system evolution, in particular through increased interoperability of existing system components, as well as adding new capabilities or techniques. In addition, the DTC provides user support for these packages in the form of Users' Guides, webpages, email helpdesks, and online and on-site tutorials.

### Testing and Evaluation

The DTC provides a trusted facility that developers and the operational community can rely on for unbiased assessments of the operational

prediction systems and potential new additions to those systems. Testing and evaluation undertaken by the developers of new NWP techniques from the research community are generally focused on case studies. However, in order to adequately assess these new technologies, extensive testing and evaluation must be performed to ensure they 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 be generated by the DTC or provided by external modeling groups. The DTC's evaluations include use of standard verification techniques, as well as new verification techniques in some cases. All verification statistics include a statistical significance (SS) and practical significance (PS) assessment when appropriate.

Two mesoscale NWP systems utilized in both research and operational forecasting applications around the world include the Weather Research and Forecasting (WRF) model and the NOAA Environmental Modeling System (NEMS). Due to the increasing number of approaches developed in the NWP research community, it is necessary to rigorously test select techniques and evaluate the performance for specific applications. During 2015, the DTC performed a comprehensive inter-comparison T&E activity employing the NEMS-NMMB model. The focus for the test was an assessment of the impact of replacing the Ferrier-hires microphysics scheme with the Thompson microphysics (ThompsonMP) scheme within NMMB for the North American Mesoscale (NAM) application. A parent domain at 12-km grid spacing and two nests at 3-km grid spacing, CONUS and Alaska, were employed. The testing period included one month per season in 2013-2014 with cases initialized every 36 hours and run out to 48 hours. For 2-m temperature (Fig. 1), a notable result was that both configurations exhibited warm biases during the summer that grew with increased forecast lead time; however, an opposite signal was seen in the winter aggregation, where there were cold biases during the daytime hours. When differences were present, ThompsonMP typically had colder median bias values than NAMOC, leading to better performance by ThompsonMP in the summer when there was a warm bias and better performance by NAMOC in the winter when cold biases were present. Another key result in this sensitivity study was the differences in shortwave radiation reaching the surface between the two configurations, where the NAMOC had consistently higher values compared to ThompsonMP. This result is directly related to those seen in the 2-m temperature bias (Fig 2). A full suite of results associated with model inter-comparison can be accessed on the DTC website at <http://www.dtcenter.org/eval>. Information distributed includes a description of the model configuration and the extensive testing that was performed. An executive summary and final report of the results is provided, along with the full set of verification plots, which include additional spatial and temporal breakdowns.

Mesoscale Model Evaluation Testbed

In order to assist the research community with conducting detailed case study testing of newly developed techniques, the DTC has established and is maintaining the Mesoscale Model Evaluation Testbed (MMET; [http://www.dtcenter.org/eval/meso\\_mod/mmet](http://www.dtcenter.org/eval/meso_mod/mmet)). The motivation of MMET is to assist the research community in efficiently demonstrating the merits of a new development that could positively impact an operational configuration in the future.

MMET provides a variety of initialization and observation data sets for a number of routine, high-impact and field campaign cases. Baseline results for select operational configurations are also produced by the DTC and made available through MMET. Through the common framework provided by MMET, researchers have the ability to perform direct comparisons between multiple innovations tested by the research community and/or against the baseline operational configurations established by the DTC.

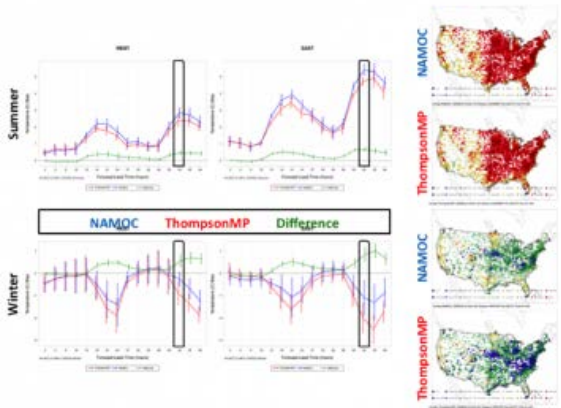


Figure 1 caption: Time series of 2-m AGL temperature (°C) median bias for all 00 UTC initializations for the CONUS West (left) and CONUS East (center) domains for the summer (top) and winter (bottom) aggregations. NAMOC is in blue, ThompsonMP in red, and the differences (NAMOC-ThompsonMP) in green. The vertical bars attached to the median represent the 99% CIs. Spatial plots of the 2-m AGL temperature (°C) mean bias for the 42-h forecast lead time for all 00 UTC initializations for the summer (top two panels) and winter (bottom two panels) aggregations.

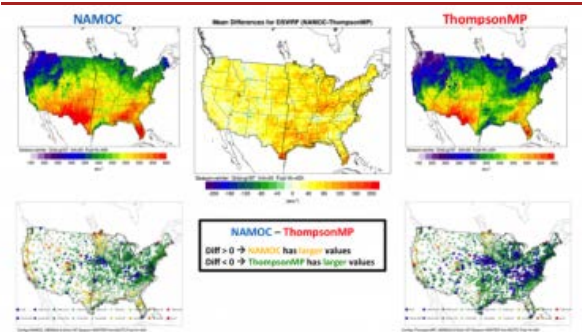


Figure 2 caption: Mean downward short-wave radiation (W m-2) for all 00 UTC initializations for the winter aggregation at the 42-h forecast lead time for the NAMOC configuration (top left), ThompsonMP configuration (top right), and mean differences (NAMOC-ThompsonMP; top center). Spatial plots of 2-m AGL temperature (°C) mean bias at the 42-h forecast lead time for all 00

During 2015, maintenance of MMET included updating all software components to the most recent released versions. Several new enhancements to the MMET workflow were also recently implemented, including: 1) nesting for both WRF-ARW and NEMS-NMMB, 2) ability to re-grid observations to post-processed forecast domain within the grid-to-grid verification step (i.e., as opposed to pre-processed outside the workflow), 3) a new WRF-ARW baseline using RAP/HRRR operational physics suites and 4) 6-hr warm-start capability using the GSI DA package (currently only functional in WRF-ARW).

UTC initializations for the winter aggregation of NAMOC (bottom left) and ThompsonMP (bottom right).

MMET has also been established to support the broader goal of streamlining the path to potential operational use for promising new science innovations developed in the research community. A testing protocol document detailing a three stage process of testing conducted by the research community, DTC and, ultimately, operational centers, discusses the research to operations (R2O) process further. It is believed that, with better coordination among the NWP community as a whole, major benefits towards improving model physics can be realized, resulting in more accurate and reliable operational NWP forecasts.

FY2016 PLANS

The JNT, working through the DTC, will continue to support various community codes, including NWP systems, GSI and MET, and help organize and support tutorials on the community codes that it supports, related to mesoscale models, data assimilation, hurricanes, and forecast verification. Relevant workshops will be offered to stimulate discussion among the research and operational modeling communities on future directions of development.

While efforts will continue related to evaluating deterministic model output, as operational centers move towards ensemble-based forecasting the JNT will become more involved in the testing and evaluation of probabilistic information, as well as new multi-scale global models.

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# ADVANCED VERIFICATION TECHNIQUES AND TOOLS

## BACKGROUND

Forecast verification and evaluation activities typically are based on relatively simple metrics that measure the meteorological performance of forecasts and forecasting systems. Metrics such as the Probability of Detection, Root Mean Squared Error, and Equitable Threat Score provide information that is useful for monitoring changes in performance of single aspects of forecast performance with time. However, they generally do not provide information that can be used to improve forecasts, or that can be helpful for making decisions. Moreover, it is possible for high quality forecasts—such as high-resolution forecasts—to have very poor scores when evaluated using these standard metrics, while poorer quality forecasts may score higher. In response to these limitations, the RAL Verification Group develops improved verification approaches and tools that provide more meaningful and relevant information about forecast performance. The focus of this effort is on diagnostic, statistically valid approaches, including feature-based evaluation of precipitation and convective forecasts, and distribution-based approaches that can provide more meaningful information (for forecast developers as well as forecast users) about forecast performance. In addition, the RAL Verification Group develops forecast evaluation tools that are available for use by members of the operational, model development, and research communities. Development and dissemination of new forecast verification approaches requires research and application in several areas, including statistical methods, exploratory data analysis, statistical inference, pattern recognition, and evaluation of user needs.

## FY2015 ACCOMPLISHMENTS

### Spatial verification methods and the spatial method inter-comparison project

The initial forecast verification methods inter-comparison project focused on comparing the capabilities of newly developed spatial forecast verification methods. That project was completed in 2011 and resulted in a special collection of articles in the journal *Weather and Forecasting*. A second inter-comparison project, developed in partnership with international collaborators, has been implemented and is known as the Mesoscale Verification Intercomparison in Complex Terrain (MesoVICT; <http://www.ral.ucar.edu/projects/icp/>). Detailed MesoVICT planning took place at the European Meteorological Society annual meeting in September 2013, and a recent kick-off meeting took place in Vienna, Austria on 2 – 3 October 2014. The meeting was well attended by key researchers and operational forecasts from various centers/institutions in Europe, as well as Russia and China. "A further meeting was held in conjunction with the *15th EMS Annual Meeting and 12th European Conference on Applications of Meteorology (ECAM)*, 7 - 11 September 2015 in Sofia, Bulgaria, which was also well attended. The cases for this project include more complex terrain and wind verification. Most of the test cases are already available, and are described along with the goals of the project in an NCAR Technical Note: <https://opensky.library.ucar.edu/collections/TECH-NOTE-000-000-000-874>.

To simplify the use of many of the spatial verification methods for the MesoVICT and other efforts, the RAL verification group has developed a spatial verification methods package in the R programming language (SpatialVx; <http://www.ral.ucar.edu/projects/icp/SpatialVx/>), which continues to be developed. The package currently includes considerable functionality for features-based verification, neighborhood methods, kernel smoothers, and many other statistical and image-based verification approaches.

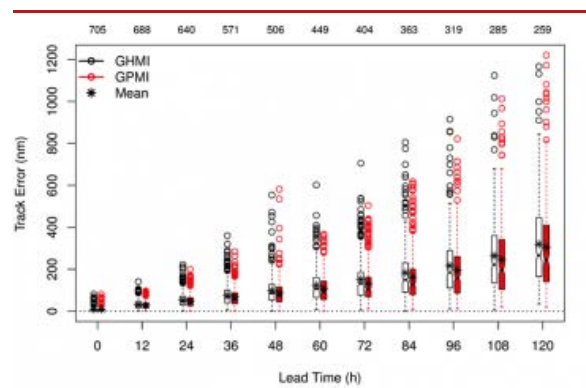


Figure 1: Boxplots of Hurricane Forecast Track Error by forecast lead time for two numerical model forecasts.



NCAR staff continued to support several packages for the R project for statistical computing. These include: distillery, extRemes, ismev, smoothie, SpatialVx, and verification packages. SpatialVx was enhanced to include the contiguous rain area (CRA) feature-based method.

An extension of the Method for Object-based Diagnostic Evaluation (MODE) tool in MET was released as a new tool within METv5.1 (see below). MODE-Time Domain, or MODE-TD, was designed to track objects through time. Objects could range from proxies for convections (e.g. updraft helicity) to climate drought indices. Figure 2 shows an example of MODE-TD objects for drought indices. In the past, many MET users have performed separate MODE runs at a series of forecast valid times and analyzed the resulting object attributes, matches and merges as functions of time in an effort to incorporate temporal information in assessments of forecast quality. MTD was developed as a way to address this need in a more systematic way. Most of the information obtained from such multiple coordinated MODE runs can be obtained more simply from MTD. As in MODE, MTD applies a convolution field and threshold to define the space-time objects. It also computes the single 3D object attributes (e.g. centroid, volume, and velocity) and paired 3D object attributes (e.g., centroid distance, volume ratio, speed difference).

**The Model Evaluation Tools (MET)**

The Model Evaluation Tools (MET) (<http://www.dtcenter.org/met/users/>) is a freely available software package for forecast evaluation that was developed and is supported by RAL/JNTP staff. METv5.1 was released to the community in October 2015. It includes a multitude of enhancements to the already extensive capability. Nearly 350 additional users registered to download MET in FY15 placing the total registered users at approximately 2900. The user base is predominantly university researchers, both in the U.S. and abroad. The METViewer database software GUI redesign was completed and users now experience a more streamlined intuitive interface. The additions to MET in METv5.1 can be grouped into new tools, enhanced controls over pre-existing capabilities, and new statistics. It may be fair to say there is something new for everyone.

In addition to including MODE-TD in the METv5.1 release, several other tools were added. The concept of automated regridding within the tools was first brought up during a discussion with the DTC Science Advisory Board in 2014. The capability was added during FY15 to enhance the DTC Mesoscale Model Evaluation Testbed (MMET). The MET team took it one step further and not only added the capability to all MET tools that ingest gridded data but also developed a stand-alone tool (regrid\_data\_plane) to facilitate regridding, especially of NetCDF files.

To address the needs of the Gridpoint Statistical Interpolation (GSI) Data Assimilation community took, the DTC Data Assimilation Team and MET team worked together to develop a set of tools to read the GSI binary diagnostic files. The files contain useful information about how a single observation was used in the analysis by providing details such as the innovation (O-B), observation values, observation error, adjusted observation error, and quality control information. When MET reads GSI diagnostic files, the innovation (O-B; generated prior to the first outer loop) or analysis increment (O-A; generated after the final outer loop) is split into separate values for the observation (OBS) and the forecast (FCST), where the forecast value corresponds to the background (O-B) or analysis (O-A). This information is then written the MET matched pair format. Traditional statistics (e.g. Bias, Root Mean Square Error) may then be calculated using the MET Stat-Analysis tool. Support for ensemble based DA methods is also included. Currently, three observation types are supported, Conventional, AMSU-A and AMSU-B.

MET developers and scientist identified several ways to enhance existing tools. Through working on a hurricane QPF project, it was determined that several tools such as Gen\_Poly\_Mask and Gen\_Circle\_Mask could be generalized into one tool, the Gen\_Vx\_Mask. The Gen-Vx-Mask tool may be run to create a bitmap verification masking region to be used by the MET statistics tools. This tool enables the user to generate a masking region once for a domain and apply it to many cases. The ability to compute the union, intersection or symmetric difference of two masks was also added to Gen\_Vx\_Mask to provide finer control a verification region.

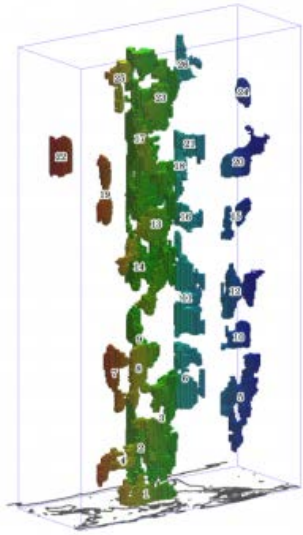


Figure 2. Example three-dimensional objects of drought index from the CCSM climate model and identified by MODE-TD.

Additionally, MET-TC was enhanced to define a rapid intensification / rapid weakening event for a tropical cyclone in a more generic way. This capability was then included in the Stat-Analysis tools to allow for identification of ramp events for renewables or extreme change events for other areas of study.

Finally, finer controls of thresholding were added to several tools to allow for more complex definitions of events used in the formulation of categorical statistics. This option is useful if a user would like to look at a particular subset of data without computing multi-category statistics (e.g. the skill for predicting precipitation between 25.4 mm and 76.2 mm). The thresholding may also now be applied to the computation of continuous statistics. This option is useful when assessing model skill for a sub-set of weather conditions (e.g. during freezing conditions or cloudy days as indicated by a low amount of incoming shortwave radiation).

In support of the need for expanded probabilistic verification capability of both regional and global ensembles, the MET team added a "climo\_mean" specification to the Grid-Stat, Point-Stat, and Ensemble-Stat configuration files. If a climatological mean is included, the Anomaly Correlation is reported in the continuous statistics output. If a climatological or reference probability field is provided, Brier Skill Score and Continuous Ranked probability score are reported in the probabilistic score output. The decomposition of the Mean Square Error field was also included in the continuous statistics computations. These options are particularly useful to the global NWP community and were added to address the needs of the NCEP/EMC Global Climate and Weather Prediction Branch.

### A new approach to testing (univariate) forecast predictive accuracy

Two new techniques have been proposed by the RAL verification group in a paper recently accepted for publication in *Meteorological Applications* (Gilleland and Roux 2014). One is a prediction comparison test first introduced in a seminal paper in the economics literature by Diebold and Mariano (1995). The Diebold and Mariano (DM) test directly accounts for temporal correlation in order to obtain accurate standard errors, or subsequently confidence intervals, for the differences in loss functions (when compared to the same observation). A recent paper by Hering and Genton (2011), who introduced a modification of the procedure, also established that the test is robust to contemporaneous correlation (i.e., if the two forecasts are correlated with each other).

In addition to the application of the DM test, Gilleland and Roux employ dynamical time warping (DTW) in order to adjust and account for timing errors in the test procedure. The DTW method can also be used in conjunction with the DM test. These procedures are univariate analogues to the spatial prediction comparison test and image warping procedures that have also been previously proposed by the RAL verification group.

### Evaluating solar forecasts

All components of the NCAR SunCast solar prediction system were evaluated routinely and through in-depth analysis several times during FY15. Evaluation of point forecasts for approximately 50 locations were performed for both Global Horizontal Irradiance and power. New metrics to test probabilistic forecasts were also tested.

### Cyclone-relative verification

New methods were explored and developed to evaluate model performance for both tropical and extra-tropical cyclones. Cyclone relative masking was employed to determine model skill for precipitation forecasts. This process required information from the cyclone tracker to shift the center of the forecasted cyclone to that of the observed cyclone (determined in this case from the National Hurricane Center "best track"). The prototype of the Gen\_Vx\_Mask tool within MET was used to generate concentric masks along the track at increasing radii. The precipitation within each mask was then accumulated to look for biases in the quantitative precipitation forecasts. Figure 3 gives an example of this form of masking. Similar approaches were explored for extra-tropical cyclones.

### FY2016 PLANS

The MET release in 2016 will include support of new data formats, potentially including support for NetCDF4 formats. This will facilitate enhanced verification methods of cloud properties and data assimilation. The capability to handle additional satellite observations will be included in the next MET release, and further research on appropriate methods for evaluating forecasts through time will be conducted and included in the release if appropriate. Additional support for calculating scores using reference or climatological fields will also be explored. This

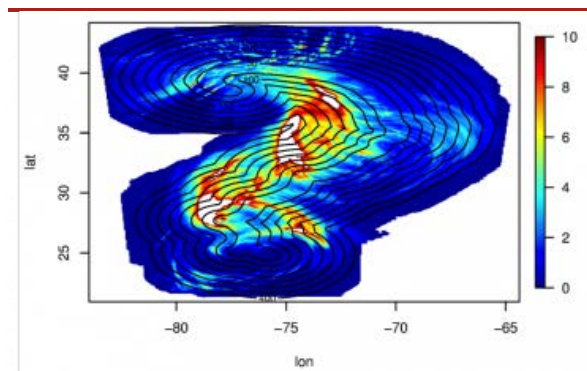


Figure 3. Example of complex masking derived from the location of the storm center.



would include formulation of skill scores and metrics relevant for global model verification. Advanced uses of numerical weather prediction indices (NWP Indices) will be explored by the verification team. Further, MODE-TD will be applied to several fields beyond precipitation (e.g. low pressure, jets and geopotential heights to evaluate extra-tropical cyclone prediction, probability fields, and climate fields.) Also, the database within METViewer will undergo refinements to optimize for “big data” and many users.

Only three primary methods remain to be added to SpatialVx: (i) contiguous rain area (CRA), (ii) image warping, and (iii) displacement amplitude score (DAS). The basic package is expected to be completed in the next year or two along with documentation.

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DATA ASSIMILATION

BACKGROUND

The goal of the Data Assimilation Team (DAT) is to provide a pathway between the data assimilation research and operational communities to help accelerate transitions from research to operations. Working closely with research and operational centers [e.g., the NOAA National Centers for Environmental Prediction (NCEP)], the DAT builds and maintains a code management framework for distributed development of new capabilities and advances in data assimilation. Under the same code management plan applied to both the operational and research communities, the DAT provides operational data assimilation capabilities to the research community in a timely manner, with complete user support and annual training opportunities. By setting up a functionally similar operational environment, the DAT conducts testing and evaluation of state-of-the-art data assimilation techniques and, therefore, provides a rational basis for enhancement of data assimilation techniques and systems; and, eventually, improvement of numerical weather forecasts and analyses. Much of this work is done under the auspices of the Developmental Testbed Center (DTC).

FY2015 ACCOMPLISHMENTS

Code Management and Community Support

The DAT currently maintains and supports a version of the Gridpoint Statistical Interpolation (GSI) data assimilation system with additional features for the research community (<http://www.dtcenter.org/com-GSI/users/index.php>). The GSI system is the operational data assimilation system for various forecasting and analysis systems and applications. As NCEP and other operational centers are moving forward to apply hybrid ensemble-variational techniques to their operational forecasts, the DAT has started to transition the NOAA ensemble based data assimilation, the Ensemble Kalman Filter (EnKF) system, to a community system. On July 31, 2015, the EnKF code was first released to the research community, along with the GSI annual release, followed by a joint GSI and EnKF tutorial hosted at the NCAR Foothills Laboratory on August 11-14, 2015. This outreach event marked the sixth Community GSI Tutorial, but the first for EnKF. This code release and the tutorial publicized the two operational data assimilation systems as community data assimilation systems, open to contributions from the research community. Both the GSI and EnKF systems are documented and supported through a joint effort of the DAT and distributed development teams as well as the DTC partners. For more information on the GSI and EnKF systems and their joint community support, please visit: <http://www.dtcenter.org/com-GSI/users/index.php> and <http://www.dtcenter.org/EnKF/users/>.

Testing and Evaluation

In FY2015 the DAT focused on two major activities:

- GSI 3D-Var observation sensitivity studies and operational mitigation support for the Air Force
- GSI-based hybrid variational and ensemble (GSI-hybrid) tests for the Hurricane WRF (HWRF) modeling system

99% CI Statistical Significance Table: SBUV vs. CTL02 (EPAC)												
TEMP RMSE		Forecast Lead Time (hr)										
		0	6	12	18	24	30	36	42	48		
Pressure Levels (hPa)	50	EXP1	EXP1	EXP1	EXP1	EXP1	EXP1	EXP1	EXP1	EXP1		
	100	EXP1					CTL0					
	250				CTL0	CTL0	CTL0	CTL0	CTL0	CTL0		
	400		EXP1	EXP1								
	500		EXP1	EXP1	EXP1	EXP1	EXP1	EXP1	EXP1	EXP1		
	700											
	925	EXP1						CTL0	CTL0			
U-Wind RMSE		Forecast Lead Time (hr)										
		0	6	12	18	24	30	36	42	48		
Pressure Levels (hPa)	50	EXP1	EXP1	EXP1	EXP1	EXP1	EXP1			EXP1	EXP1	
	100	EXP1	EXP1			CTL0						
	250						CTL0					
	400	EXP1	EXP1	EXP1	EXP1	EXP1						
	500	EXP1			EXP1			CTL0				
	700		EXP1	EXP1	EXP1							
	925	CTL0	EXP1	EXP1								
V-Wind RMSE		Forecast Lead Time (hr)										
		0	6	12	18	24	30	36	42	48		
Pressure Levels (hPa)	50	EXP1	EXP1	EXP1	EXP1	EXP1	EXP1	EXP1				
	100	EXP1										
	250		EXP1	EXP1								
	400	EXP1	EXP1	EXP1	EXP1							
	500	EXP1	EXP1	EXP1								
	700	EXP1	EXP1	EXP1	EXP1							
	925		EXP1	EXP1			EXP1					
SPFH RMSE		Forecast Lead Time (hr)										
		0	6	12	18	24	30	36	42	48		
Pressure Levels (hPa)	50											
	100											
	250							CTL0		CTL0		
	400	CTL0		EXP1	EXP1	EXP1						
	500				EXP1	EXP1	EXP1	EXP1	EXP1	EXP1		
	700		CTL0									
	925				CTL0	CTL0	CTL0	CTL0	CTL0	CTL0	CTL0	CTL0

Table 1. Statistical significance table for temperature, wind components and humidity generated by SBUV (green) and control runs (blue; following Air Force operational configuration).

These activities include performing in-depth impact studies for alternative data assimilation configurations and observation types and assisted the specific sponsors on the improvement of the operational forecasts. The test results provided a good evaluation of the GSI/GSI-hybrid system in regional applications and therefore are also valuable to general researchers and users.

**GSI 3D-Var observation sensitivity studies and operational mitigation support**

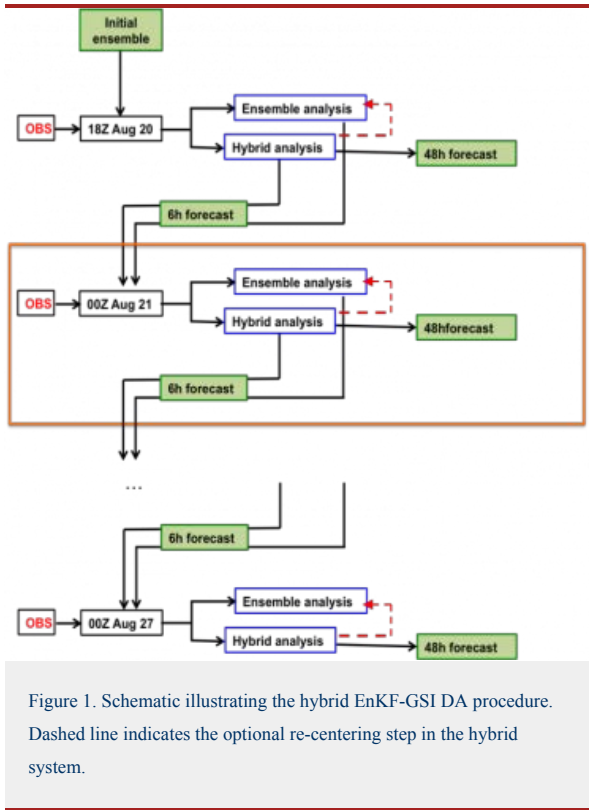
The 3D-Var tests were particularly focused on sensitivity studies of non-traditional data types as identified by the Air Force. Additionally, the DAT was tasked to provide mitigation support for GSI operations. For all these tests and experiments, the DAT runs a functionally-similar testing environment aimed to complement the real-time pre-operational Air Force system.

The DAT performed sensitivity studies for the following data types:

- NOAA-16/18/19 Solar Backscatter Ultraviolet (SBUV)/2 profile ozone
- METOP-A Global Ozone Monitoring Experiment (GOME)-2 total ozone
- NPP Cross-track Infrared Sounder (CrIS) radiance

To enable the radiance and ozone data assimilation, the DAT also performed additional tests to evaluate the latest released Advanced Research WRF (ARW) code with the model top increased from 10 hPa to 2 hPa. The observation sensitivity studies include use of traditional observation denial experiments, as well as the adjoint-based Forecast Sensitivity to Observations (FSO) tool developed by NCAR. The verification was performed using the Model Evaluation Tools (MET) toolkit developed by the JNTP.

In summary, the model top increase generally shows positive impacts on the data assimilation and forecasts. When focusing on the utility of ozone data in GSI coupled with ARW, there are statistically significant improvements, particularly in the upper levels of earliest lead times for temperature and wind. Since ozone is not a prognostic variable in ARW, impacts of ozone data assimilation on forecasts are indirect through the impacts of the radiation computation inside the radiative transfer model used by GSI. Compared with GOME, assimilation of SBUV shows more promise with larger statistically significant differences over the control configuration. Table 1 shows the statistical significance of the Root Mean Square Errors (RMSE) for temperature generated by SBUV and control runs (excluding SBUV assimilation). The DAT discovered neutral forecast impacts from CrIS data assimilation over the current operational suite. The FSO runs suggest these results were due to negative impacts from certain channels currently selected in the control configuration. A close examination of the channel selection for the CrIS configuration is recommended to the Air Force for improvement of the utility of these data.



Two mitigation requests from the Air Force were received and solved through this fiscal period. They are associated with the reported Sea Level Pressure (SLP) anomaly issue and the operational CrIS data usage issue. During the investigation, the DAT identified issues associated with the GSI surface moisture quality control procedure and developed new code resulting in an improvement of the surface moisture analysis and, consequently, the derived SLP analysis. Moreover, the DAT discovered a critical issue when using GSI and ARW together, due to the mismatch of the GSI analysis variables and the ARW prognostic and diagnostic variables. The DAT adopted a rebalance code from NOAA’s RAPid Refresh (RAP) system and tested impacts of applying this code to the Air Force operational suite. Details on these tests, along with the full set of verification plots can be found in the final project report: ([http://www.dtcenter.org/eval/data\\_assim/reports/fy14\\_dtc\\_1\\_5\\_1+1\\_5\\_4.pdf](http://www.dtcenter.org/eval/data_assim/reports/fy14_dtc_1_5_1+1_5_4.pdf)).

**GSI-hybrid tests for HWRF**

The DAT performed a retrospective study of the intensity spin-down issue (intensity biases dropped from positive to negative in the first 12 hours) discovered during the HWRF 2014 pre-operational testing. The comparison of the 2013 and 2014 HWRF configurations indicates the 2014 HWRF configuration assimilated additional satellite radiance data in the middle domain (9km). However, observation denial experiments show that the radiance data assimilation had limited contribution to the Tropical Cyclone (TC) intensity forecasts. The inner core data assimilation and its interaction with the vortex initialization are still the key components for this spin-down issue. The DAT discovered the data assimilation step is

the largest contributor to the sharp changes in surface pressure at the initial stage of the forecasts. This outcome indicates the analysis from the data assimilation step shocked the forecast model due to lack of appropriate balancing.

The DAT studied the balance algorithm as part of the HWRF vortex initialization procedure and the potential to apply this information to the GSI data assimilation as a post-processing step. The DAT also studied and tested the impacts of applying the Tangent-Linear Normal-Model Constraint (TLNMC) to the analysis for a TC forecast. Studies show that it is possible to apply TLNMC to the TC case and the constraint may help reduce the noise level produced by the inner core data assimilation and improve the intensity forecasts.

The DAT also investigated ways to improve how the flow-dependent background error is prescribed. The DAT set up a complete hybrid EnKF-GSI for HWRF system (Figure 1) to conduct regional ensemble experiments, and then compared the results to the 2014 operational HWRF system. Results show the 2014 operational configuration (Figure 2, green) generated the best intensity scores at analysis time for Hurricane Irene. However, TC intensity biases increased rapidly and stayed relatively large throughout the rest of the forecast. A similar spin-down issue was confirmed using the 2015 HWRF system, but with smaller biases. The GSI-hybrid system using the GFS ensemble (without vortex initialization, Figure 2, cyan) generated the biggest intensity biases. Two experiments using an HWRF ensemble (Figure 2, red and blue) generated smaller intensity biases for forecasts beyond 12-24 h. The two-way hybrid system (blue) was set up based on the GFS DA scheme, using the GSI deterministic analysis to re-center the ensemble members at each analysis time. The one-way hybrid system (red) skipped the re-centering step. This re-centering step reduced the ensemble spread for TC center locations and intensity. Consequently, the one-way hybrid system using regional ensembles performed better than the other systems for TC intensity forecasts beyond 12 h. Descriptions of the test set-up, experimental design, and results, as well as the previous DA balance study, are provided in this report available at [http://www.dtcenter.org/eval/data\\_assim/](http://www.dtcenter.org/eval/data_assim/).

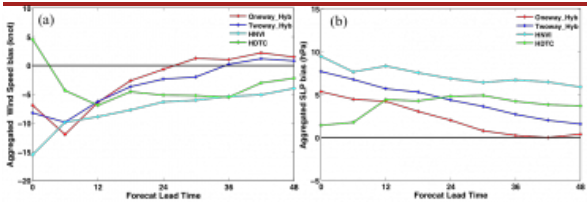


Figure 2. Aggregated bias for (a) maximum surface wind speed, and (b) minimum sea level pressure averaged over all forecasts as a function of forecast lead time. Analyses and forecasts were generated from the HWRF system with the 2014 operational configuration (green), GSI one-way hybrid system using GFS ensemble (without vortex initialization, cyan), GSI one-way hybrid system using HWRF ensemble (red), and GSI two-way hybrid system using HWRF ensemble (blue).

FY2016 PLANS

The DAT will continue its GSI and EnKF code management and community support efforts to facilitate the transitions from research to operations, in collaboration with developers. The DAT plans to organize a tutorial for these two systems in the upcoming summer. The DAT also plans to test four-dimensional EnVar for hourly cycling data assimilation in regional domains. In collaboration with other NCAR colleagues, the DAT will also work on the cloudy radiance data assimilation development for different satellite instruments and perform testing and evaluation.



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# TROPICAL CYCLONE

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## BACKGROUND

The Tropical Cyclone Modeling Team (TCMT) within RAL's Joint Numerical Testbed Program works closely with the Developmental Testbed Center and NCEP's Environmental Modeling Center (EMC) to support the Hurricane-Weather Research and Forecasting (HWRF) system to the research community. The team also tests new capabilities coming from the research community to determine their potential for improving the forecast skill of HWRF. The goals of this work are to accelerate the improvement in TC forecasts by providing a more timely mechanism for transitioning research into operations, and through extensive testing of new capabilities to determine their impacts on operational predictions.

## FY2015 ACCOMPLISHMENTS

### Developmental Testbed Center

#### Advancing the Connections between Radiation and Clouds in HWRF

During FY2015, the DTC's Hurricane team extended its FY2014 work toward connecting the Rapid Radiative Transfer Model for GCMs (RRTMG) radiation scheme with the SAS convection parameterization. To account for the missing connection between convective clouds and the RRTMG radiation scheme, a cloud fraction scheme based on Sundqvist et al (1989) was implemented in WRF combined with a first-guess "scale-aware" relative humidity threshold that requires higher humidity values to make sub-grid clouds as the resolution increases. The water vapor and explicit cloud variables were not modified. The only changes were the incorporation of the partial cloudiness scheme into the shortwave and longwave radiation treatment that subsequently causes the explicit microphysics scheme to produce its own clouds. The existing WRF RRTMG scheme has a cloud fraction scheme attributed to Xu and Randall (1996), however, in practice, the scheme produces a binary 0 or 100% cloud fraction based on the absence or presence of explicit cloud condensate by the microphysics scheme. The details of the cloud fraction scheme implementation and the tests are available at [http://www.dtcenter.org/eval/hwrf\\_hdrf\\_hdgf/](http://www.dtcenter.org/eval/hwrf_hdrf_hdgf/). This work was transitioned to EMC, and the WRF RRTMG with the partial cloudiness scheme was included in the 2015 HWRF implementation.

#### HWRF Quantitative Precipitation Forecasts

A comprehensive evaluation of HWRF Quantitative Precipitation Forecasts (QPF) was conducted for the 2014 HWRF model. The model output used for this evaluation, which was provided by EMC, consisted of pre-implementation runs for 22 storms from 2011 to 2013 Hurricane seasons and a subset of operational forecasts from the 2014 season. Three basic approaches were applied to gain insight into the performance of HWRF QPF: 1) a large-scale assessment looking at HWRF QPF accumulated over 24 h for the parent domain, 2) 24-h accumulations for a circular region with a 600-km diameter centered on the observed storm location (with and without corrections for track forecast error), and 3) run-total storm-scale QPF for the innermost domain with 3-km grid spacing. The Climate Prediction Center's CMORPH analyses and NCEP's Stage IV analyses (available only over the CONUS region) were used as sources of quantitative precipitation estimates (QPE) for these assessments.

For the large-scale assessment, the model QPF and the CMORPH and Stage IV analyses were re-gridded to a 0.25° “Mega Domain” (25S-60N, 150W-10E) defined by the range of HWRF parent domain locations for the sample. Operational Global Forecast System (GFS) forecasts were used as a baseline against which to benchmark the HWRF’s parent domain precipitation. The full Mega Domain aggregations are based on CMORPH only. In addition to verifying for the full Mega Domain, statistics were also computed for sub-domains located over the Atlantic (AL) and eastern North Pacific (EP) basins and the CONUS. Statistics for the ocean basins are based on CMORPH QPE, whereas those for the CONUS are based on Stage IV QPE. These comparisons revealed that both HWRF and GFS generally over-predict rainfall with HWRF’s over-prediction being larger than that of GFS for most lead times and regions (not shown). Over the CONUS, Equitable Threat Scores (ETS) for different thresholds indicate that GFS outperforms HWRF at all lead times, except for the higher thresholds (2 and 3”) at 96 and 120 h (not shown).

The location of the forecasted precipitation associated with a tropical cyclone (TC) will be strongly dependent on the track forecast. Hence, assessments of storm-centric precipitation forecasts based on grid-to-grid comparisons will be influenced by both track errors and errors in the representation of the storm structure. To reduce the impact of track error on QPF skill for the storm-centric assessment, the entire QPF field was horizontally shifted to match the observed storm location (Marchok et al. 2007). Verification statistics for this approach used the CMORPH QPE regridded to the 0.25° Mega Domain for the entire evolution of the storm. Figure 5 shows the ETS for GFS and HWRF without and with the correction for track error. In general, GFS shows higher forecast skill than HWRF. The increase in ETS shown for both models after the shifting to correct for track errors reflects the contribution from incorrect forecast tracks to the QPF error.

For the run-total storm-scale QPF (a.k.a swath data) assessment, the CMORPH and Stage IV data were re-gridded to 0.05° to match the grid-spacing of HWRF’s innermost domain. Bands 50 km wide were drawn out to 400 km around the forecasted storm track for the HWRF data and around the Best Track for the observed datasets. Figure 6 shows these bands for a single Hurricane Sandy forecast. The QPF distribution was then evaluated against CMORPH when the forecasted track was over water, and against Stage IV when it was over land. The boxplots in Fig. 6 show the QPF and QPE distributions, separately over land and water, for the different bands including the full swath (0-400 km). As shown in this example, the bulk of observed and predicted rainfall occurs within 0-100 km, which is consistent with previous studies. When combined for the whole storm, in general, HWRF overestimates precipitation over land and water, but the over-prediction is larger over water (not shown).

Rapid Intensification and Rapid Weakening Forecasts

Rapid intensification (RI) events, which are defined as an intensity increase of 30 kt or more over water in 24 h (Kaplan and Demaria 2003), are rare and difficult to predict. For this study, evaluations were done using retrospective runs for the Atlantic and eastern North Pacific

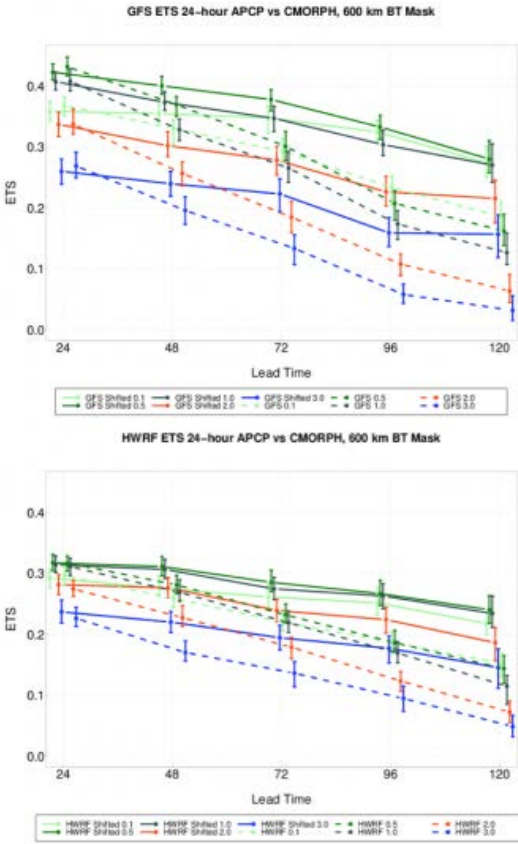


Figure 5. Equitable threat scores with respect to lead time for GFS (top) and HWRF (bottom) before shifting (dashed lines) and after shifting (solid lines) of the grids. Verification were done against CMORPH data over a 600 km mask around the observed storm center. The different thresholds shown here are 0.1” (light green), 0.5” (dark green), 1.0” (army green), 2.0” (red) and, 3.0” (blue).

(EP) basins from the 2014 Stream 1.5 exercise (sample includes storms from 2011-2013 Hurricane seasons), as well as real-time runs during the 2014 Hurricane season. Given the higher frequency of RI events in the western North Pacific (WP) basin, HWRF’s ability to capture RI events was also evaluated for the WP basin for the 2013 and 2014 seasons. Additionally, an evaluation was conducted using 2015 HWRF pre-implementation tests conducted by EMC.

For the AL and EP basins combined, the 2014 HWRF system tended to under-predict the magnitude of the intensity change when it correctly forecasted a RI event. HWRF over-predicted intensity change by 15-20 kt for false alarms and under-predicted by 20-25 kt for missed RI events. On the other hand, when validated for the WP basin, the magnitude of the intensity change was not biased for correctly forecasted RI events, whereas missed events and the false alarms for the WP basin were similar to that for the AL and EP basins. A homogeneous comparison of the 2014 and 2015 HWRF systems indicated the 2015 HWRF model was better at capturing intensity change. The full report for the RI/RW evaluation is available on the DTC webpage: [http://www.dtcenter.org/eval/hwrf\\_rirw/](http://www.dtcenter.org/eval/hwrf_rirw/).

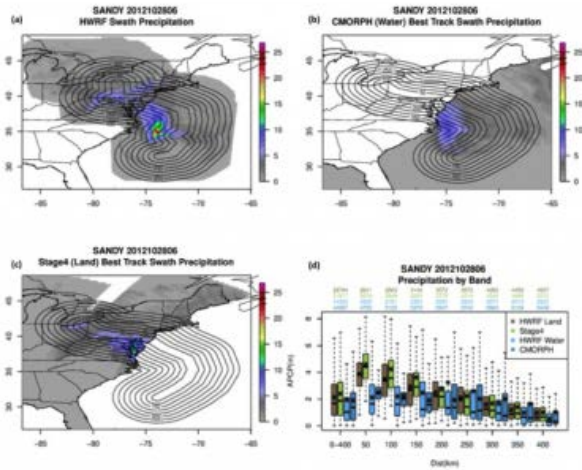


Figure 6. Precipitation (mm) swath data of Hurricane Sandy initialized at 06UTC October 28, 2012 accumulated over 5 days for (a) HWRF, (b) CMORPH over water, (c) Stage IV over land. The bands shown are 0-50,50-100, etc. out to 350-400 km around the forecasted storm track for (a) and Best Track for (b) and (c). The boxplot distributions of the precipitation are shown in (d). The mean is shown as asterisk (\*). Precipitation (inches) of HWRF over land (brown), Stage IV over land (green), HWRF over water (light blue) and CMORPH over water (dark blue) are shown for different bands shown on the x-axis. The numbers of points taken into consideration for the four boxes are shown on the top of each band.

FY2016 PLANS

Developmental Testbed Center

For FY2016, the DTC will continue its work toward improvement of the HWRF physics. The source of the degraded performance when using the Thompson microphysics scheme coupled to the RRTMG radiation scheme in HWRF (results from retrospective tests conducted in FY2014) will be investigated. Retrospective forecasts using the most recent HWRF model version will be conducted to evaluate the performance of the configuration. Upgrades to the atmospheric component of HWRF will be passed to EMC to be included in its pre-implementation testing for the HWRF 2016 implementation.

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- Improving the representation of hydrologic processes in Earth System Models
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- Snow hydrology
- Understanding the land-atmosphere interactions and enhancing WRF high-resolution climate modeling capabilities
- Studies of the Global Water Cycle and Drought

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HIGH-RESOLUTION MODELING OF CURRENT AND FUTURE CLIMATE OVER NORTH AMERICA

The Colorado Headwaters high-resolution climate modeling effort was expanded to consider all of North America. The primary goal of this project is to examine how key physical processes such as precipitation, snowfall, snowpack, runoff and evapotranspiration are impacted by climate change using a model with sufficient resolution to capture them. This effort was made possible through the award of 27.5 M core hours on the NCAR Yellowstone computer. The first year of the project tested and evaluated the model configuration and parameterizations necessary to produce a faithful simulation of the current climate. To date, nine years of the current climate simulation at 4 km resolution has been completed (Oct. 2000 – March 2010). The model faithfully reproduces the observed precipitation and snowpack in the western regions. (Figs. 1 and 2).

A significant warm and moist bias occurs in the central U.S. in the summertime. This is a well-known problem with many weather and climate models and is an active research area for the Water System program and in the community.

Nine years of Pseudo Global Warming (PGW) simulations have been completed. These simulations were forced by a modified ERA-Interim reanalysis achieved by adding the CMIP5 climate model monthly mean perturbations of temperature, humidity, winds, and geopotential height to the re-analysis. The output of the model runs will be used by NCAR Water System and university scientists to examine western snowfall and snowpack changes in a future climate, as well as convection in the central U.S. Scientists at the University of Saskatchewan will use the model output to examine climate change and water in the Canadian prairies. University of Quebec at Montreal scientists will examine climate change impacts on extreme winter storms, while University of Albany scientists will examine the impact of future climate change on the water cycle in the Northeast U.S. and snow albedo. A BAMS paper is being written about the dataset and to advertise its availability to the community.

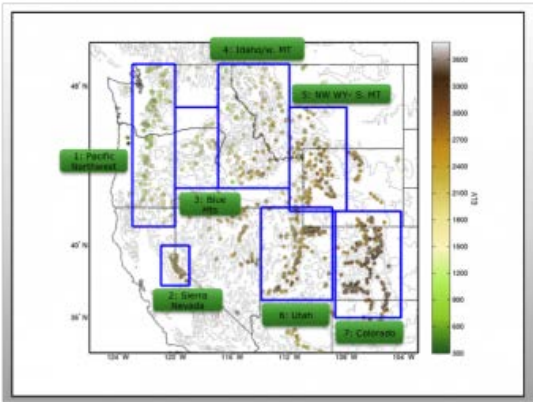


Figure 1: Regions 1–7 and SNOTEL sites (colored circles) used for evaluating the WRF model output.

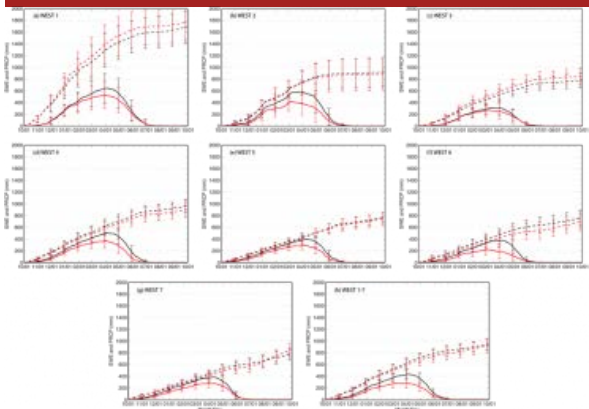


Figure 2: Time series plots of 9-year climatology of precipitation accumulation from the current climate simulation (red) and SNOTEL observations (black) over various mountain ranges in the Western U.S. (Fig. 1). The accumulation curves are the average of observations or the model values at the observation site. Vertical bars indicate year-to-year variation from the 9-year climatological values. Panel h is the average of observations and model values at all SNOTEL sites in

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# UNDERSTANDING THE IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

Closely aligned with the WRF CONUS runs, research in the past year has advanced understanding on how the different methods used for climate downscaling and hydrologic modeling affect the portrayal of climate change impacts over the contiguous USA. An important research effort is in collaboration with the University of Colorado, in support of the doctoral research of Pablo Mendoza who was housed at NCAR to work closely with the Water Systems team. Dr. Mendoza has published a series of papers that demonstrate how the selection and configuration of hydrologic models affects portrayals of the impact of climate variability and change on the terrestrial water cycle (Mendoza et al., 2015a; 2015b; 2015c). A key result is that decisions made in selecting and configuring hydrologic models affect the sign of climate impacts on hydrology, even when models are well calibrated. A broader effort has been conducted by Naoki Mizukami, who examines the relative impact of the choice of climate downscaling method and the choice of hydrologic models, for climate assessments across the contiguous USA (Mizukami et al., 2015a). Results of these analyses demonstrate that the choice of hydrologic models is just as important as the choice of climate downscaling methods, focusing attention on improving continental-domain hydrologic model simulations. Work is now focused on methods to better characterize and reduce uncertainties in model simulations of the terrestrial water cycle (Archfield et al., 2015; Clark et al., 2015a; 2015b; Mendoza et al., 2015d), in order to provide better information to support water resources planning and management.

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# WARM SEASON PRECIPITATION OVER THE U.S. CENTRAL PLAINS

Lower-tropospheric temperature and moisture biases and their relationship to the diurnal cycle of simulated precipitation were examined in twelve-day continuously running WRF simulations over the central U.S. at convection-allowing horizontal grid resolutions. Two periods of heavy precipitation were selected that occurred in contrasting warm-season synoptic regimes. One regime featured a persistent quasi-stationary surface front where precipitation occurred predominately at night and was restricted to a narrow latitudinal “corridor” (Fig. 1a) along and north of the front. In the second regime, the precipitation was more widespread (Fig. 1b) and had a less pronounced diurnal cycle.

In the “corridor” simulations, biases in lower-tropospheric water vapor and temperature were regionally dependent and driven primarily by the model’s ability to accurately simulate subtle aspects of the synoptic pattern. In simulations where the lateral boundary conditions for the high resolution domain ( $\Delta x, y = 3$  km) were allowed to drift significantly from those obtained from data-driven model analyses, lower-tropospheric conditions were too warm and dry (cold and moist) within (south of) the observed corridor precipitation region. This aspect influenced regional precipitation biases. In single-domain high-resolution simulations, where the synoptic pattern was better specified in the lateral boundary conditions, the temperature and moisture biases were generally small ( $\leq 1-2$  K and  $1 \text{ g kg}^{-1}$ ) and precipitation was accurately simulated. These results suggest the possibility that lower-tropospheric thermodynamic biases that influence simulated precipitation in longer-range regional climate simulations can have a significant component that arise from errors in the simulated synoptic pattern, in addition to more locally-forced errors arising from uncertainties in model physics.

A single 12-day convection-allowing ( $\Delta x, y = 4$  km) simulation was examined for the second synoptic regime that was characterized by more widespread precipitation (Fig. 1b). In this simulation the near-surface water vapor bias was small ( $\leq 1 \text{ g kg}^{-1}$ ) but there was a significant diurnally varying near-surface temperature bias. Here, simulated conditions were too cool in the late afternoon and too warm overnight (Fig. 2). This bias may be influenced by the particular PBL scheme (MYJ) that was used and other schemes still need to be tested for this period. Biases in the diurnal precipitation cycle varied regionally

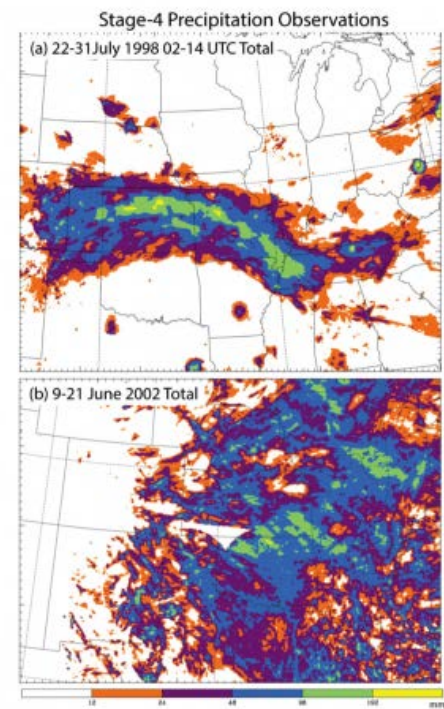


Fig. 1. Total observed Stage-4 precipitation for the indicated periods.



and could not be easily linked to the diurnal temperature bias.

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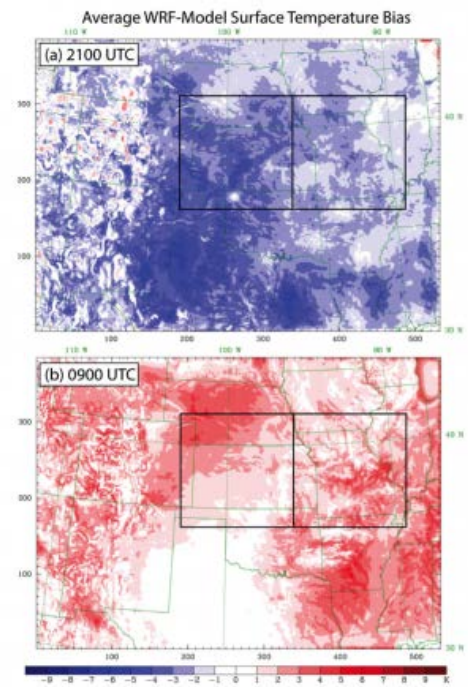


Fig. 2. Average temperature bias at the lowest model level (~ 25 m AGL) at the indicated times in the diurnal cycle (as determined from differences from Eta-model analyses) for a 12-day WRF-model simulation from 9 to 21 June 2002.

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HYDROLOGICAL MODELING WITH THE COMMUNITY WRF-HYDRO SYSTEM

A cornerstone of the NCAR/RAL Water Systems program is the development and support of community modeling tools for both process-based research and hydrometeorological forecasting applications. These tools are co-developed by NCAR in close collaboration with University researchers and government agencies in the U.S. and around the world. NCAR/RAL and the Water Systems program serve as focal points for training and collaboration in the hydrometeorological community. The Community WRF-Hydro System provides scientists and forecasters extensible modeling tools to engage in process-based research into land-atmosphere coupling, hillslope routing processes, surface water-groundwater interactions and multi-scale hydrologic evaluations. As a forecasting tool the WRF-Hydro System can run coupled or uncoupled to atmospheric prediction models and provide so-called ‘hyper-resolution’ forecasts of terrestrial hydrologic conditions such as soil moisture, snowpack, shallow groundwater, soil ice, streamflow, evapotranspiration and inundating waters.

Hydrometeorological modeling research with the Community WRF-Hydro modeling system has produced many significant advances over the past year including a major expansion of model options. Version 3 of WRF-Hydro was released in May of 2015 with several new test cases and model pre-processing tools. Numerous improvements to the WRF-Hydro code have been made as well which have enabled:

- Improved simulation of snowpack and snowmelt from high-mountain regions
- Upgraded baseflow parameterization to permit multiple subsurface flow responses
- Enhanced reach-based routing methodologies
- Support for the RAPID channel routing package
- Parallelization of the NoahMP land model driver for enhanced computational efficiency
- Expanded spatially distributed parameter datasets for improved model configuration
- Development of real-time Web Mapping Service for visualization of WRF-Hydro model forecasts and other real-time data
- Updated WRF-Hydro GIS pre-processing package for ArcGIS
- Suite of Powerpoint Tutorial Slides

[Read more on WRF-Hydro.](#)

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HYDROLOGIC MODEL DEVELOPMENT: SUMMA

A major accomplishment in the last year is the development and publication of the first version of a new modeling framework termed SUMMA (the Structure for Unifying Multiple Modeling Alternatives). SUMMA was published as a two-part paper in *Water Resources Research* (Clark et al., 2015a, 2015b), with full technical details published as an NCAR Technical Note (Clark et al., 2015c). The SUMMA code has been migrated to a publicly available web-based source code repository, including definitions of coding conventions and mechanisms for community engagement. The first version of the SUMMA code was published on 15 July 2015, doi:10.5281/zenodo.20372, which enables the SUMMA source code to be used and cited in research applications. To support SUMMA applications we have developed a series of synthetic and field data test cases for SUMMA – this provides known solutions for the SUMMA simulations, and enables users to test their implementation and compare with other modeling approaches. The SUMMA source code, test cases and other resources are all available on the SUMMA web site <https://www.ral.ucar.edu/projects/summa>.

SUMMA is developed as a next-generation hydrologic model, providing multiple options to simulate all dominant biophysical and hydrologic processes from the treetops to the stream. The SUMMA framework is centered on the structural core, which comprises the conservation equations for the hydrologic and thermodynamic states within the model domain, and general algorithms for their numerical solution. Different process representations and different spatial configurations are integrated into the structural model core, which enables users to decompose the modeling problem into the individual decisions made as part of model development and evaluate different “fine grain” model development decisions in a systematic and controlled way. The overall intent of SUMMA is to help modelers select among modeling alternatives (to improve model fidelity) and pinpoint specific reasons for model weaknesses (to better characterize model uncertainty and prioritize areas needing more research and development). SUMMA is beginning to see widespread use and is a core component of many new projects within RAL.

In addition to SUMMA the team has devoted considerable effort to building core capabilities for continental-domain hydrologic modeling. This includes development of 671-basin benchmarking data set to evaluate hydrologic models (Newman et al., 2015a), a new probabilistic forcing data set for land models (Newman et al., 2015b), and development of continental-domain river routing capabilities (Mizukami et al., 2015b).

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## IMPROVING THE REPRESENTATION OF HYDROLOGIC PROCESSES IN EARTH SYSTEM MODELS

Water System program research is also focused on improving the representation of hydrologic processes in Earth System Models (Clark et al., 2015). NCAR has partnered with the Consortium of Universities for the Advancement of Hydrologic Sciences Incorporated (CUAHSI) to use the NCAR Community Land Model (CLM) as a vehicle for hydrologists to engage in community modeling. This effort has supported strong and effective collaboration among scientists in CGD and RAL and between NCAR and the university community, including RAL contributions to the code development in CLM5 (using some concepts from SUMMA to improve simulations of the storage and transmission of water through soils). A community workshop was held at NCAR in October 2015, and the project team is now actively working to incorporate advanced representations of lateral subsurface flow processes in CLM.

REFERENCE

Clark, M. P., Y. Fan, D. M. Lawrence, J. C. Adam, D. Bolster, D. J. Gochis, R. P. Hooper, M. Kumar, L. R. Leung, and D. S. Mackay, R.M. Maxwell, C. Shen, S.C. Swenson, and Z. Zeng (2015c): Improving the representation of hydrologic processes in Earth System Models. *Water Resources Research*, **51**, doi: 10.1002/2015WR017096.

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THE INTERMEDIATE COMPLEXITY ATMOSPHERIC RESEARCH MODEL (ICAR)

A joint project between the NCAR Water System program and the U.S. Army Corps of Engineers has led to the development of the Intermediate Complexity Atmospheric Research model (ICAR). ICAR combines a simplified representation of atmospheric dynamics with physical parameterizations including microphysical and land surface processes. The model simplifications permit ICAR to perform high-resolution simulations 100 to 1000 times faster than a traditional atmospheric model such as the Weather Research and Forecasting model (WRF). This is particularly important for climate downscaling applications. Such applications are computationally constrained because end-users desire large ensembles of simulations to adequately represent the uncertainty in future climate projections.

To simplify the dynamics, ICAR uses linear mountain wave theory to predict the perturbations to flow over topography. This theory provides an analytical solution to the three dimensional wind speed and direction as a function the background atmospheric stability, wind speed and direction, and the underlying topography. The resulting wind fields are consistent with the results obtained from WRF over idealized topography (Figure. 1). By combining this theory with the three-dimensional flow field from a coarse resolution atmospheric model, such as a climate model, ICAR is able to reasonably simulate orographic effects as well as large-scale convergence and divergence in the flow.

Idealized simulations comparing WRF to ICAR show that ICAR is able to represent approximately 95% of the variability in precipitation predicted by WRF for typical cool-season precipitation conditions (Gutmann et al 2016). WRF and ICAR have both been used to perform idealized 2D hill simulations with a wide range of environmental conditions. Both the spatial pattern of precipitation from these simulations and the bulk precipitation amounts across a wide range of simulations are highly correlated between the two models when run with identical microphysical parameterizations.

Finally, simulations of real weather with both WRF and ICAR show that ICAR is able to capture approximately 70-85% of the variability in cool season precipitation over the Colorado Rockies (Gutmann et al 2016). WRF and ICAR were both used to simulate precipitation over the Colorado Rockies for October 2000 through September 2001. WRF and ICAR both simulate realistic distributions precipitation over the region when compared with the Parameter Regression on Independent Slopes Model (PRISM) observation based product (Figure 2).

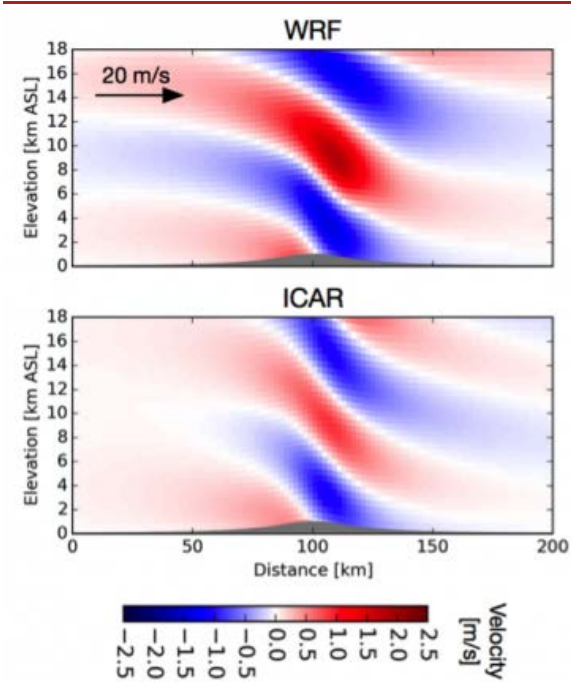


Figure 1. Topography (grey) and the vertical wind component for flow over an ideal hill for WRF (top) and ICAR (bottom) with a 20 m/s background wind speed (black arrow), flow is from left to right.

FY2015 ACCOMPLISHMENTS

In FY2015 ICAR has been documented in the peer-reviewed literature and many refinements to the model have been developed and are in process. The first paper documenting ICAR (Gutmann et al 2016) has been accepted pending minor revisions at the Journal of Hydrometeorology. Substantial refinements to ICAR this year have included a substantially improved representation of spatial variability in the linear wind solution and the addition and refinement of many physics schemes. New physics schemes include the Noah land surface model, a sea surface flux parameterization, simplified shortwave and longwave radiation parameterizations, a simple planetary boundary layer (PBL) scheme, and the MPDATA advection algorithm. In addition, the YSU PBL scheme, as well as the Tiedke and Kain-Fritsch cumulus schemes are in the process of being incorporated. Furthermore, the infrastructure for ICAR has been improved to permit extensive sensitivity testing of many of the parameters that are often simply hard-coded in atmospheric model physics parameterizations.

FY2016 PLANS

Plans for ICAR in 2016 include further model development as well as the application of the model to a wide range of climate scenarios and locations. Model development will focus on improving the flexibility of the model for sensitivity tests, improvement of the representation of convection, improvements to simple, fast, physics parameterizations, and incorporation of additional physical parameterizations. Applications of ICAR will include simulations forced by CMIP5 climate model output over Hawaii, Alaska, and the Contiguous United States, as well as Norway and Nepal. Additional applications over other parts of Europe, Canada, and South America have also been discussed.

Reference

Gutmann, E. D., I. Barstad, M. P. Clark, J. R. Arnold, and R. M. Rasmussen (2016), The Intermediate Complexity Atmospheric Research Model, *J. Hydrometeorol*, accepted pending minor revisions.

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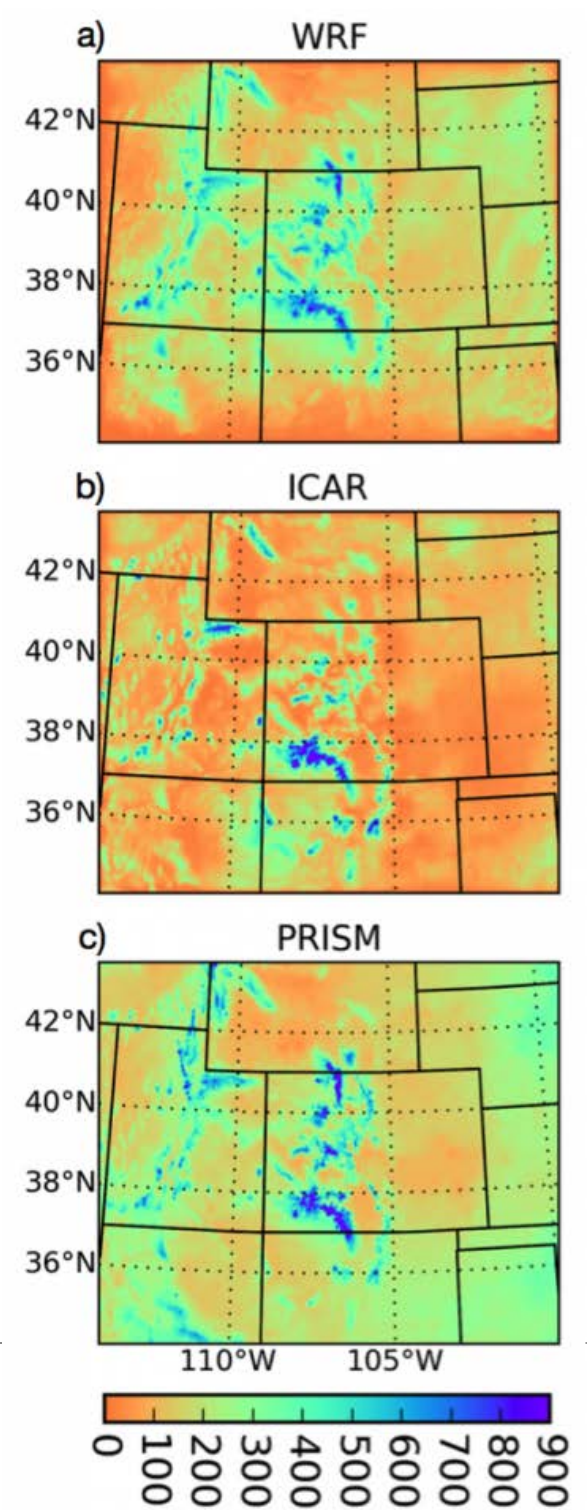


Figure 2. Precipitation totals [mm] simulated by (a) WRF, (b) ICAR, and estimated by (c) PRISM for the period October 1st 2000 through May 1st 2001.

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HIGH-RESOLUTION MODELING OF CURRENT AND FUTURE CLIMATE FOR NORTH AMERICA USING WRF AND ICAR MODELS

High-resolution WRF and ICAR regional climate model simulations are being performed to assess the importance of climate internal variability on the water system. These simulations are following on the successful Colorado Headwaters project and mimicking the domain from that program. These simulations are using boundary conditions developed from the CESM large ensemble (Deser et al, 2014) for the time periods 1990-1999, 2025-2035, and 2070-2080. The simulations reveal that the spatial variability in precipitation predicted by the CESM is enhanced in a cloud-resolving regional climate model (Fig. 1).

In addition to these WRF simulations, ICAR simulations are being performed over this and other domains covering the Contiguous United States (CONUS). The ICAR model (Gutmann et al, 2016) was developed in cooperation with the US Army Corps of Engineers as a physically based approach to downscale climate data, but with a fraction of the computational requirements of a model like WRF. ICAR simulations are being performed with the CESM model data, as well as other climate models from the CMIP5 archive.

Reference

Gutmann, E. D., I. Barstad, M. P. Clark, J. R. Arnold, and R. M. Rasmussen (2016), The Intermediate Complexity Atmospheric Research Model, *J. Hydrometeor*, accepted pending minor revisions.

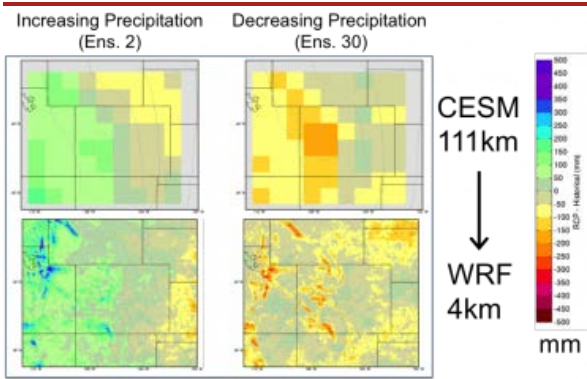


Figure 1. Changes in annual precipitation (2025-2035) predicted by two ensemble members (left and right) from the CESM large ensemble (top) and a 4km WRF simulation (bottom) forced by the CESM ensemble members show greater extremes in the WRF simulation, and these changes are often focused on regions of complex terrain.

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OBSERVATIONS OF MOUNTAIN SNOW PROCESSES

Recent work as part of the Water System program has focused on observing aspects of the water cycle that are very difficult to quantify. This work has had three primary thrusts. First, work developing low-cost terrestrial scanning lidars has shown that it is possible to continuously map snow deposition and redistribution in high-alpine areas that are often inaccessible by other measurement techniques, recent work has begun investigating the potential to make these measurements with even lower cost lidar systems or with time-lapse imagery. Second, measurements of snow in a remote region of the Sangre de Cristo mountain range has revealed that spillover of orographic precipitation can result in twice as much snow being deposited in the downwind side of a mountain range than on the upwind side. This can have important consequences for water resource management. Third, new measurements of tree sway and tree stem compression have informed work to measure snowfall interception in the tree canopy. Interception can cause the loss of 10-50% of snowfall, but direct measurement of interception has not been possible previously. An unintended finding of this work has revealed that these measurements also 1) quantify progressive freezing of the tree stem, a process that can have important ecological effects and 2) quantify the transfer of momentum from the atmosphere to the tree canopy.

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SNOW HYDROLOGY

Considerable effort has been devoted in the past year to expand research on snow hydrology, often in collaboration with university investigators. Work is focused in four main areas. First, the initial development and implementation of the SUMMA modeling framework (the Structure for Unifying Multiple Modeling Alternatives), as described above, was focused on snow hydrology, including as developers key snow hydrologists from different universities across the USA, most notably, Jessica Lundquist from the University of Washington and David Tarboton from Utah State University. Prof. Lundquist spent her sabbatical at NCAR working on SUMMA, and has one paper already published from that effort (Lundquist et al., 2015) and several other papers in preparation. Second, a broader collaboration with Lundquist’s group has been developed and additional papers have been published on mountain precipitation and rain-on-snow events (Henn et al., 2015; Lundquist et al., 2015b; Raleigh et al., 2015; Wayand et al., 2015). Third, a strong collaboration with the University of Saskatchewan, most notably with Profs. John Pomeroy and Howard Wheater, has been developed. Martyn Clark has visited the University of Saskatchewan twice in the past year, students and postdocs from the University of Saskatchewan have had extended visits to NCAR to help run the CONUS WRF simulations, and several joint papers are expected to emerge in the next several years. Finally, a new collaboration with Prof. Glen Liston at Colorado State University has been initiated, focused on examining how small-scale process understanding can be used to improve large-domain hydrology simulations, with focus on Alaska. These four efforts, in sum, considerably extend current work on snow hydrology and enable NCAR scientists to actively participate in the international snow hydrology community.

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# UNDERSTANDING THE LAND-ATMOSPHERE INTERACTIONS AND ENHANCING WRF HIGH-RESOLUTION CLIMATE MODELING CAPABILITIES

A collaborative effort among NCAR, NCEP, NASA, and university groups has been established to develop and improve the community Noah-MP LSM, which is a critical component in WRF-Hydro and RAL/HAP WRF high-resolution climate modeling. To enhance its global applicability, the Noah-MP model was evaluated using snow and surface-heat-flux observations obtained in the Colorado Headwaters (Chen et al. 2014), Tibetan Plateau in China (Gao et al. 2015), and Boreal Ecosystem Research and Monitoring Sites (BERMS) in Canada (Chen et al. 2015). Based on these evaluations, numerous Noah-MP physics parameterization have been improved such as canopy snow interception and sublimation for forested regions. New parameterizations of organic soil (Chen et al. 2015), sparse vegetation rhizosphere (Gao et al. 2015), and simple nitrogen dynamics (Cai et al. 2015) have been introduced to Noah-MP and evaluated against field observations. To represent the seasonal interactions between crop phenology and regional climate, dynamic crop growth modules were implemented in Noah-MP and evaluated with AmeriFlux data (Liu et al. 2015). The Noah-MP-Crop model is able to capture seasonal and annual variations in corn and soybean phenology and biomass such as LAI (Fig. 5), and produce better agreement with observations compared regarding seasonal crop phenology and biomass such as LAI to current available methods in Noah-MP. It led to improved surface heat fluxes (Fig. 6), especially in the early period of the growing season where current Noah-MP significantly overestimated LAI.

These enhanced physics and the Noah-MP-Crop model are planned to be implemented in the next community release of WRF-Hydro. In addition, we improved the non-iterative solutions for surface fluxes under unstable conditions in WRF (Li et al. 2015) and used the CASES-97 field data to evaluate the performance for simulating nocturnal boundary layer features of major PBL parameterization schemes in WRF (LeMone et al. 2014).

A collaborative and interdisciplinary team from Arizona State University and NCAR jointly develops advanced predictive and assessment tools necessary to examine hydroclimatic impacts and economic and social benefits/tradeoffs associated with agricultural and urban land use/cover changes accompanying localization of food production within cities. This five-year (2015-2019) project is sponsored by NSF and USDA. The team

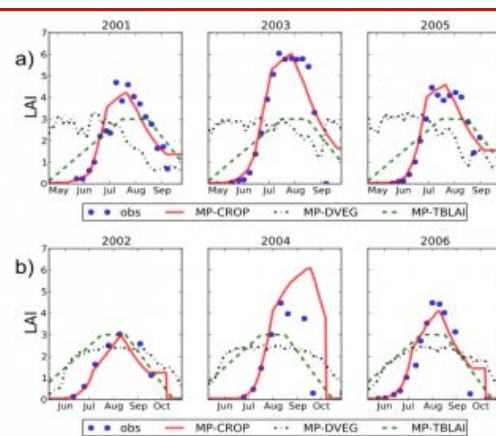


Figure 1. a): Comparisons of simulated LAI for corn at the Bondville (Illinois) site; b): Comparisons of simulated LAI for soybean at the Mead (Nebraska) site. MP-Crop: simulation with Noah-MP-Crop model; MP-DVEG: simulation with default Noah-MP dynamic vegetation model; NP-TBLAI: simulation using the Noah-MP look-up table LAI.

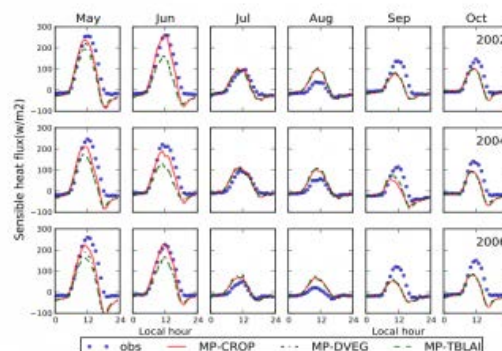


Figure 2: Comparison of simulated sensible heat flux at the soybean

develops a conceptual framework to evaluate economic and social impacts of community gardens and urban farms, quantifies socioeconomic benefits, and recommends geographically dependent strategies for sustainable integrated agri-urban development.

site in Mead, NE.

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STUDIES OF THE GLOBAL WATER CYCLE AND DROUGHT

Research in this area, led by Dr. Aiguo Dai of NCAR/RAL and the State University of New York Stony Brook, is focused in two main areas: 1) Assessing how natural variations associated with the Pacific Decadal Oscillation (PDO) or the Inter-decadal Pacific Oscillation (IPO) affect apparent decadal to multi-decadal trends in historical precipitation and related variables of the global water cycle, such evapotranspiration (ET), streamflow/runoff, and soil moisture content or drought indices (e.g., PDSI), as well as the global warming rate and 2) How atmospheric blocking affects winter extreme cold events and summer heat wave and drought events. Among these papers, the study by Dai et al (2015) on the IPO's major role in explaining the current and past slowdown in the decadal global warming rate ("warming hiatus") has received considerable attention. Together with several other recent studies, it strongly suggests that the current warming hiatus is mainly due to IPO and other natural oscillations (Fig. x), while any missed external forcing in CMIP5 model simulations is likely a secondary factor; and that large decadal variations in global warming rate should be expected rather than taken as surprises. Furthermore, as the IPO reverses course, global warming rate is likely to accelerate during the next few decades.

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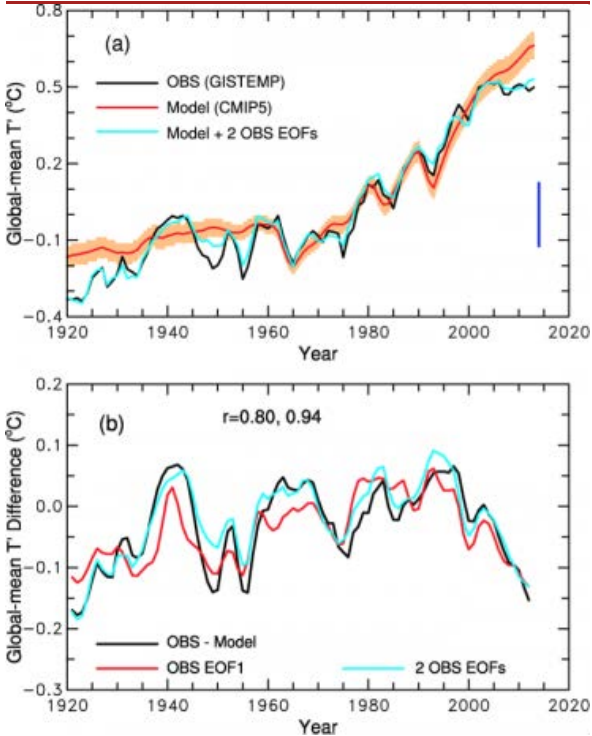


FIG. 1. Time series of the near-global (60oS-75oN) mean surface temperature anomalies ( $T'$ , all relative to the 1961 to 1990 mean) from 1920 to 2013. In (a), the annual  $T'$  from the GISTEMP observational data set (black) is compared with the ensemble mean surface air temperature (red) from 66 historical all-forcing runs from 33 CMIP5 models multiplied by a scaling factor of 0.863, and the blue line is the scaled model  $T'$  plus the  $T'$  represented by the two leading EOFs shown in Fig. 2 of Dai et al. (2015) (blue line in panel b). In (b), the black line is the GISTEMP minus the scaled model  $T'$  difference. Also shown in (b) are the global-mean  $T'$  represented by the first EOF (red) and the first plus the fourth leading EOFs (blue). Three-year moving averaging was applied to local  $T'$  time series before averaging or EOF analyses in this study and also to the lines in (b). In (b) the correlation coefficient ( $r$ ) is for the black verses red and black verse blue lines. The orange shading in (a) represents the 95% confidence interval of the model ensemble mean (red curve) and the blue vertical bar



indicates the 10th to 90th percentile range of the internal variability of T' estimated using the CESM1 30-member ensemble simulations. (Dai et al. 2015).

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## STEP (INTEGRATED HYDROMETEROLOGICAL SHORT TERM FORECASTING)

In FY15, RAL's STEP effort continued to emphasize the research and real-time demonstration of the integrated Hydromet Prediction System (Figure 1) (STEP-Hydromet hereafter). The overarching objective of this effort was to advance the prediction of heavy rainfall, flash floods and streamflow through the integration of state-of-the-art rainfall estimation, precipitation forecasting/nowcasting, and hydrology modeling techniques into one seamless system. Two major activities related to this objective were conducted in FY15. One was the evaluation and verification of the real-time data collected during the 2014 STEP Hydromet Experiment; the other was the operation of another real-time Hydromet Experiment during the summer season from 1 July to 15 August in the Colorado Front Range. Additionally, RAL continued to lead the STEP research theme on the improvement of WRF microphysics parameterization scheme as in previous years. In FY15, RAL also participated in the NSF-sponsored field experiment PECAN (see <http://pecan15.org>).

- STEP-Hydromet
- Improving WRF physics for improved prediction of high impact weather
- Study on convective initiation with PECAN data

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STEP-HYDROMET

BACKGROUND

In FY15, RAL’s STEP effort continued to emphasize the research and real-time demonstration of the integrated Hydromet Prediction System (Figure 1) (STEP-Hydromet hereafter). The overarching objective of this effort was to advance the prediction of heavy rainfall, flash floods and streamflow through the integration of state-of-the-art rainfall estimation, precipitation forecasting/nowcasting, and hydrology modeling techniques into one seamless system. Two major activities related to this objective were conducted in FY15. One was the evaluation and verification of the real-time data collected during the 2014 STEP Hydromet Experiment; the other was the operation of another real-time Hydromet Experiment during the summer season from 1 July to 15 August in the Colorado Front Range. Additionally, RAL continued to lead the STEP research theme on the improvement of WRF microphysics parameterization scheme as in previous years. In FY15, RAL also participated in the NSF-sponsored field experiment PECAN (see <http://pecan15.org>).

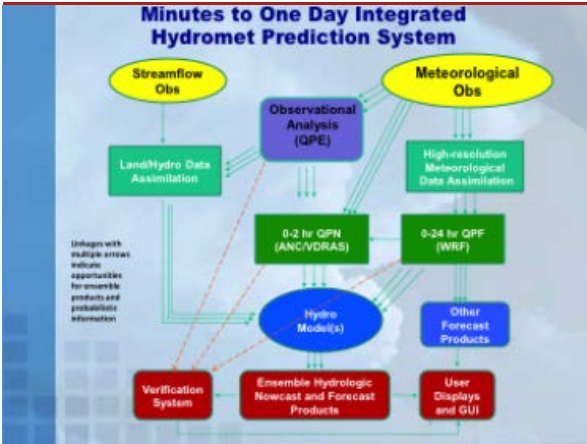


Figure. 1. Flowchart for the STEP Hydromet Prediction System.

DEVELOPMENT AND DEMONSTRATION OF STEP-HYDROMET

The goal of STEP-Hydromet is to provide prediction on the time scale of minutes out to one day, with particular emphasis on 0-12 hour forecasts and 0-1 hour nowcasts on very high-resolution spatial grids (from 100 m – 3 km in resolution). In addition to active research activities that support the development of the hydromet system, the integrated system has been demonstrated in real-time using the Colorado Front Range as a testbed since 2014. In FY2014, all components of STEP-Hydromet were run in real-time in an integrated fashion (<http://nar.ucar.edu/2014/ral/short-term-explicit-prediction-step-program>). The components included in the fully integrated system are: 1) radar-based quantitative precipitation estimation (QPE) and rain gauge QPE; 2) quantitative precipitation nowcasting (QPN) from 10 min to 1 h from the heuristic-based Autonowcaster/Trident system. High-resolution winds and buoyancy analyses from VDRAS are also produced; 3) quantitative precipitation forecasts (QPF) from the WRF 3DVar NWP models with radar data assimilation and frequent update cycles; 4) streamflow prediction on a spatially-continuous 100 m resolution grid, from the WRF-Hydro coupled atmosphere and hydrology model; and 5) near-real time performance evaluation of the QPE and QPF fields using Model Evaluation Tools (MET) statistical techniques. Ongoing research efforts towards improving the different components of this system are discussed below.

In summer 2015, STEP-Hydromet was demonstrated again from 7 July to 31 August with a number of upgrades. Compared with 2014, the modeling domain was extended to the east to fully cover the PECAN experimental region (Figure 2). The WRFDA (<http://www2.mmm.ucar.edu/wrf/users/wrfda>) radar data assimilation used a new configuration that allowed the hourly assimilation of radar observations driven by continuous WRF 3-hourly analyses rather than that of GFS as in 2014. In addition, the newly released version of WRF (WRF3.7) was used as the forecast model. The Autonowcaster/Trident nowcasting system was modified for the 2015 real-time experiment to incorporate satellite information into the nowcasts using a revised set of membership functions and weights. The hydrological system WRF-Hydro was run with a prototype of the new version that is under development. As in the previous year, the Numerical Weather Prediction (NWP) forecast models and the WRF-Hydro model ran on NCAR’s Yellowstone supercomputer, while the AutoNowcaster, Trident and VDRAS nowcasting systems, MET/MODE statistical tools, and the EOL QPE mosaics ran on workstations located in RAL and EOL. A dedicated web page ([https://ral.ucar.edu/projects/step\\_hydromet\\_test](https://ral.ucar.edu/projects/step_hydromet_test)) was set up for real-time viewing of precipitation accumulation fields, forecast and nowcast products, streamflow prediction, and statistical performance. The JAZZ interactive java-based display system was set up for viewing all the real-time observations (radar, satellite, surface station data), STEP nowcasts and NWP model forecast fields and was easily accessible on any workstation by clicking on a link on the dedicated STEP web site.

Most of the heavy rainfall and flash flood events along the Front Range occurred during June (prior to the start of the experiment) and in August. Rainfall accumulations of > 1 inch occurred on 15 days in June; flash floods occurred on 8 of those days. In contrast, July and August had a combined 20 days of >1 inch rainfall; flash floods occurred on 11 of those days. The Denver Metropolitan region is especially prone to flash flooding during the summertime. On 24 June, >2 inches of rainfall fell in one hour, resulting in flooding in many parts of Denver. Figure. 3 shows the intensity of storms in the Denver Metro region and the 2 hour rainfall accumulation during the flashing flooding.

Quantitative Precipitation Estimation (QPE)

An evaluation of a variety of radar QPE methods was conducted using QPE fields and rain gauge data collected during the summer of 2014 along the Colorado Front Range. The emphasis was on the performance of these methods during heavy rainfall events, so only one and two hour rainfall amounts > 14 mm were considered. The radar-based QPE methods (see Fig. 3d, for example) were compared with approximately 220 rain gauges that are located along the Front Range. Six radar QPE methods were examined which included the NSSL MRMS, the NOAA Dual Pol, Stage IV, and EOL hybrid methods. Results indicate that the Stage IV QPE is significantly smoothed and underestimates the heavy rain by a factor of two so should not be used for evaluation of heavy rainfall over small areas; the MRMS was generally similar in accuracy to the

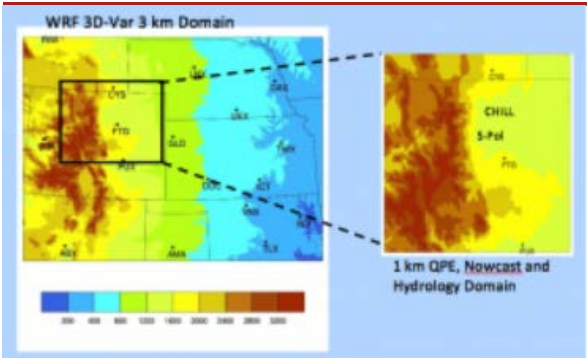


Figure 2. Topographic images showing Hydromet Prediction System domains for the STEP 2015 Hydromet Experiment.



polarimetric radar methods but shows a tendency for overestimation of rain amount within the cores of heavy rain areas; and the polarimetric methods (NOAA Dual Pol, EOL hybrid) that use precipitation identification (hail, rain hail mixture, heavy rain, light rain) to decide which radar parameters ( $Z_h$ ,  $Z_{dr}$ ,  $K_{dp}$ ) and equations to use in estimating the rain amount are the preferred methods.

Quantitative Precipitation Nowcasting (QPN)

The Autonowcaster/Trident nowcasting system was modified for the 2015 real-time experiment to incorporate satellite information into the nowcasts. This included using a revised set of membership functions and weights. The 2014 and 2015 versions of the software were run simultaneously in real-time. Software to provide near real-time validation of the nowcasts in graphical form was also installed for the real-time experiment. Frequently the heaviest rainfall and flash flooding along the Front Range occurs during the late afternoon during rush hour in the urban areas resulting in high impact weather for Denver, Ft. Collins and Colorado Springs metropolitan regions and usually in conjunction with low-level upslope flow in those regions. Analysis of the 2015 flash flood events in Denver has shown that a majority of these events occur following the collision of gust fronts in the area (as in Fig. 3a) and subsequent initiation and merger of storms (Fig. 3c) that produce intense rainfall (Fig. 3d) over a very short period of time. Thus the detection of convergence regions (Fig. 3b) and associated vertical motions provided by the VDRAS analysis system, are an important component of the short-term nowcasts provided by the Autonowcaster/Trident system. NWP models typically are unable to predict these outflows or the secondary convection initiation that results. Efforts to improve the VDRAS-derived wind flow along the complex terrain are ongoing.

Figure 4 is an example of an Autonowcaster/Trident 1 h nowcast for a rapidly developing flash flood event in the DIA terminal area and along the north side of the Denver metropolitan area. The nowcast is shown in the left panel and the verification of the nowcast 1 h later, using the MRMS radar-based QPE accumulation, is shown in the right panel. While the placement of the nowcast precipitation is reasonable, there is still work to be done to improve the quantitative precipitation amounts.

Qualitative Precipitation Forecasting (QPF)

The model-based QPF effort had three focus areas in FY15. First was the evaluation and verification of the real-time results from the 2014 STEP Hydromet Experiment; second was the continued development of convective-scale data assimilation using WRFDA; and third was the real-time demonstration of data assimilation and QPF systems along with other STEP-Hydromet components during the summer of 2015.

The evaluation and verification of 2014 real-time QPFs was done for eight convective days for five WRF 0-12h QPF systems/configurations. The verification was performed against MRMS gauge-corrected

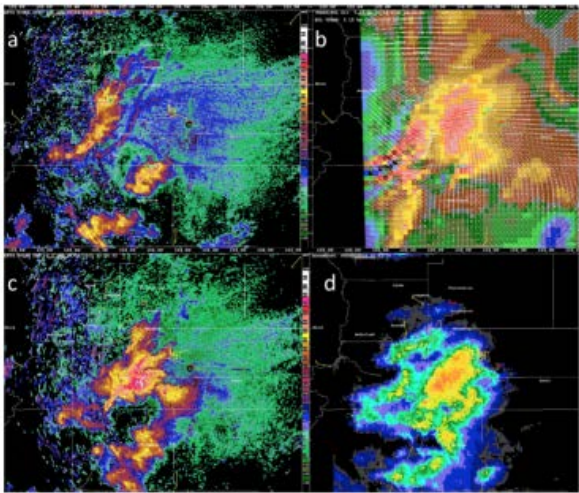


Figure 3. Flash flood even on 24 June 2015 over the Denver Metro region. a) Colliding gust fronts (thin lines) over Denver; b) VDRAS winds and convergence associated with collision; c) flash flood-producing storm with 65 dBZ reflectivity intensities; d) Two hour rainfall accumulation from radar-based QPE.

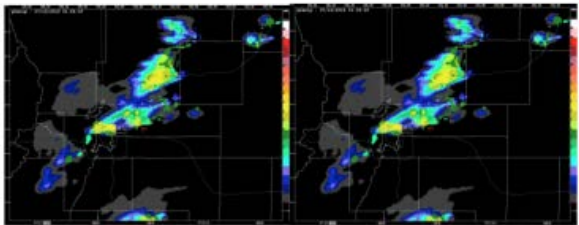


Figure 4. Example of a 1 hour nowcast of rainfall accumulation for a Denver flash food event on 9 July 2015 for 18:00-19:00 (Local Time; LT). The yellow colors represent rainfall in excess of 25 mm and the reds in excess of 50 mm. The left panel is the Autonowcaster/Trident nowcast rain accumulation for the period from 18-19 LT, made at 18 LT and the right panel is the radar-based verifying accumulation for the hour 18-19 LT.

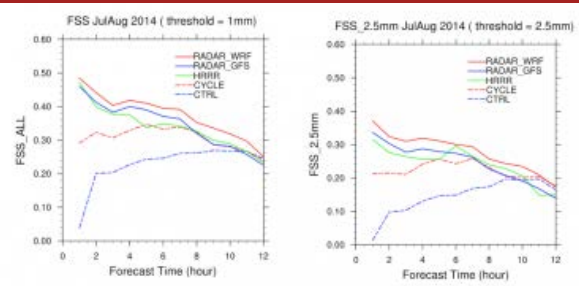


Figure 5. Fractions Skill Score (FSS) of hourly-accumulated rainfall

precipitation analysis. The Fraction Skill Scores for 1mm and 2.5mm are shown in Fig. 5a and Fig. 5b respectively, each compares the skills for the following QPF runs:

CTRL: initialized by GFS global analysis;

CYCLE: initialized by WRFDA 3DVar analysis with continuous 3-hourly update cycles,

assimilating only conventional observations;

HRRR: operational HRRR mapped to the same domain as the other runs;

RADAR\_GFS: initialized by WRFDA 3DVar with hourly radar data assimilation cycles

using GFS as background every third hour; and

RADAR\_WRF: same as RADAR\_GFS but using WRFDA 3DVar analysis from CYCLE as background every third hour.

The results in Figure 5 indicate that the runs with radar data assimilation (HRRR, RADAR\_GFS, RADAR\_WRF) show improved skill over CTRL and CYCLE although their positive impacts last for different forecast lengths. While the WRFDA 3DVar-based radar data assimilation run RADAR\_WRF has higher skill than HRRR over the 12h forecast range, the other run using the same system but different cycling setup (RADAR\_GFS) has higher skill than HRRR only in the first few forecast hours. Further evaluation is being carried out to identify the weaknesses and strengths of the current radar data assimilation scheme with the ultimate goal to improve the data assimilation and hence QPF.

The effort to improve convective-scale data assimilation in FY15 focused on the improvement of water vapor analysis via a more objectively based cloud analysis, the assimilation of “no rain” observations from radar, and surface data assimilation. The WRFDA 4DVar radar data assimilation system was also actively studied and developed with leveraged external fund from the Central Weather Bureau of Taiwan.

During the STEP Hydromet Experiment conducted in the summer of 2015, the QPF systems were run on a larger 3km domain (Fig. 2) than 2014 to cover the PECAN field area. Seventeen NEXRAD radars were assimilated by WRFDA to provide initial conditions for WRF 0-12h QPF. The new cycling configuration, as in RADAR\_WRF described above, was implemented. The latest released WRF model (WRF3.7) was used to produce 0-12h forecasts. Figure 6 gives an example of the real-time precipitation forecasts initialized by WRFDA with radar (top right) and without radar (bottom left), and from the NCEP operational system HRRR (bottom right) on 10 August when a flash flood event struck Manitou Springs, Colorado. The stage IV rainfall product is shown (top left) for verification. The only WRF 3-h forecast that successfully captures the flood-producing storm cell (indicated by the black arrow) is the one with WRFDA 3DVar radar data assimilation. Besides HRRR, the other two forecasts also successfully predict the heavy rainfall near Denver (indicated by the blue arrow).

Streamflow prediction from WRF-Hydro

Starting in 2014, the WRF-Hydro development team has participated in the STEP summer hydrometeorological prediction experiments. First year efforts focused on the real-time implementation of WRF-Hydro for the Colorado Front Range region and the development of operational workflows which manage the processing of meteorological forcing data inputs into the WRF-Hydro system, basic evaluation and calibration of the WRF-Hydro model, and the development of some basic forecast products for visualization of real-time forecast results (Figure 7). The WRF-Hydro group within STEP also coordinated two different data collection efforts, one focusing on the collection and processing of

for the thresholds of 1mm (left) and 2.5mm (right) over the WRF 3km domain. The radius of influence used in the FSS computation is 10km. Skills from 5 experiments (explained in the text) are compared.

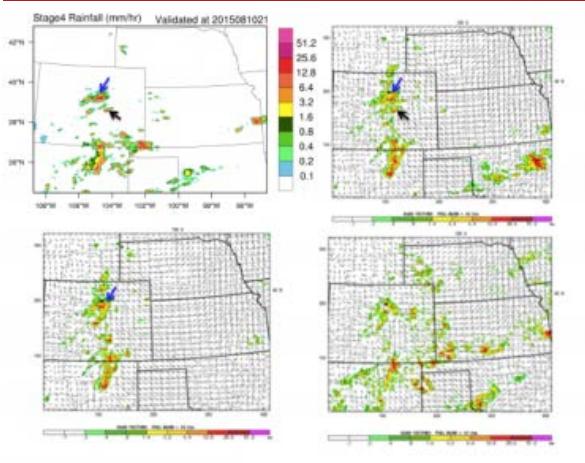


Figure 6. Observed (top left) and forecast 1-h accumulated precipitation valid at 21 UTC, 10 August 2015. The forecasts are from WRFDA with radar (top right), without radar (bottom left), and HRRR (bottom right), all initialized at 18 UTC, 10 August 2015. The black arrow shows the local rainfall that caused the flash flood at Manitou Springs, Colorado. The blue arrow shows the heavy rainfall near Denver.

precipitation station data from the Front Range region, and a second focusing on the launching of daily noon-time GPS radiosondes from the NCAR Foothills Laboratory. The precipitation station data collection process was finalized and has been used again in 2015 as the foundational station dataset for QPN/QPF evaluation in both 2014 and 2015. The radiosonde data collected during 2014 was quality controlled in real-time and submitted to the MMM WRF data assimilation group for assimilation into the WRF model. The WRF-Hydro group also has developed scripts for the collection and formatting of real-time streamflow data from the NWS, Colorado Division of Water Resources and the U.S. Geological Survey.

Development activities in 2015 principally focused on making improvements to the WRF-Hydro modeling system and the development of a comprehensive real-time web display system and model verification system. WRF-Hydro features a significantly upgraded version of the NoahMP column land surface scheme which has been enhanced with improved snowpack representation and improved descriptions of land cover characteristics/types using land cover data based on the USGS 30m National Land Cover Dataset as opposed to the older USGS-AVHRR based land cover dataset. These enhancements largely improve the representation of fine-scale hydrologic processes occurring in the Front Range high mountain and foothill regions as well as improve the characterization of urban land cover on the plains. The real-time web display system uses a Java-based processing engine and an open-source web mapping service to provide user-specified and scalable, interactive displays of STEP precipitation and hydrological model forecast products. This system ran in a prototype mode in 2015 on a 'borrowed' server which is now being migrated to a dedicated server for future applications. During 2015 an R-based hydrological model evaluation system ('rwrhydro') was also developed which now provides a very deep range of hydrological model evaluation capabilities (Figure 8). The 'rwrhydro' system is now being used to consistency quantify the assessment of WRF-Hydro analyses and forecasts as compared against existing observed streamflow conditions from 2014 and 2015.

Evaluation and verification of system performance

In 2015, various efforts were made to evaluate the performance of the STEP-Hydromet components. Subjective evaluation of the QPE products was conducted for heavy rainfall estimate (see previous description under QPE). The verification effort on 0-1h QPN and 0-12h QPF using 2014 summer data has also begun. Figure 5 shows an example of the QPF verification result. A verification system for the evaluation of WRF-Hydro analysis and forecast was developed and Figure 8 shows its initial result.

Verification of the 2014 summer QPF results was also made using the Model Evaluation Tool (MET). The verification was conducted over the entire period of the STEP Hydromet Experiment 2014 for a region east of the Continental Divide on the 3km WRF domain. Figure 9 shows a performance diagram in which several skill scores of the QPFs with/without radar data assimilation as measured by the probability of detection, success ratio, bias, and CSI. The result indicates that, while in

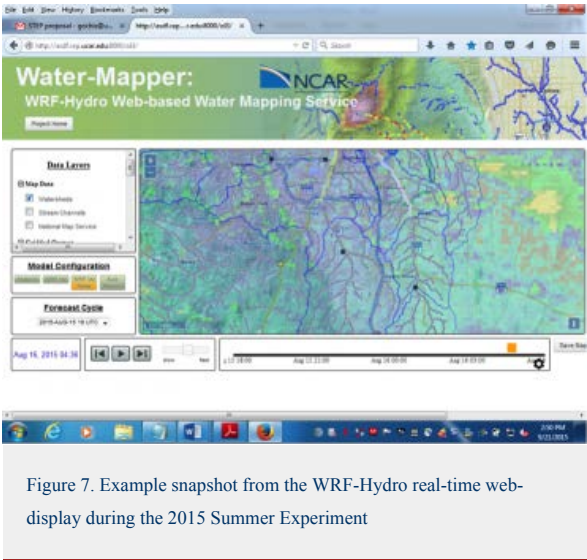


Figure 7. Example snapshot from the WRF-Hydro real-time web-display during the 2015 Summer Experiment

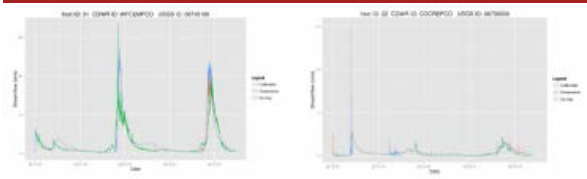
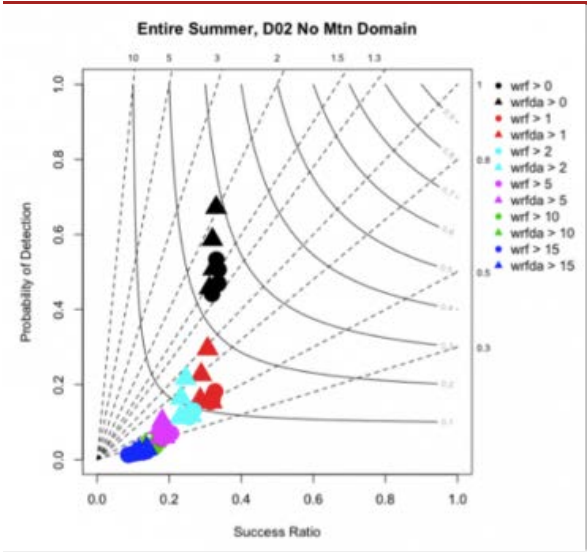


Figure 8. Sample simulated streamflow hydrographs from the rwrhydro model analysis package for the 2.5 year period (2013-2015) including the 2015 summer. Plot on left is from a high mountain watershed (West Fork of Clear Creek), plot on right is from a Foothills watershed (Coal Creek). Green-observed flow, blue-uncalibrated model streamflow, red-calibrated model streamflow.





general the radar data assimilation improves the probability of detection, it fails to improve the success ratio, which implies that the false alarm ratio is not improved by radar data assimilation.

For FY2016, several STEP groups will enhance their verification and evaluation efforts. These efforts will be coordinated and an initial real-time verification capability will be implemented in the summer of 2016.

FY16 PLANS

The STEP Hydromet Experiment will be conducted during the summer of 2016 using upgraded system components. In addition to testing various new research and developmental ideas in data assimilation, QPN, QPF, and WRF-Hydro, a 1km nested domain over the Front Range region will be added to the WRF configuration. The WRF-Hydro team will test a newly developed nudging-based data assimilation system. Other research plans for each of the STEP-Hydromet components are summarized below:

Figure. 9. Performance diagram showing multiple verification statistics for the period of STEP Hydromet Experiment 2014. This diagram simultaneously shows POD (vertical axis), SR (horizontal axis), CSI (solid line), and Bias (dashed line) for various lead times and precipitation thresholds. The different colors represent the precipitation thresholds used to define the precipitation events and individual points represent different forecast lead times. The best scores are in the upper right corner. The triangle and dot represent forecasts respectively from WRFDA with and without radar data assimilation.

QPE

- The performance of radar-based QPE algorithms for hailstorms, which occur relatively frequently along the Front Range, will be examined and evaluated. The presence of hail within storms can result in precipitation estimates that are too high. A study will be conducted to determine if modifications to QPE algorithms are needed in hail regions, and if so, changes will be made to the EOL QPE algorithm

QPN

- Detailed analyses will be conducted on the evolution of heavy rainfall and flash flood events, particularly along the urban corridor.
- Analyses and evaluation of the performance of the Autonowcaster/Trident nowcasts will be conducted during FY2016. The impact of 10 min – 1 h nowcasts on the WRF-Hydro streamflow prediction will also be assessed for selected heavy rainfall/flash flood events along the Front Range.
- FINECAST analysis will be improved by combining radar and surface data assimilation with a new surface data assimilation scheme
- Develop and evaluate an model-based 0-2h nowcast capability using the cloud model in FINECAST

QPF

- Continue the verification and evaluation effort on the QPF performance using both 2014 and 2015 real-time STEP-Hydromet data. As part of this effort, work will be undertaken with other STEP groups to determine a real-time evaluation tool.
- Improve the reflectivity data assimilation in WRFDA by improving the cloud analysis scheme and pseudo-humidity observation estimate, and the assimilation of “no precipitation” data.
- Evaluate the impact of divergence constraint and other constraints in WRFDA and examine their effectiveness in suppressing analysis noise.
- Improve WRFDA background error statistics using ensemble forecasts and evaluate the impact on 0-12h QPF. This work will be in collaboration with MMM ensemble forecast group.

WRF-Hydro

- Verification and continued calibration of WRF-Hydro simulated and forecasted streamflow using the rwrhydro analysis package. The package will be expanded to include a basic ensemble verification toolset. This work will be done in collaboration with RAL/JNT staff.
- Implementation of a real-time, nudging-based streamflow data assimilation (DA) system. During FY2016, the DA system will be calibrated for Front Range streamflow predictions and will be run operationally during the 2016 summer demonstration project.
- Implementation of a baseline, experimental ensemble streamflow forecasting capabilities using time-lagged ensembles from the operational NWS/HRRR model. This work will use selected case studies of the impact of ensemble methodology construction on probabilistic forecast skill.

Verification

- Coordinate the various verification efforts among the different STEP components
- Determine real-time verification matrices for QPN, QPF, and streamflow prediction
- Implement real-time verification algorithms for the STEP-Hydromet Experiment 2016

< STEP (Integrated Hydrometeorological Short Term Forecasting)	up	Improving WRF physics for improved prediction of high impact weather >
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IMPROVING WRF PHYSICS FOR IMPROVED PREDICTION OF HIGH IMPACT WEATHER

IMPACT OF MICROPHYSICS AND RADAR DATA ASSIMILATION ON SQUALL LINE SIMULATION

Continued investigation of the impact of model microphysics parameterization on short-term forecasts of convective initiation, evolution, and quantitative precipitation forecasts (QPF) was conducted with a squall line case study. The event studied was a squall line observed on 20 June 2007 in central Oklahoma. Idealized simulations of the case had previously shown the parameterization for raindrop breakup to have a strong influence on the evolution of organized convection via its impact on the cold pool (Morrison et al. 2012). Additionally, previous sensitivity tests varied the prescribed graupel density in the Thompson et al. (2008) bulk microphysics scheme, which showed that the cold pool strength and depth is impacted greatly by prescribed graupel density. In a low-density scenario, additional melting of graupel drove a stronger and faster propagating squall line due to the additional cooling from the melting process (Figure 10a). Surprisingly, rain evaporation processes were not noticeably altered. A new real

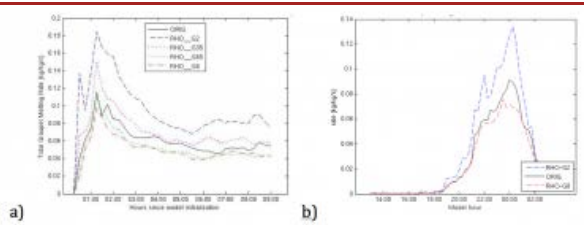


Figure 10. Time series of domain total graupel melting rate from a) the 9-h idealized simulation of the 20 June 2007 squall line and b) the 7-8 August 2014 real case simulation for each of the sensitivity tests that varied graupel density. The baseline simulation (“ORIG”) used the default graupel density of  $500 \text{ kg m}^{-3}$  (solid black line), while the other tests varied it below that (200 and  $350 \text{ kg m}^{-3}$ , blue dashed and pink dotted, respectively) and above that ( $650$  and  $800 \text{ kg m}^{-3}$ , green



simulation case study was also added to this investigation, in order to test this sensitivity in another case and under non-idealized conditions. The new case investigated was a squall line from 7-8 August 2014 observed in northeastern Colorado. It also showed the strong sensitivity of having a lower graupel density leading to higher graupel melting rate (Figure 10b), yet the impact on the cold pool was not as strong as in the idealized case. This work again included the mentorship of a SOARS undergraduate student.

In order to promote more accurate initiation of convective features in non-idealized simulations of 20 June 2007 squall line, RAL's Real-Time Four-Dimensional Data Assimilation (RTFDDA) system that utilizes a latent heat nudging technique was used and showed that radar data assimilation (RDA) improved the squall line forecasts consistently. Numerical experiments were conducted to test the RDA technique, as well as to evaluate the effect of changes in the microphysics scheme (such as treatment of raindrop breakup and evaporation and graupel density). The graupel density tests in the RDA system showed very subtle changes to the squall line; the most notable change was less graupel in the low-density case. However, this did not manifest as a strong impact on the latent cooling and cold pool as it had in the idealized case.

IMPROVING THE THOMPSON MICROPHYSICAL SCHEME

During 2014, a detailed evaluation was performed to assess the performance and impacts of using the newly coupled Thompson et al (2008) microphysics scheme with the RRTMG radiation scheme in WRF. The newly coupled physics were included as one of the OU-CAPS Spring Experimental Forecast ensemble members during their real-time forecast exercise in May and early June 2013. In 2014, the coupled scheme was included in the WRF version 3.5.1 code release and then used as the "control" member of the OU-CAPS ensemble. Analysis of 29 days of 48-hour forecasts from the 2013 OU-CAPS experiment was performed to compare the sensitivities of the coupling to surface temperature and precipitation as well as cloud and radiative properties in conjunction with surface pyranometer and geostationary satellite data. The results indicated that the coupling resulted in a subtle impact overall, however the impacts varied by cloud type. As an example, there was a general cold bias in the uncoupled run compared to surface measurements in the central U.S. on 8 May 2013 (Figure 2 top panel). However, the coupling resulted in a general warming of the surface temperatures relative to the uncoupled run at these points (Figure 11 bottom panel), thereby improving the representation of surface temperature at those locations. A journal manuscript was published presenting the methodology for this new coupling and results of the evaluation using the 2013 OU-CAPS results.

A new algorithm was developed and implemented to output a maximum hail size at each grid point from WRF model forecasts. This algorithm was implemented and run as part of the 2015 STEP Hydromet real-time experiment. Additionally, the project coordinated with the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) in the Colorado Front Range to request additional volunteers report hail measurements in the region, which will be used as a source of model algorithm evaluation in the coming year.

FY16 PLANS

- Continue development of a variable density (3-moment) graupel/hail hybrid category in the Thompson microphysics scheme to improve forecasted convective storm structure, evolution, and QPF
- Evaluate and improve the new maximum hail size algorithm
- Coordinate with the STEP data assimilation teams on how to improve data assimilation of microphysical quantities

dotted and red dash-dotted, respectively).

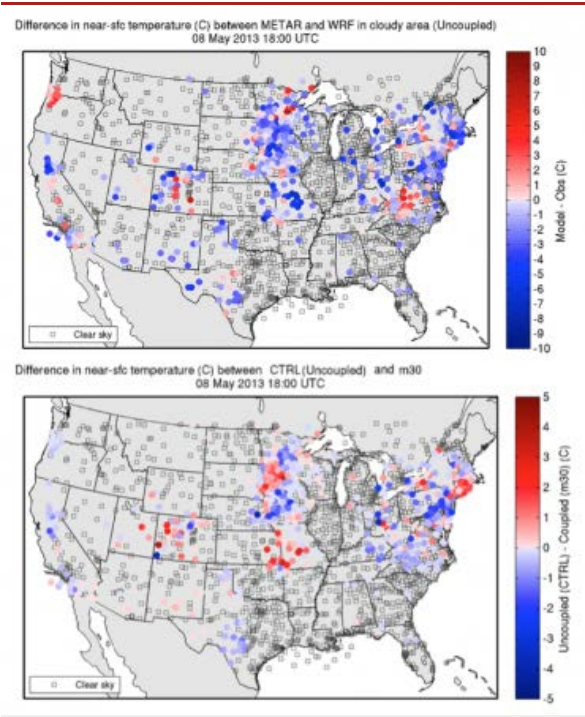


Figure 11. Example of the difference in surface temperature between the uncoupled (2013 "control") model and surface METAR observations in cloudy locations (top) and the difference between the uncoupled and coupled ensemble members (bottom) on 8 May 2013 at 18:00 UTC.

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STUDY ON CONVECTIVE INITIATION WITH PECAN DATA

PARTICIPATION IN THE PECAN 2015 EXPERIMENT

Roberts and Wilson participated as Co-PIs in the NSF-sponsored PECAN experiment conducted from 1 June -15 July (see <http://pecan15.org>) In preparation for PECAN, they provided scientific hypotheses for nocturnal elevated convective storm initiation (ECI) over the Great Plains and worked with PECAN forecasters on identifying forecast scenarios for ECI. During the experiment they participated in the daily planning and conduct of field operations. Figure 12 shows an example of the deployment of mobile platforms for collection of data on low level jet nocturnal intensification and its role in the initiation of nocturnal elevated convection. An excellent data set was obtained that should provide unique research opportunities to obtain new insight into nocturnal storm evolution.

The radar data assimilation and rapid update analysis system FINECAST (previously named VDRAS) was run in real-time over the PECAN domain to support the field experiments. Data from 5 operational radars and the

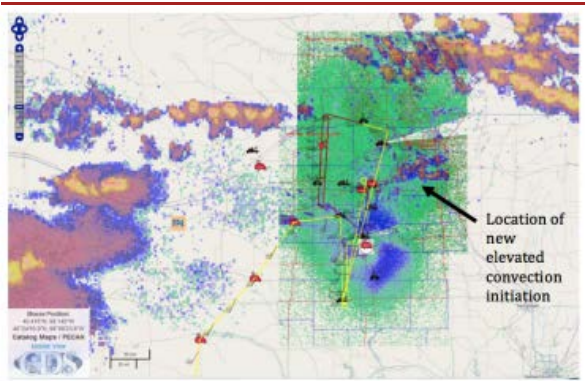


Figure 12. Field catalog map showing deployment of PECAN mobile facilities on 24 June 2015 during a low-level jet and elevated convection initiation mission. Aircraft tracks (yellow and red lines)

NCAR’s research radar S-Pol along with surface observations were assimilated with the 4DVar scheme in FINECAST, producing 15min updated analyses of 3D wind, temperature, and humidity.

POST-EXPERIMENT CASE STUDY

Work has begun to evaluate the FINECAST analysis quality, to improve the data assimilation method, and to study the initiation processes of elevated convection. The case of convective initiation occurred on 2 July has been chosen as the first case study.

To improve the FINECAST data assimilation and analysis quality, a new surface data assimilation scheme that has been recently developed was tested and compared with the old scheme. The new scheme enables the assimilation of AWS data with a 5 min interval instead of an hourly interval as in the old scheme, allowing a better use of the frequent AWS data. Figure 13 compares the temperature analyses from the real-time using the old scheme (top left) and the rerun using the new scheme (top right). The temperature analysis with the new surface data assimilation scheme clearly shows more details, with the largest difference near the strong convective storm in northern Kansas close to the border of Kansas and Nebraska (shown by bottom panels). Quantitative verification is being performed to validate the results.

FY2016 PLANS

- Analyses of PECAN cases will be conducted in collaboration with scientists from EOL and MMM to understand the processes associated with nocturnal elevated convection initiation, and the predictability of these events.
- Continue the PECAN 2 July 2015 case study to improve the quality of FINECAST analysis and the understanding of the initiation processes.

and mobile radars and profiling systems (black and red vehicle icons) are overlaid onto the radar reflectivity mosaic.

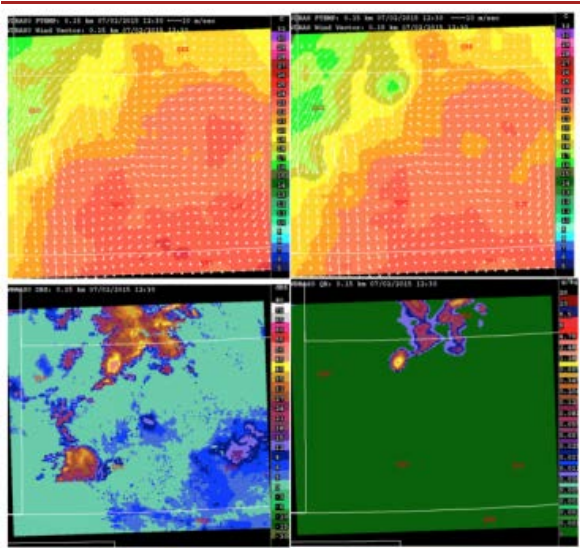


Figure 13. FINECAST temperature analysis overlaid with wind analysis at  $z = 0.15$  km with the old surface data assimilation scheme (top left) and new scheme (top right). The mosaic reflectivity (bottom left) and rainwater mixing ratio (bottom right) are also shown.

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# WRF-HYDRO MODELING SYSTEM

## HYDROLOGICAL MODELING WITH THE COMMUNITY WRF-HYDRO SYSTEM

A cornerstone of the NCAR/RAL Water Systems program is the development and support of community modeling tools for both process-based research and hydrometeorological forecasting applications. These tools are co-developed by NCAR in close collaboration with University researchers and government agencies in the U.S. and around the world. NCAR/RAL and the Water Systems program serve as focal points for training and collaboration in the hydrometeorological community. The Community WRF-Hydro System provides scientists and forecasters extensible modeling tools to engage in process-based research into land-atmosphere coupling, hillslope routing processes, surface water-groundwater interactions and multi-scale hydrologic evaluations. As a forecasting tool the WRF-Hydro System can run coupled or uncoupled to atmospheric prediction models and provide so-called 'hyper-resolution' forecasts of terrestrial hydrologic conditions such as soil moisture, snowpack, shallow groundwater, soil ice, streamflow, evapotranspiration and inundating waters.

Hydrometeorological modeling research with the Community WRF-Hydro modeling system has produced many significant advances over the past year including a major expansion of model options. Version 3 of WRF-Hydro was released in May of 2015 with several new test cases and model pre-processing tools. Numerous improvements to the WRF-Hydro code have been made as well which have enabled:

- Improved simulation of snowpack and snowmelt from high-mountain regions
- Upgraded baseflow parameterization to permit multiple subsurface flow responses
- Enhanced reach-based routing methodologies
- Support for the RAPID channel routing package
- Parallelization of the NoahMP land model driver for enhanced computational efficiency
- Expanded spatially distributed parameter datasets for improved model configuration
- Development of real-time Web Mapping Service for visualization of WRF-Hydro model forecasts and other real-time data
- Updated WRF-Hydro GIS pre-processing package for ArcGIS
- Suite of Powerpoint Tutorial Slides

These activities have been performed collaboratively with partners in the U.S. and internationally. Two notable publications



analyzing WRF-Hydro model performance were published in 2015 documenting the skill of the WRF-Hydro modeling system in simulating different types of hydrometeorological forecast problems. Dr. Gochis of NCAR worked with Dr. Ismail Yucel of the U. of Ankara on the first paper by Yucel et al (2015) which explored the value of WRF-Hydro model calibration and WRF-model atmospheric data assimilation on flash flood forecast skill in the region of Northern Turkey. They found that, use of atmospheric data assimilation produced measureable increased in WRF-Hydro model predicted streamflow due improvements in WRF-model simulated rainfall character which more closely matched the character of rainfall used to calibrate the WRF-Hydro model.

Dr. Gochis collaborated with Dr. Alfonso Senatore of the U. of Calabria on a second paper (Senatore et al., 2015) assessing the impact of WRF-Hydro in both a fully-coupled and uncoupled mode with the WRF atmospheric model in the simulation of seasonal water supply simulations in southern Italy. They found that inclusion of WRF-Hydro in a two-way coupled mode produced small but significant improvements in overall model skill, in terms of modeled rainfall and streamflow. The impact of WRF-Hydro formulations on modeled precipitation were most notable in summer rainfall versus winter precipitation to the respectively greater impact of local thermodynamic forcing in the summertime in southern Italy.

A major WRF-Hydro modeling effort that began in 2015 was a project aimed at improving seasonal water supply forecasts for the Upper Rio Grande river basin in southern Colorado. This project had both modeling and observational components, the observational component of which is described below. The goals of the modeling activities in this project were to demonstrate the fidelity of a state-of-the-art hydrometeorological modeling system as a means to improve the representation of multiple hydrologic variables, including snowpack, snowmelt, soil moisture, shallow groundwater and streamflow. Additionally, another principle goal of the project as to assess the impact of the use gap-filling radars to measure winter snowfall in Colorado’s mountain regions. WRF-Hydro modeling work on this project to date has demonstrated high resolution modeling of mountain snowpack and streamflow is feasible with a physics-based modeling system and that the use of gap-filling radars can provide significant value in terms of improving the snowfall, snowpack and, therefore, streamflow simulations in otherwise data-sparse regions of the western U.S. This improved simulation of seasonal runoff is illustrated in Figure 1 below which shows WRF-Hydro accumulated runoff results when it is driven by the currently operational NLDAS2 precipitation product and the NSSL radar product. It is important to note that no parameter tuning of these model runs was performed and each simulation is performed with the exact same configuration and differ only by the precipitation forcing.

Work on the Rio Grande water supply forecasting improvement project is continuing during the 2015 and 2016 season and the WRF-Hydro system is currently running in near-real time for the region of southern Colorado providing regular updates on snowpack and streamflow conditions. This effort is utilizing the new WRF-Hydro real-time forecast web mapping display system.

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COMMUNITY MODEL TRAINING WITH WRF-HYDRO

In addition to work designed to improve the Community WRF-Hydro modeling system, the WRF-Hydro team has partnered with the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. (CUAHSI) to conduct WRF-Hydro model training and tutorial activities. The first of these collaborative tutorial sessions was conducted at NCAR in May of 2015 and hosted 25 students and early career scientists in both seminar and hands-on training exercises. Another joint tutorial workshop is planned for the spring of 2016.

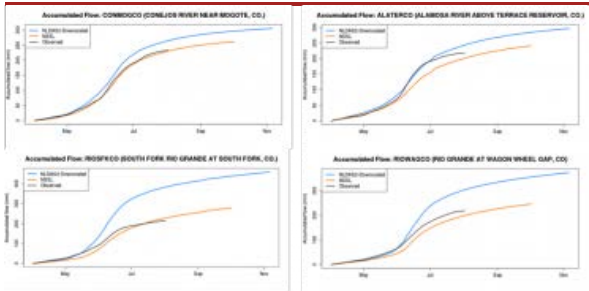


Figure 1: Observed and simulated accumulated runoff for the Conejos River, Alamosa River, South Fork Rio Grande, mainstem Rio Grande at Wagon Wheel Gap. Black-observed, blue-operational NLDAS2 forced WRF-Hydro, orange-NSSL radar forced WRF-Hydro. (Images created by Aubrey Dugger)

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COMMUNITY MODELING FOR URBAN AND AGRICULTURAL APPLICATIONS

DEVELOPING THE WRF-CROP MODELING CAPABILITY

This project aims to improve the representation of cropland-atmosphere interactions in the community Noah-MP land-surface model (LSM) with the ultimate goal of coupling it with the WRF numerical weather prediction and regional climate model. Croplands cover 12.6% of the global land and 19.5% of the continental United States. Through seasonal change in phenology and transpiration, crops can efficiently transfer water vapor from the crop root zones to the atmosphere. Crops have a detectable influence on regional distributions of atmospheric water vapor and temperature, and can affect convective triggering by modifying mesoscale boundaries. Therefore, croplands can significantly influence land-atmosphere coupling, surface exchanges of heat, water vapor, and momentum, which in turn can impact boundary layer growth and mesoscale convergence/convection.

Despite considerable improvements in LSMs, the representation of dynamic cropland processes within the WRF model has been largely absent. Therefore, developing a computationally efficient and flexible spatio-temporal resolution regional crop-growth modeling capability in WRF is necessary. Enhanced regional simulations of crop-atmospheric interactions are not only crucial to improving WRF model performance and the assessment of weather and climatic variability impacts on crop yields, but can also help explain the two-way interactions between weather and crops.

As the first phase of study conducted in FY15, dynamic corn and soybean growth models and field management (e.g., planting date) were introduced into Noah-MP (see Fig. 1) and the enhanced model (Noah-MP-Crop) was evaluated at field scales using crop biomass datasets, surface heat fluxes, and soil moisture observations.

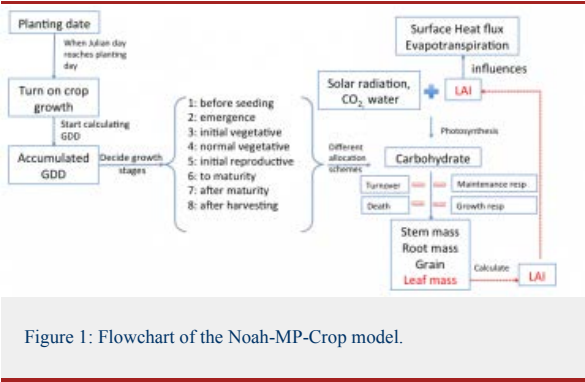


Figure 1: Flowchart of the Noah-MP-Crop model.

Compared to the generic dynamic vegetation and prescribed-LAI driven methods in Noah-MP, the Noah-MP-Crop showed improved performance in simulating leaf area index (LAI) and crop biomass. This model is able to capture the seasonal, annual variability of LAI and differentiate corn and soybean in peak values of LAI as well as the length of growing seasons (see Fig. 2). Improved simulations of crop phenology in Noah-MP-Crop led to enhanced surface heat flux simulations, especially in the early period of growing season where current Noah-MP significantly overestimated LAI. The addition of crop yields and Growing Degree Days (GDD) as model outputs expands the application of Noah-MP-Crop to regional agriculture studies. There are limitations in the use of current GDD criteria to predict growth stages, and it is necessary to develop a new method that combines GDD with other environmental factors, to more accurately define crop growth stages. This work is described in a paper submitted for publication in the *Journal of Geophysical Research*.

The Noah-MP-Crop model will be included in the public release of the WRF model in 2016. Work in 2016 will focus on enhancing the modeling system with the incorporation of global crop-type maps and modeling dynamic crop rooting depth and density.

ENHANCING HYDROLOGIC MODELING IN THE COUPLED WRF-URBAN MODELING SYSTEM

Global population has become increasingly urbanized: to date 52% of the world’s population live in cities, and this proportion is projected to increase to 67% by 2050. Urbanization modifies surface energy and water budgets, and has significant impacts on local and regional hydroclimate. In recent decades, a number of urban canopy models have been developed and implemented into the WRF model to capture urban land-surface processes. Most of these models are inadequate due to the lack of realistic representation of urban hydrological processes.

In this study, physically-based parametrizations of urban hydrological processes were implemented into the single layer urban canopy model in the WRF model. The new single-layer urban canopy model features the integration of, (1) anthropogenic latent heat, (2) urban irrigation, (3) evaporation from paved surfaces, and (4) the urban oasis effect. The new WRF–urban modeling system is evaluated against field measurements for four different cities (Fig. 3).

Results of evaluation against surface flux data collected at 4 cities show that the model performance is substantially improved as compared to the current schemes, especially for latent heat flux (see Fig. 4). In particular, to evaluate the performance of green roofs as an urban heat island mitigation strategy, we integrate in the urban canopy model a multilayer green roof system, enabled by the physical urban hydrological schemes. Simulations show that green roofs are capable of reducing surface temperature and sensible heat flux as well as enhancing building energy efficiency. These new modeling features were released in the public WRF V3.7 in FY15. An assessment of impacts of hydrological processes on urban meteorology using an integrated WRF-urban modeling system in FY16.

Development of the WRF-Urban modeling system was recognized as RAL’s pre-eminent achievement in the area of scientific and technical advancement in 2015.

Reference

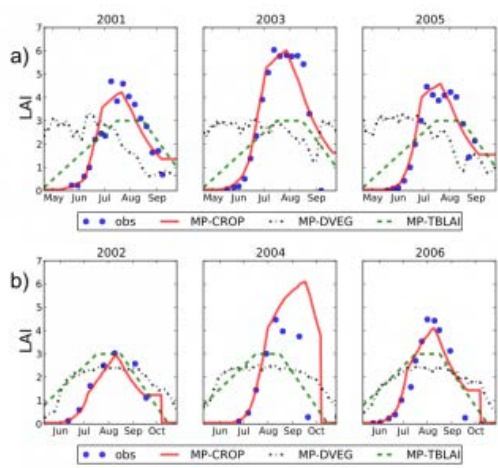


Figure 2: a): Comparisons of simulated LAI for corn at the Bondville (Illinois) site; b): Comparisons of simulated LAI for soybean at the Mead (Nebraska) site. MP-Crop: simulation with Noah-MP-Crop model; MP-DVEG: simulation with default Noah-MP dynamic vegetation model; NP-TBLAI: simulation using the Noah-MP look-up table LAI.

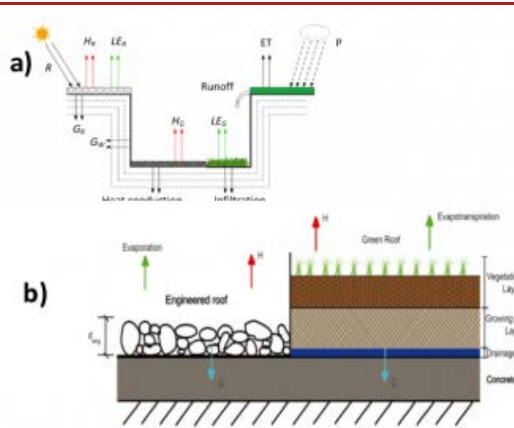


Figure 3: Schematics for a) the single-layer urban canopy model, and b) a green roof and an engineered roof. Subscripts R, W, and G denote properties of roof, wall and ground, respectively; deng in b) is the maximum water-holding depth of the paved surface.

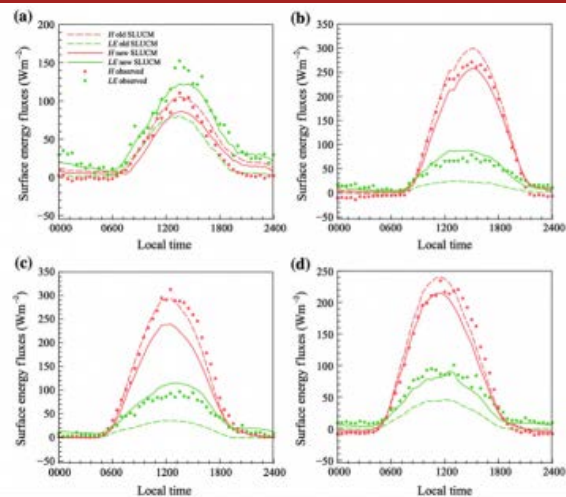


Figure 4: Averaged diurnal profiles of modeled and observed H (in

Yang, J., Z.-H Wang, F. Chen, S. Miao, M. Tewari, J.A. Voogt, S. Myint, 2015: Enhancing hydrologic modeling in the coupled WRF-urban modeling system. *Boundary Layer Meteorol.* 155, 87–109, DOI 10.1007/s10546-014-9991-6.

red) and LE (in green) in summer for a) Beijing, b) Phoenix, c) Vancouver and d) Montréal.

< WRF-Hydro Modeling System	up	Development of an Operational Streamflow Forecasting Capability for the CONUS based on WRF-Hydro >
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## DEVELOPMENT OF AN OPERATIONAL STREAMFLOW FORECASTING CAPABILITY FOR THE CONUS BASED ON WRF-HYDRO

RAL scientists are currently collaborating with the NOAA National Weather Service and National Water Center in the development of a new national hydrologic prediction system. Unlike past operational streamflow forecast models which were designed to provide river flow and stage forecasts only at specific points along river systems, the new national prediction system is being developed to provide continuous soil moisture, snowpack, evapotranspiration and streamflow forecasts for the entire nation. Figure 1 below illustrates this dramatic change in the spatial coverage of forecast points for the Upper Potomac River basin. To achieve this capability the NOAA/National Water Center (NOAA/NWC) selected the community WRF-Hydro modeling system as the modeling framework for translating operational weather information from radars, satellites and numerical weather prediction models into hydrologic predictions. The products to be developed from this new system will be nationwide, 1 kilometer gridded analyses and forecasts of soil moisture, snowpack and evapotranspiration, 250 meter gridded analyses and forecasts of shallow groundwater and surface water depth and predictions of stream and river channel flows on over 2.6 million river reaches crisscrossing the continental U.S. (CONUS).

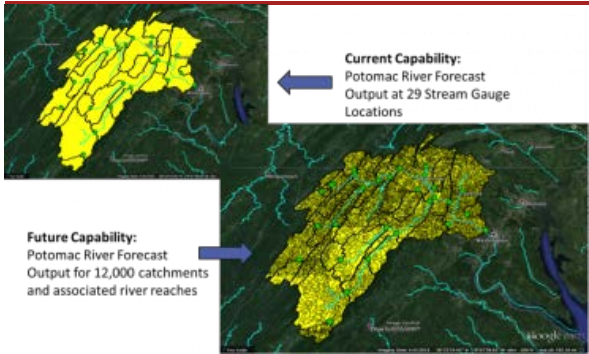


Figure 1: Current (upper left) and Planned (lower right) distribution of water forecast locations. Current river forecast capability is limited to location of 29 green dots in the upper left map. Future forecast points shown in lower right are designated by river reaches (not shown) which are associated with each of the ~12,000 small catchments delineated with thin black lines. (Image courtesy Ed Clark of the NOAA National Water Center)

Enhancing the WRF-Hydro system to generate operational streamflow forecasts over a large national domain required a new holistic, strategic approach to model development which encompassed not only consideration of new model physics components but also the strategic development and integration of several additional capabilities which include:

- Four CONUS-wide WRF-Hydro model implementations

- CONUS land surface hydrologic parameter datasets
- High performance computing
- Real-time Hydrologic Data Assimilation
- Hydrologic Verification System Development (“rwrhydro”)
- Meteorological Forcing Engine Processor
- National Flood Interoperability Experiment

The new capabilities associated with these strategic development areas are summarized in the following sections.

FOUR CONUS-WIDE WRF-HYDRO MODEL CONFIGURATIONS

In order to provide high-quality situational awareness and forecast information, the WRF-Hydro system is being configured for four different operational implementations. These configurations are as follows:

- Hourly Hydrologic Analysis and Assimilation
- Hourly Hydrologic Short-Range Forecasts out to 18 hours
- Daily Hydrologic Medium-Range Forecasts out to 10 days
- Daily Ensemble, Hydrologic, Long-Range Forecasts out to 30 days

Figure 2 shows a schematic of these four model configurations and lists forecast frequency, forecast duration and source of meteorological data being used to drive the WRF-Hydro system. These 4 specific configurations of WRF-Hydro, referred to as the “Initial Operating Capability (IOC)”, are currently in the process of being transferred into operations in collaboration with the National Water Center and National Center of Environmental Prediction staff. The expected date for public forecast production is in June of 2016. Preliminary model results shown as unregulated simulated values of Mean Flow Rate for the nation are illustrated in Figure 3.

CONUS LAND SURFACE HYDROLOGIC PARAMETER DATASETS

The national implementation of WRF-Hydro has required the integration and enhancement of numerous existing land cover, soil classification and river channel network datasets. Most prominently, streamflow forecast information will be provided on Version 2 of the USGS/EPA National Hydrography Dataset Plus (NHDPlus) which provides catchment and river reach delineations of most of the nation’s waterways. As part of the IOC the WRF-Hydro team has been working to adapt the NHDPlus dataset for use in WRF-Hydro and, in particular, deriving new catchment and river reach definitions for tributary areas outside of the U.S. and Canada where data do not currently exist in the native NHDPlus dataset. Similar enhancements have had to be made to provide spatially continuous, consistent descriptions of soil hydraulic parameters, land cover and vegetation parameters and lakes and reservoirs.

HIGH PERFORMANCE COMPUTING

Implementing the WRF-Hydro system for sub-kilometer model resolution for the nation requires the effective utilization of significant high performance computing resources. The main driver of improved computational efficiency is the need to complete model forecasts in as short of time as possible to ensure timely forecast delivery. As such, a significant amount of new model development work has focused on improving the parallel computational structure of the WRF-Hydro code for large computing systems. Most significantly, many of the largest model input/output (I/O) datasets had to be refactored to utilize parallel I/O structures. The transition towards parallel I/O for operational models run at NCEP is somewhat of a novel implementation and the WRF-Hydro system developed by NCAR is one of only two modeling systems operating at NCEP that will be utilizing parallel I/O making this a significant software engineering advancement for operational hydrologic prediction models. The product of this effort has been an improvement in runtime performance by over 50% for the CONUS domain compared to prior versions of the modeling system.

REAL-TIME HYDROLOGIC DATA ASSIMILATION

As with modern weather models a critical component of operational hydrologic prediction is the utilization of data assimilation to minimize

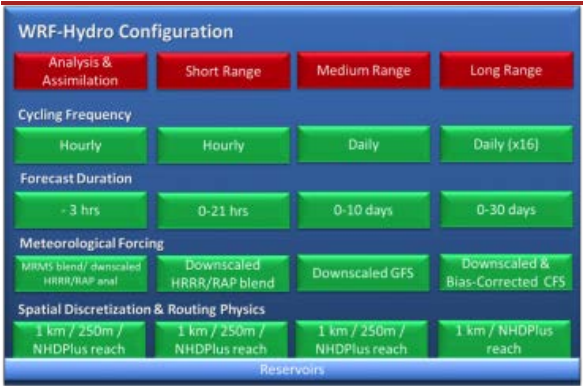


Figure 2: Schematic listing the 4 different Initial Operating Capability (IOC) configurations of WRF-Hydro; Analysis & Assimilation, Short Range Forecast, Medium Range Forecast and Long Range Forecast.



Figure 3: Map of uncalibrated and unregulated model simulated Mean Annual Flow conditions from the national implementation of WRF-Hydro. Values of river flow are plotted only at locations which have USGS stream gauge. Units of dot size and color are in cubic meters per second. (Image created by Aubrey Dugger.)

errors between observations of natural conditions and model analyses at the start or “initialization” of a given forecast. For the operational implementation of WRF-Hydro a new national, real-time streamflow data assimilation system has been developed which ingests data from nearly 8,000 real-time USGS streamflow gauges across the country. This work entailed significant code design, new data quality control procedures, GIS development work to standardize gauge and channel network attribution as well as laying the groundwork for more forward development on the assimilation of other hydrologic variables. Demonstration and optimization of this new capability is now underway and preliminary results shown in Figure 4 illustrate a functional system that can maintain model simulated flows inline with local observations. This capability will have significant beneficial impacts on downstream locations during short term forecasts.

HYDROLOGIC VERIFICATION SYSTEM DEVELOPMENT (“RWRPHYDRO”)

While building a new national modeling system is a significant task, the ultimate quality of the system is of paramount importance so that users and decision-makers can determine how much trust to place on model forecasts. To assess that quality the WRF-Hydro team has developed an entirely new, comprehensive hydrologic verification and evaluation system called “rwrphydro” using the open-source ‘R’ statistical analysis package. This new system provides comprehensive suites of analyses of hydrologic variables like streamflow, evapotranspiration and snowpack and draws observational data from a variety of federal and community data resources. Due to the size of many of the datasets being generated from the IOC instance of WRF-Hydro a lot of the development of rwrphydro has also had to center on the implementation of parallel job threading in order to optimize analysis time. An example of the output from rwrphydro is provided in Figure 5 below which illustrates the national view of precipitation skill as measured by the Root Mean Square Error metric aggregated over HUC-6 watersheds for the nation.

METEOROLOGICAL FORCING ENGINE PROCESSOR

Preparation of all the meteorological data for the IOC instance of WRF-Hydro required the development of several new tools to ingest, regrid, downscale and bias-correct multiple streams of operational meteorological model and radar information. To handle this task the WRF-Hydro development team has developed a new, integrated meteorological “Forcing Engine” which allows users to process and prepare WRF-Hydro input data from all of the NWS’s frontline meteorological models (e.g. CFS, GFS, HRRR, RAP, NAM) and the new operational national radar mosaic (MRMS) developed by the NOAA National Severe Storms Laboratory. This forcing engine regrids data to user-specified WRF-Hydro model grids, provides downscaling of variables like temperature, humidity, surface air pressure and incoming shortwave radiation, and also layers together meteorological data from multiple data sources. For the “Long Range Ensemble” WRF-Hydro configuration, NCAR RAL scientists have also developed and implemented a novel bias correction methodology to correct operational CFS model biases with respect to the operational NLDAS2 gridded analysis. An example of downscaled incoming shortwave radiation from the operational GFS model is shown in Figure 6, illustrating the impact of complex terrain slope and aspect in the western U.S. on local insolation and the land surface.

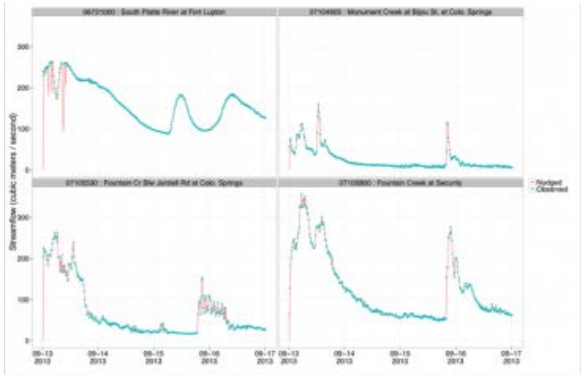


Figure 4: Plots of USGS observed and WRF-Hydro model assimilated streamflow at gauge assimilation sites. Note greater variations between observed and assimilated flows in the upper left image which is due to model spinup on the large South Platte River. (Image created by James McCreight.)

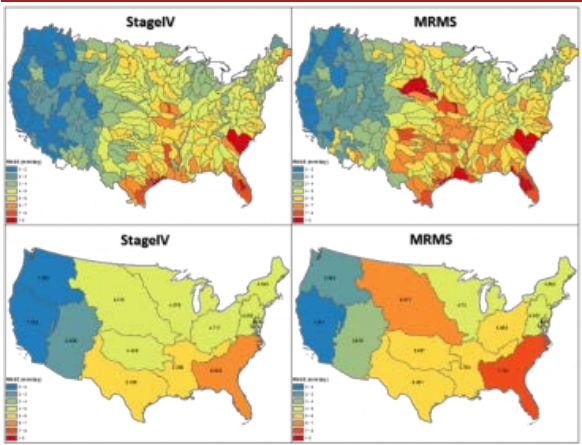


Figure 5: rwrphydro-generated statistics maps HUC-6 basin and RFC-region aggregate root-mean-squared-error values from the operational Stage-IV and MRMS precipitation estimate products as compared against GHCN station data. (Image created by Arezoo Rafieei-Nasab.)

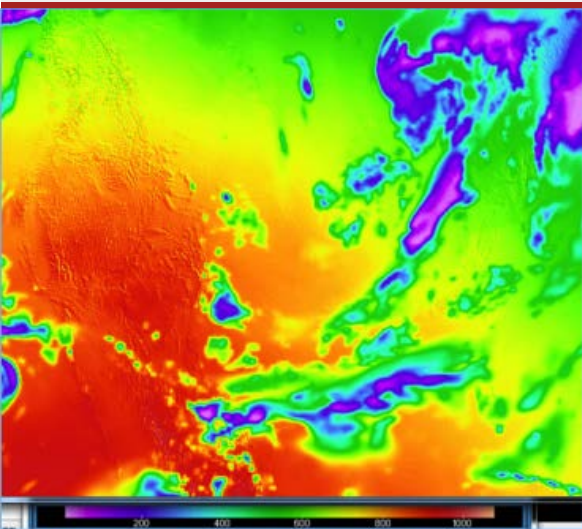
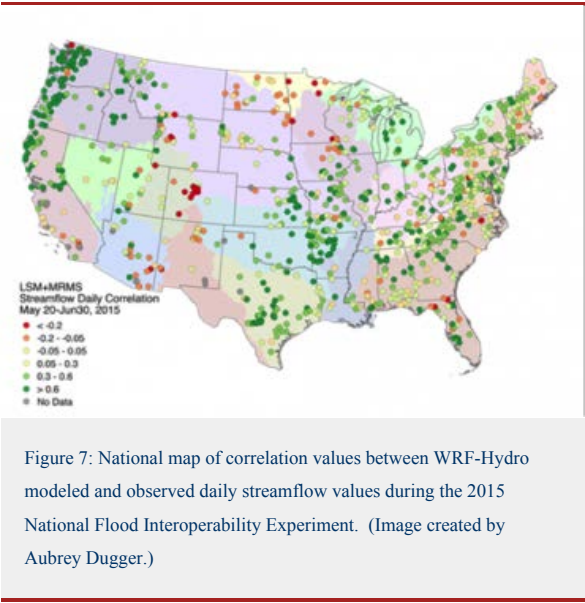


Figure 6: WRF-Hydro Forcing Engine downscaled GFS-model incoming shortwave radiation. Valid on Sept. 11, 2015 21Z. Units in Watts per square meter. Fine scale variations in radiation can be seen in the western (left) part of the domain.



NATIONAL FLOOD INTEROPERABILITY EXPERIMENT

During the summer of 2015, a simplified version of the IOC instance of WRF-Hydro was implemented and tested during the 1<sup>st</sup> National Flood Interoperability Experiment (NFIE) which was hosted by the NWC and the Consortium of Universities for the Advancement of Hydrological Sciences, Inc. (CUAHSI) at the new NWC facility on the campus of the University of Alabama-Tuscaloosa. The NFIE brought together professors, graduate students and operational forecasters to evaluate new methods of producing flood and flood impacts forecast products. Over 30 students from various academic departments around the country participated and NCAR supported these students with hands-on training on the use of the WRF-Hydro system, and advising in the design and interpretation of their research. Most notably, NCAR supported the entire NFIE effort with real-time execution of the WRF-Hydro system for the nation which was run every three hours on the U. of Texas/NSF-XSEDE ‘stampede’ supercomputer. Model outputs from the real-time WRF-Hydro runs were then transferred to the NCAR, Yellowstone supercomputer for analysis and archival. An example plot of the verification of NFIE model runs is shown in Figure 7 below, which illustrates the correlation values of WRF-Hydro analyzed streamflow at nearly 1000 unregulated USGS gauging stations.



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HYDROMETEOROLOGICAL OBSERVATION RESEARCH

BACKGROUND

Scientists in RAL’s Hydrometeorological Applications Program (HAP) are actively engaged in numerous observational studies aimed at improving understanding of critical processes that control various linkages in the water cycle. In FY2015 staff have engaged in several field observation efforts focused on winter precipitation, snowpack, snowmelt and runoff. In addition to requiring a comprehensive scientific research strategy, these projects demand significant integration of instrument engineering and field work skills to collect research-quality data in Colorado’s extreme mountain environments.

WINTER HYDROMETEOROLOGICAL OBSERVATIONS: UPPER RIO GRANDE WATER SUPPLY

One of the major field research projects carried out in the last year focused on improving seasonal water supply forecasts for the upper Rio Grande River basin through the use of coordinated in-situ and remotely sensed measurements. Funded by the State of Colorado’s Water Conservation Board and the U.S. Bureau of Reclamation, RAL partnered with research groups from the NOAA National Severe Storms Lab (NSSL) and NASA Jet Propulsion Laboratory (JPL) in a season long observational campaign.

The RAL team, led by Dr. David Gochis, designed and built 6 remotely operating ‘SNO-LITE’ stations to provide continuous, backcountry measurements of snowfall, snow depth, solar radiation, wind, temperature, humidity, soil moisture and streamflow. These stations were deployed and maintained throughout the winter of 2014-2015 and are operating again through the 2015-2016 winter to provide critical ground validation measurements of snowfall, hydrometeor type for a research polarimetric radar operated by NSSL and of snowdepth for an airborne lidar system aboard the NASA Airborne

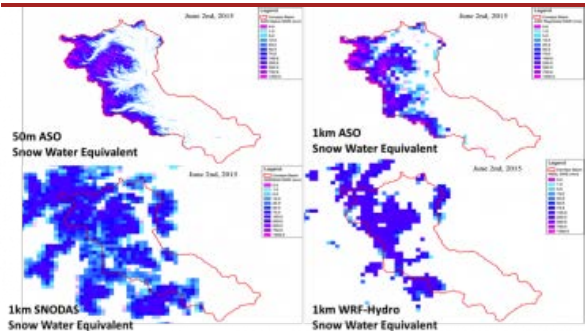


Figure 1: Comparison of NASA-ASO snow water equivalent estimates (top 2 panels) against operational SNODAS (lower left panel) and WRF-Hydro simulated snow water equivalent. (Images created by Logan Karsten)

Snow Observatory (ASO). All of these data were quality controlled, inter-compared and then fed into the WRF-Hydro modeling system as key inputs in a broader effort to improve water supply forecasts.

The major findings of this study thus far are that existing operational precipitation and snowpack measurement systems in the region were inadequate to properly characterize the patterns of snowfall and snowpack accumulation and melt out and that use of existing operational data led to large errors in seasonal water supply forecasts. This issue is illustrated in Figure 1 below which shows an analysis of snowpack conditions from the WRF-Hydro model in early June, 2015.

NCAR’s data from the Upper Rio Grande basin project is currently being used to improve snowfall estimates from polarimetric radars which are now being proposed for use in Colorado’s mountain regions.

**SPACE-BORNE REMOTE SENSING GROUND VALIDATION: NASA SMAP-GPM FIELD CAMPAIGN IN SOUTHERN ARIZONA (SMAPVEX-15)**

Remote sensing of the Earth’s environment from space is one of the greatest challenges in hydrometeorological observation system development. During the late summer of 2015, RAL staff participated in a large coordinated ground validation campaign for the NASA Soil Moisture Active/Passive (SMAP) satellite and the NASA-Global Precipitation Measurement mission (GPM). The team deployed 25 rain gauges in the border region of southern Arizona to provide high density, ground-based precipitation measurements to validate spaceborne measurements of precipitation from GPM and to help assess patterns of soil wetness from SMAP. Analysis of this data is underway as of this writing. Preliminary temperature (black) and accumulated precipitation (blue) data processed during the field campaign in late August is shown in Figure 2 below.

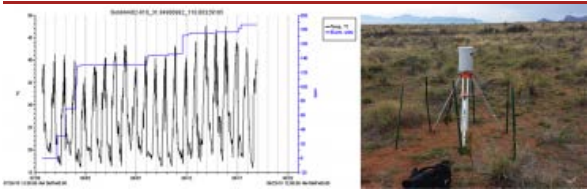


Figure 2: Preliminary temperature (black) and accumulated precipitation (blue) from surface rainfall and temperature measurements station deployed in southern Arizona as part of the NASA SMAP/GPM ground validation experiment.

**Marshall Pit-Gauge Facility: The standard for rainfall instrumentation**

A foundation of good field research measurements is proper instrument calibration, a fact which is particularly true for many rainfall measurements. During 2015, Dr. Gochis led the installation of a set of below-ground pit gauges at the Marshall Field instrument site to serve as a WMO-standard reference for benchmarking the performance of rainfall gauges. The new pit installation (See Figure 3) facilitates cross-referencing of different precipitation sensors and permits improved evaluation of the impacts of wind on rainfall measurement instrumentation. Over time, RAL scientists will use the facility in the development of instrument transfer functions to permit improved data comparisons when quality-controlling and evaluating measurements from different sensor designs. In combination with other activities underway at the Marshall Test Site, such as the WMO SPICE program, a broader array of hydrometeorological observations is being developed at the site to serve as a representative site for high prairie hydrometeorological conditions as well as fundamental instrumentation development and testing.

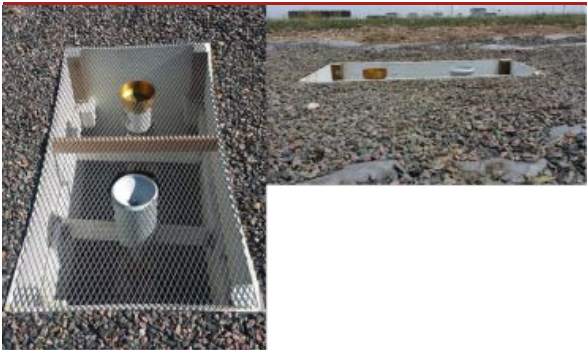


Figure 3: New rainfall instrumentation pits at the NCAR Marshall Test Site

**WILDLAND FIRE RECOVERY MONITORING: FOURMILE CANYON AND HIGH PARK BURN AREAS**

Wildland fire introduces numerous changes in previously forested landscapes that result in fundamental and often long-lasting changes in hydrologic structure and function and, therefore, risks from hydrologic events. Following the active fire period from 2010-2013 NCAR/RAL scientists collaborated with several other local research groups from the USGS, the Col. School of Mines and Col. State University in post-wildfire research in many Colorado Front Range burn areas. This work is now culminating with up to 4 years of post-fire instrument records in places like Fourmile Canyon near Boulder, Colorado and in the High Park burn area west of Fort Collins, Colorado. Instrument stations such as those shown in Figure 4 provide real-time precipitation monitoring to help

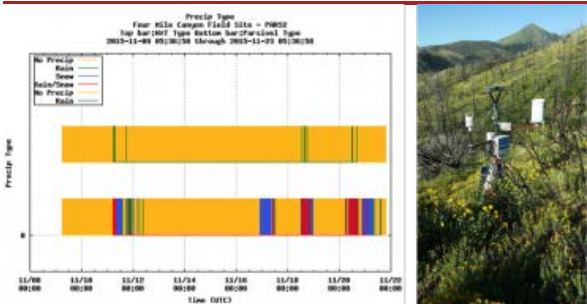


Figure 4: Plot of real-time hydrometeor identification data from



validate radar-estimates of heavy rainfall intensity and hydrometeor structure (i.e. rain-hail partitioning). These data are actively being used in streamflow forecasting projects such as the NCAR-STEP program in addition to basic process research on post-wildfire recovery processes.

sensors located in the Fourmile Canyon burn scar.

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HYDROMETEOROLOGICAL DATASETS AND METHODS

BASIN BENCHMARK DATASET

A key accomplishment in the last year has been publishing a benchmark dataset for evaluating hydrologic models (Newman et al., 2015a). The dataset includes hydrometeorological forcing data for 671 unregulated basins in the contiguous USA, along with streamflow data for all dates available in the 1 Jan to 31 Dec 2012 period. Retrospective model forcings are derived from multiple deterministic datasets (Daymet, N-LDAS, and Maurer), and recently also from a new probabilistic forcing dataset developed by our group (Newman et al., 2015b). Real-time data updates are now being provided.

Following generation of the forcing data, the hydrologic model used by the NWS River Forecast Centers, the SNOW-17 and Sacramento soil moisture accounting (SAC-SMA) based hydrologic modeling system, was

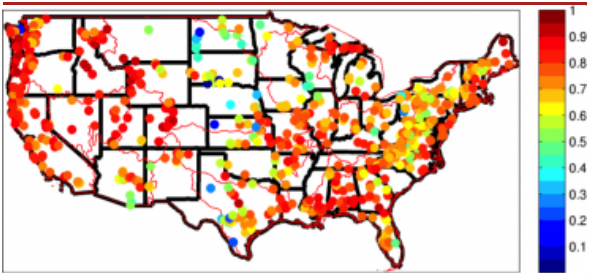


Figure 1. The spatial distribution of calibration performance using Daymet forcing data as measured by the Nash-Sutcliffe Efficiency (NSE) score

calibrated using the shuffled complex evolution (SCE) optimization approach. Results indicate that the SNOW-17/SAC-SMA optimized model parameters perform quite well overall, with arid basins and basins along the high plains of the US generally having worse model performance (Figure 1 and 2). These calibrated results are being used as a benchmark to identify performance that may be possible using more complex models.

All the basin metadata (shapefiles, locations, etc), hydrometeorological forcing data, streamflow data, model summary statistics, raw model output and model parameters have been packaged in a large-sample basin scale hydrometeorological dataset.

ENSEMBLE GRIDDED METEOROLOGICAL REANALYSIS

Hydrologic model forcing data are subject to uncertainties that are often poorly quantified. Newman et al. (2015b) describes the generation of a statistically reliable ensemble forcing dataset for the contiguous United States (CONUS). This method uses locally weighted regression in which spatial attributes from the station locations (i.e. elevation) are used as explanatory variables to predict the spatial variability in precipitation. Regression models are used to estimate the cumulative distribution function (CDF) of precipitation and temperature at each grid point. Ensembles of precipitation and temperature are generated using spatially correlated random fields to sample from the estimated precipitation and temperature CDFs.

An example of monthly accumulations for June 1993 during the Great Flood of 1993 is shown in Figure 3. The ensemble permits the ability to estimate precipitation and temperature uncertainties that vary in time and space realistically. The flood zone over the Upper Midwest had more spatially and temporally consistent precipitation, while the heavy rain over SE Texas was more spatially and temporally heterogeneous, which should have larger uncertainties.

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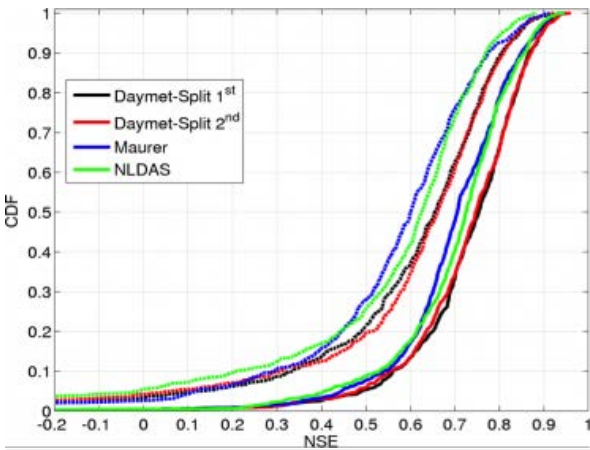


Figure 2. The cumulative distribution function (CDF) of the 671 basins for the calibration and validation evaluation periods for all forcing data. Daymet is split so that the first 15 years (1st split) and last 15 years (2nd split) are used for calibration to test if the two time periods are statistically harder to simulate.

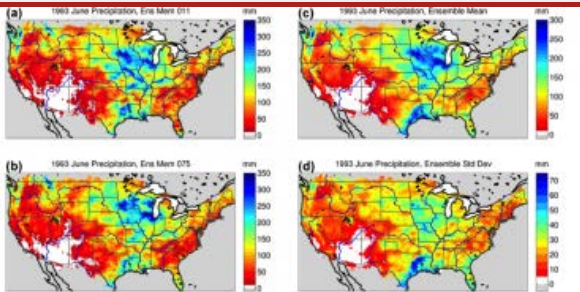


Figure 3. (a,b) Example June 1993 accumulation for two ensemble members, (c) ensemble mean accumulation and (d) ensemble standard deviation. All units are mm.





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DOWNSCALING

Downscaling climate data for hydrologic applications is a key component of any climate change projection. This downscaling is traditionally done in one of two ways, either statistical re-scaling of climate model precipitation (Gutmann et al., 2014), or dynamical downscaling of climate model atmospheric data using a regional climate model (Rasmussen et al., 2014). However, both of these methods have substantial drawbacks; statistical downscaling relies on many assumptions that may not be valid in a future climate, and dynamical downscaling is too computationally expensive to be used for large ensembles. This project has both evaluated existing methodologies and developed new methods to advance the state-of-the-science in this field.

Key findings from this work are that many statistical downscaling methods that are popular in the water management community produce hydroclimate representations with too much drizzle, too small extreme events, and improper representation of spatial scaling characteristics that are relevant to hydrology (Gutmann et al, 2014). These deficiencies vary by method, significantly impacting results of hydrologic simulation

(Mizukami et al., 2015a; Figure 4). This prompts us to improve downscaling methods through a more explicit recognition of what information is needed for hydrology, and what can be reliably extracted from GCMs versus what must be parameterized or generated through analysis of local watershed hydroclimatology.

Two approaches to improve downscaling methods. First, an intermediate complexity atmospheric model (ICAR) was developed for quasi-dynamical downscaling applications (see description in the Water system program). Second, a statistical method conditioned on atmospheric circulation patterns instead of climate model precipitation was developed. The first publication documenting the development of ICAR is in review (Gutmann et al 2016), and the circulation-based downscaling method is undergoing further refinement. In a joint study with the NCAR Water System program, CONUS-scale WRF simulations are being carried out to evaluate dynamically downscaled simulations, and regional WRF simulations are being performed with the CESM large ensemble to evaluate variability in dynamically downscaled simulations. These three methods--ICAR, circulation based downscaling, and WRF simulations--provide better coverage of the downscaling sensitivity and diversity space, along with a high degree of fidelity to current climate.

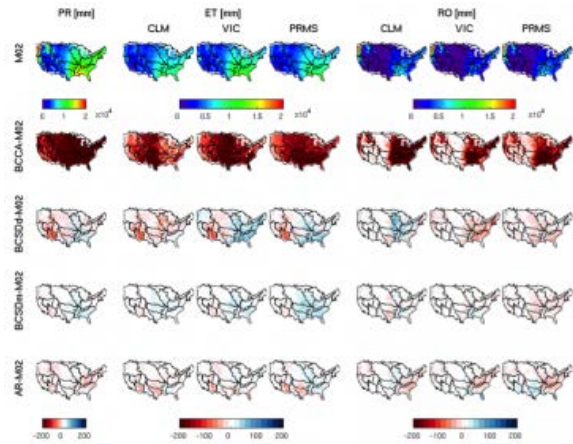


Figure 4. Impact of statistical downscaling methods on the partitioning of precipitation into evapotranspiration and runoff. Figure from Mizukami et al. (2015a).

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In addition to SUMMA, the team is working with multiple extant hydrologic models to examine how the impact of model choice and decisions made in model applications affects the portrayal of climate change impacts. The key models applied include VIC, PRMS, Noah, Noah-MP, CLM, and HEC-HMS (see the papers by Mendoza et al., 2015a; 2015b; and Mizukami et al., 2015a). As an example of this work, Figure 6 illustrates how impact of model choice affects the portrayal of climate change impacts for three basins in the Upper Colorado River (from Mendoza et al., 2015a). Looking forward, this small ensemble of hydrologic models will be replaced with a large ensemble of models formulated using SUMMA.

Moreover, the team has developed a multi-method continental-domain routing model, *mizuRoute*, to efficiently route streamflow through digital river networks throughout the contiguous USA (Mizukami et al., 2015b). The initial application is demonstrated by routing spatially distributed streamflow simulations through river networks from the United States Geological Survey (USGS) Geospatial Fabric (GF) dataset, which contains over 54 000 river segments across the contiguous United States (see Figure 7). The *mizuRoute* tool can assist model-based water resources assessments including studies of the impacts of climate change on streamflow.

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Figure 5. Conceptual diagram illustrating a framework for supporting multiple alternative model options for a range of physical processes, integrated as part of a common numerical solver.

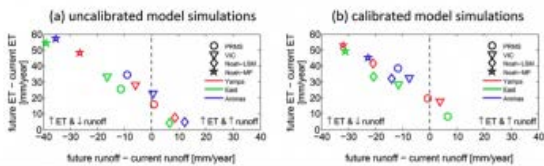


Figure 6. Projected changes in basin-averaged mean annual runoff and evapotranspiration across different model structures and basins. Results are displayed for (a) uncalibrated and (b) calibrated model simulations

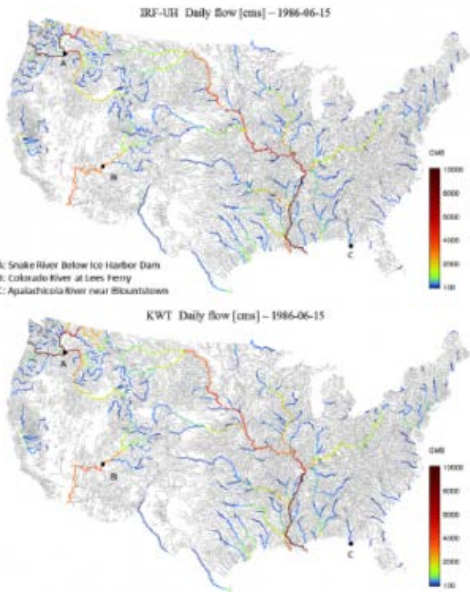


Figure 7. Example of multi-method routing capabilities using *mizuRoute*.

METHODS

Work over the past year has focused on a key hydrologic modeling challenge: defining model parameters that adequately represent the physical properties of the landscape (e.g., parameters that define the storage and transmission properties of soil). Typically model parameters are estimated individually for each basin through model calibration, though application of traditional calibration methods can result in compensatory errors across different parts of the model – the right answers for the wrong reasons – and the associated difficulties in transferring model parameters across space. Taken to its extreme, individual basin calibration efforts can create a “patchwork quilt” of spatial parameter maps that contaminate spatial assessment of changes in hydrologic conditions.

Current efforts are focused on implementing and extending modern scale-aware spatially consistent parameter estimation methodologies in order to improve parameter estimates in national-domain hydrologic models and advance nationwide water resource assessments. Specifically, work is based on the Multi-scale Parameter Regionalization (MPR) method of Samaniego et al. (2010). The MPR method has two main innovations: First, it estimates coefficients in the global transfer functions used to relate geophysical attributes to model parameters, instead of spatial maps of model parameters, which greatly reduces the dimensionality of the parameter estimation problem and provides spatially consistent parameter estimates across large geographical domains. Second, the MPR method estimates the parameters in the transfer functions at the (small) spatial scale of the geophysical data (e.g., soil polygons), and uses selected upscaling operators to obtain parameters at the model scale, i.e., the parameter upscaling represents non-linear relationships between small-scale processes and large-scale fluxes.

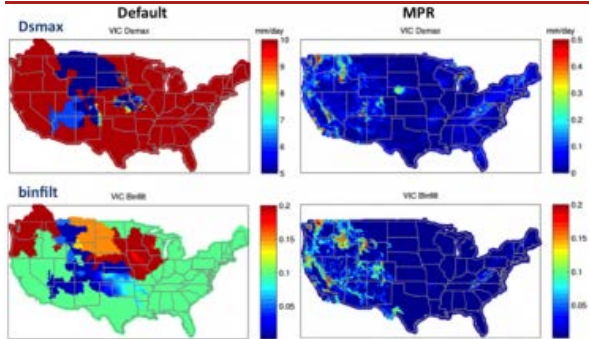


Figure 8. Generating spatially realistic parameter fields using MPR, making the “pathwork quilt” of manual calibration a relic of popular parameter estimation methods of yesteryear.

Research in the past year has focused on continental-domain parameter estimation with the VIC model, since VIC was used for previous water security assessments over the contiguous USA. The work included (1) sensitivity analyses with VIC to identify the most important model parameters; (2) defining new transfer functions for the new VIC parameters; and (3) building the model-agnostic MPR software to enable application of parameter estimation to VIC, and, ultimately, multiple hydrologic models. The initial results are encouraging: spatially realistic parameter fields have been generated without degrading the skill of the manual calibration. For example, Figure 8 shows the spatial fields of two VIC parameters in which the unrealistic basin outlines are no longer present in the MPR calibrations. Work over the next year will further improve these parameter estimates through application of clustering methods and multiple-objective parameter estimation.

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## ENSEMBLE STREAMFLOW FORECASTING

Department of Interior Bureau of Reclamation (Reclamation), the U.S. Army Corps of Engineers (USACE), and the National Center for Atmospheric Research (NCAR) are partnering to evaluate: (1) the application of state-of-the-science forecasting methods and datasets in an experimental real-time operational platform serving a selection of watersheds across the contiguous U.S., and (2) the performance of these methods and datasets in 'over-the-loop' forecasting. The first objective is motivated by a lack of experience with various advanced methods (such as data assimilation) implemented in an integrated operational workflow. The second objective is prompted by a perceived need to adjust parts of the current operational forecasting workflow in order to realize fully the benefits of various advanced methods in streamflow forecasting and water management support. The perception is that advanced forecasting methods require a great degree of automation in order to realize their potential benefits through the use of an over-the-loop forecaster role. A working hypothesis of this activity is that over-the-loop forecasting will unlock potential of advanced forecasting methods to inform water resources management, yet Reclamation and USACE need greater understanding of this paradigm's practicality for real forecast operations. There has been insufficient real-time, publicly available testing, demonstration, and evaluation of over-the-loop forecasting from the perspectives of workflow feasibility, product delivery reliability, and forecasting skill. This work is intended to help fill these gaps and further enhance and inform the advanced forecasting methods that are

being evaluated. The project builds on methods, models and datasets developed through ongoing FY2013-2015 collaboration project, “The Predictability of Streamflow across the Contiguous United States”.

**FY2015 ACCOMPLISHMENTS**

**Configure and calibrate hydrology and routing models for project basins**

The project basins list was expanded to approximately 50 locations across CONUS, including four basins targeted for forecasting interactions with BOR and USACE field offices. This selection was made by gathering and analyzing reservoir location information from the USACE National Inventory of Dams and from NASA remote sensing based water body products, since no single comprehensive database on reservoirs exists. Watersheds were chosen based on their flow contributions to reservoirs, and their performance in calibration. A dialogue was initiated with the NWS California-Nevada River Forecast Center to implement a Russian River forecast location, but this is still pending. As a result of discussions with the Reclamation Boise Area Office, work is also planned for the Prineville, OR reservoir location in support of the Reclamation Reservoir Operations Pilot study.

**Establish retrospective and real-time hydrometeorological data system**

Work is still underway to extend the probabilistic forcing dataset from Project 2 to support a real-time analysis. The backbone of the real-time experimental system has been implemented using the ECMWF ECFlow software at both University of Washington and NCAR. The Python-based software system maintains real-time workflows for downloading and processing meteorological and streamflow data, and provides a monitoring capability for the workflows. As of this report, work to operationalize the real-time hydrologic states, which depends on the probabilistic forcings, is nearly complete. Figure 9 depicts current forcing generation results over a pilot forecasting domain the Pacific Northwest.

**Meteorological forecast implementation and hydrologic forecasting**

Seasonal forecasting approaches initially explored under Project 2 have been expanded to facilitate the intercomparison of a range of strategies (from simple statistical use of teleconnections to hierarchical combinations of dynamical, ESP-based predictions with statistical forecasts). Hindcasts for these approaches have been conducted and are being assessed for the ~50 forecasting testbed locations.

Real-time seasonal water supply forecasts were operationalized as of October 2015 for the case study water resources basins. Figure 10 shows an example graphic that was distributed to water managers in the Boise Area Office of Reclamation.

**Implement streamflow forecast post-processing**

Post-processing for seasonal forecasts was implemented in various forms, including bias-correction, and merging of statistical and dynamical forecasts via resampling (using equal weights and skill weights) and Bayesian Model Averaging.

**Implement automated data assimilation**

For a subset of study locations (approximately 12), assessment of snow water equivalent (SWE) data assimilation for seasonal runoff prediction using the ensemble Kalman Filter technique has progressed, with positive results for most basins. A paper is under preparation and the results were presented at the AGU Fall Meeting.

**Establish forecast website and display capability**

A website framework was created at NCAR to present case-study results as they become available. This website ([http://www.ral.ucar.edu/staff/wood/case\\_studies\\_wr/](http://www.ral.ucar.edu/staff/wood/case_studies_wr/)) will be upgraded and expanded as the project continues. At present it serves real-time as well as hindcast results.

**Hindcasting and verification**

Extensive seasonal forecast hindcasts have been conducted for the case study locations, and for a variety of statistical, dynamical and hybrid

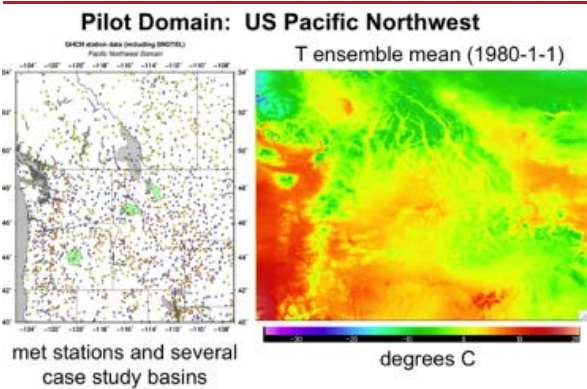


Figure 9. Real-time meteorological data streams and 1/16th degree ensemble forcing generation over a pilot forecasting domain in the Pacific Northwest.

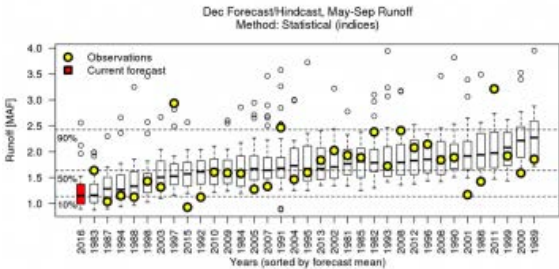


Figure 10. Real-time water supply volume forecast for the Hungry Horse Reservoir in Montana. (Source: [http://www.ral.ucar.edu/staff/wood/case\\_studies\\_wr/](http://www.ral.ucar.edu/staff/wood/case_studies_wr/))



techniques. A paper on benchmarking seasonal forecast approaches, focusing on water supply forecasts, is under preparation. Figure 11 shows examples of ensemble streamflow hindcasts for short-to-medium range lead times.

### Analysis and dissemination of results

Analysis and results were presented in telecons with the Reclamation Boise Area Office, with the Reclamation Reservoir Pilot Operations team, and with the Northwest River Forecast Center. Findings from the project were also shared in public meetings, including an international seasonal streamflow forecasting workshop at the Swedish Meteorological and Hydrological Institute; and at a forecasting workshop of the International Association for Hydrological Science (IAHS) in Prague, Czech Republic.

### Collaboration

PI Wood co-organized a HEPEX workshop on seasonal hydrologic forecasting (<http://hepex.irstea.fr/hepex-workshop-on-seasonal-hydrological-forecasting/>) with collaborators from the international forecasting community, and hosted an NCAR-supported summer visit (1 week) from Dr. MH Ramos (Irstea, France) to collaborate on forecasting methods.

At the workshop, Dr. Wood launched an international subseasonal-to-seasonal streamflow forecasting intercomparison experiment, which he will co-lead with a representative from the Australia CSIRO. Operational forecasting centers and entities including ECMWF, SMHI, Deltares, CEH-Wallingford, and the Australian Bureau of Meteorology. The collaboration will expand the community consensus on the efficacy of different approaches for seasonal streamflow prediction.

Outcomes from the project will be shared with the World Meteorological Organization (WMO) through participation in an effort organized by the Committee on Hydrology to develop WMO official guidance on extended range streamflow forecasting.

The modeling dataset used for the case studies was adopted by Brigham Young University researchers for forecast method development, class projects, and also content development for the US National Weather Service (NWS) National Forecast Interoperability Experiment (NFIE), held at the National Water Center.

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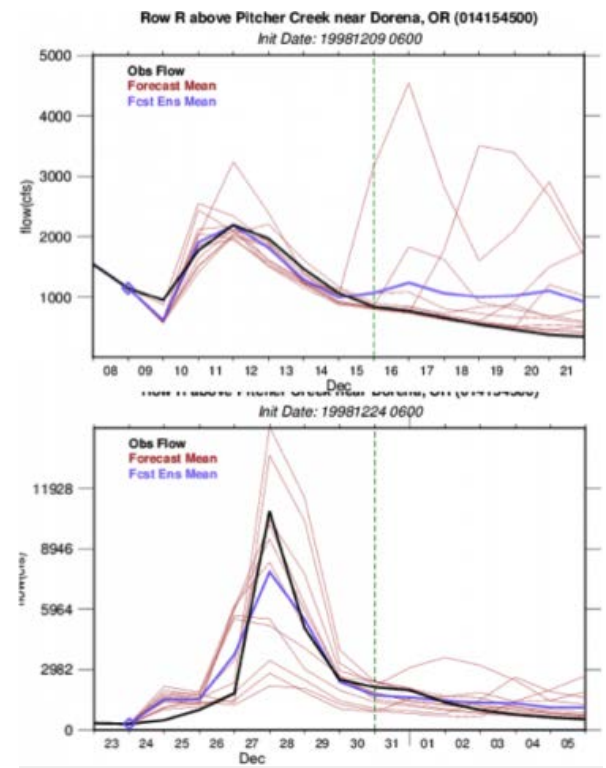


Figure 11. Selected GEFS-based 11-member hindcasts for a 15-day lead time, including 7 days of downscaled GEFS merged with a climatological ensemble, as meteorological forecast inputs to a two-zone Snow17/Sacramento model.



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## CLIMATE CHANGE IMPACTS

Many planning and management decisions involve understanding the vulnerability of hydrologic systems to a wide range of different stresses. A key challenge is to identify defensible options for the design and operation of systems under an uncertain and changing climate. In the water resources sector, this requires defining a range of different climate change scenarios in order to evaluate the vulnerability of infrastructure and the effectiveness of different adaptation strategies to manage climate-related stresses. For many users, the range of climate scenarios is most compatible with decision processes when it is distilled into a set of discrete hydrologic “storylines”, each representing key features from the full range of scenarios.

Interactions with the water management community have revealed the limitations of contemporary planning assessments, where (most critically) adaptation-planning assessments often rely on single methods for climate projection downscaling and hydrologic analysis. The reliance on single methods can mean current climate assessments are over-confident. To address this issue, the community needs access to

projections developed using a diversity of methods. Figure 12 illustrates the approach explicitly characterizing uncertainties in climate models, climate downscaling methods, and hydrologic models. Following this approach requires developing methods to improve methods to characterize uncertainty in climate downscaling (Gutmann et al. 2016) and hydrologic modeling (Clark et al., 2015a).

Current work is moving beyond the common ad-hoc approach of defining a limited set of climate change scenarios based on a small collection of models and methods with known problems. Two parallel paths are being followed: first, explicit characterization of the uncertainties throughout the modeling process (rather than using an ad-hoc “ensemble of opportunity”); second, reduction of uncertainties through development of criteria for excluding poor methods/models (e.g., inferior statistical downscaling methods; inferior climate models), as well as with targeted research to improve modeling capabilities. Key research tasks include:

- Comprehensively characterizing uncertainties in global climate modeling, climate downscaling, and hydrologic modeling, and develop “storylines” describing trajectories of hydrologic change that reflect these myriad uncertainties;
  - Improving characterization of uncertainty in global climate models, by enhancing development and use of perturbed physics and large ensemble simulations, and additional research on the selection and/or weighting of climate models;
  - Improving characterization of uncertainty in regional climate downscaling, by enhancing development of perturbed physics approaches (including more extensive use of dynamical models of intermediate complexity), through further development of statistical downscaling methods that can represent metrics important for hydrology (spatial scaling characteristics; extremes), and through abandoning downscaling methods that have limited merit for hydrologic impact studies;
  - Improving characterization of uncertainty in hydrologic modeling, using frameworks designed to accommodate multiple spatial configurations, multiple process parameterizations, and multiple model parameter values; reduce hydrologic model uncertainty through advances in hydrologic process representation (explicitly simulate dominant processes and improve estimates of model parameters, especially for continental-domain applications);
  - Identifying changes in climate and hydrologic processes where we have some confidence, such as declining snowpack, using quantitative concepts such as the emergence of statistically significant signals;
  - Improving the use and communication of uncertain projections by enhancing the working relationship between the providers and recipients of climate services, as well as managing user expectations about scientific capabilities through more explicit statements about uncertainty in climate service products.
- Such research into revealing, reducing and representing uncertainties is essential for defining plausible ranges of hydrologic storylines of climate change impacts to support water resources planning and management.

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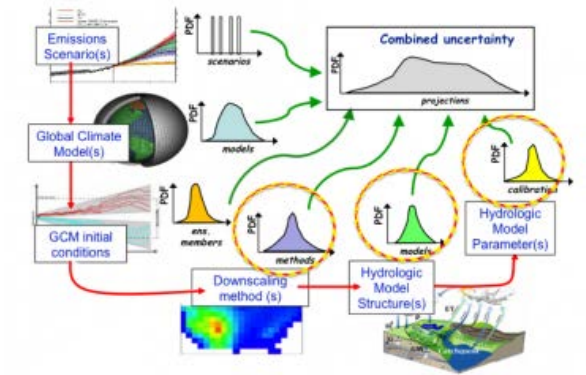


Figure 12. Characterizing uncertainties in the impacts of climate change on water resources, emphasizing the need to explicitly characterize uncertainties in climate downscaling and hydrologic modeling.

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# CLIMATE RISK MANAGEMENT

## BACKGROUND

A number of projects conducted within RAL focus on assisting decision and policy-makers in better understanding the impact of climate change and extreme weather events on water resources. Using the Water Evaluation and Planning (WEAP) model, co-developed by Dr. David Yates and scientists at the Stockholm Environment Institute, we are helping to address the growing need around the globe for new tools and methods to assess the impact of future climate-predicted precipitation on water availability and quality. By coupling physical hydrology and water planning and management information within a single framework, WEAP can be used by planners and managers to develop scenarios and strategies for more robust water management decision-making in their watershed, city or state. In addition to the WEAP model, RAL scientists work with stakeholders to adapt regional and global climate models and datasets to their needs. Education, training, and capacity building are fundamental components of this risk management effort.

## FY2014 ACCOMPLISHMENTS

### Decision-centric adaptation appraisal for water management across Colorado's Continental Divide

In collaboration with Robert Wilby, University of Loughborough U.K, and Lurna Kaatz, Denver Water, RAL scientists Kathy Miller and David Yates developed an experimental application of a decision-centric approach for evaluating climate adaptation options. The team modelled the operation of Denver Water's Upper Colorado Basin reservoirs and transbasin water diversions as conditioned by the existing legal definitions of their water rights, and the agreements and management protocols that govern storage operations and downstream flow obligations. The model was built on the Water Evaluation

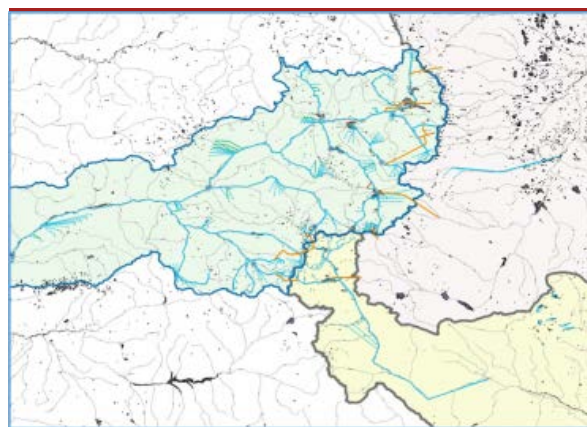


Fig. 1. West Slope WEAP model (WsWEAP), with inset showing the Upper Blue River basin, which a main water supply source for both Denver Water and Colorado Springs Utilities.

and Planning (WEAP) platform, and is referred to as the 'West Slope' supply model (WsWEAP; Figure 1) as it is also being used for some work with Colorado Springs Utilities.

The WsWEAP model was developed and used to simulate the performance of the water management system under plausible scenarios of future climate change and associated changes in watershed conditions both with and without a specific drought mitigation policy in place. Specifically, the team illustrated its approach by simulating the performance of the Shoshone Call Relaxation Agreement (SCRA) [the adaptation measure], using the WsWEAP model [the hydrologic cycle and water systems model]; and the Statistical DownScaling Model (SDSM-DC) [the stochastic scenario generator]. Scenarios relevant to the decision community were analyzed, and results indicate that this drought management measure would provide a very small benefit in offsetting the impacts of a shift to a warmer and drier future climate coupled with related environmental changes. The analysis demonstrates the importance of engaging water managers in the development of credible and computationally efficient decision support tools that accurately capture the physical, legal and contractual dimensions of the decision problem. A paper describing this work has been submitted to the journal *Climate Risk Management* and attached with this report.

A major accomplishment is the submission of a paper to the Journal of Climate Risk Management, (Yates, D., K. Miller, R. Wilby and L. Kaatz), *Decision-centric adaptation appraisal for water management across Colorado's Continental Divide*, which has been accepted with minor revision.

### Managing Drought in the Apalachicola-Chattahoochee-Flint (ACF) River Basin through the Development of Improved Drought Indicators and Policy Alternatives

This effort, sponsored by the NOAA SARP, is conducted in collaboration with Auburn University. It addresses a key problem in the ACF Basin, rapid expansion of irrigated agriculture in the Flint River Basin, which has contributed to the depletion of streamflows during drought episodes. Such low-flow conditions both imperil a set of endangered mussel species in South Georgia's streams and contribute to inter-state conflict with Florida over the flow of the Apalachicola River at the state line. Part of the RAL work focuses on developing decision models to explain the spatial dynamics of increasing irrigated acreage in the study region under current state law, and under possible new regulations. That work will contribute to the larger project's objective of building the capacity to simulate the spatially-explicit dynamics of groundwater/surface water interactions in the basin. In addition, RAL scientists are examining the within-season temporal dynamics of irrigation demand under varying weather conditions. The models will be used to evaluate the impacts of proposed drought-year water use regulations that might be imposed in response to current inter-state litigation. Results from this project are described in a journal article, co-authored by David Yates entitled, "The Effect of ENSO-Induced climate variability on groundwater levels in the Lower Apalachicola-Chattahoochee-Flint River Basins", *Transactions of the ASABE*, which has been accepted with minor revisions.

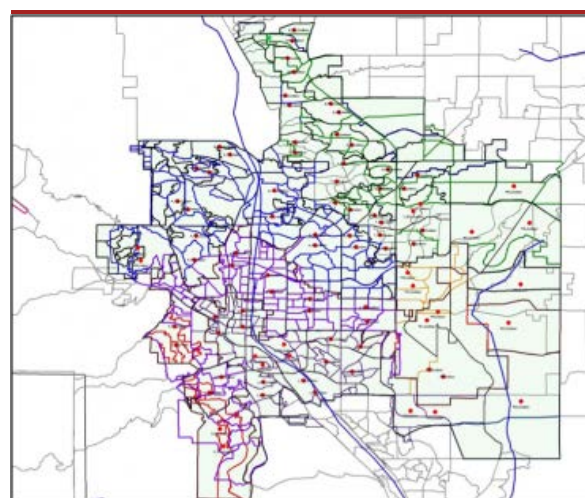


Fig. 2. The spatial extent of the Colorado Springs Utilities WEAP demand model (WEAPDemand).

### Water Utilities

RAL scientists Yates and Miller have collaborated with Colorado Springs Utilities (CSU), David Groves of the RAND Corporation, and Casey Brown at the University of Massachusetts in an ongoing Integrated Water Resource Planning (IWRP) planning process being undertaken by CSU. The IWRP seeks to develop a long-term strategic plan, to provide a reliable, sustainable water supply in a cost-effective manner. It is a holistic approach to water resource planning that incorporates water supply and demand analysis, water quality aspects, infrastructure reliability, environmental protection, water reuse, financial planning, energy use, regulatory and legal concerns, and public participation. In support of the IWRP, Yates has developed models of the CSU water supply and demand systems, including a 'West Slope' supply model (WsWEAP; Figure 1 above) and a detailed spatial-multiple regression model of indoor and outdoor, residential and commercial water demand for the city of Colorado Springs (CSUDemand; Figure 2). Both models are built on the Water Evaluation and Planning (WEAP) platform, with their novelty being that both explicitly consider climate variables in simulating the water supply and demand. Since they are both climatically driven models, they can directly explore the implications of climate variability and change on important water system reliability metrics that are being defined through CSU's IWRP process. Working with Casey Brown and his graduate students, Yates is helping define future climate projections, which are considered in both models. Figure 1 shows the geographic domain of the WsWEAP model, which is

the same model used in the work with Denver Water, while Figure 2 is a screen-capture of the CSUDemand model.

A major accomplishment from this work is the recently published report from the Water Research Foundation, co-authored by David Yates, *Developing Robust Strategies for Climate Change and Other Risks: A Water Utility Framework* [October 2014, Project #4262]

### **Pathways to Water Resilience in Da Nang City, Vietnam**

This goal of this work is to ensure that planning for future water resource needs for Da Nang City is resilient to potential climate change impacts. This work has involved assessment of current water availability and quality, evaluation of water access and consumption in the city, and water stresses affecting vulnerable population groups. Using this information, the P.I., Dr. David Yates has developed scenarios for future water supply and demand in the city using the Water Evaluation and Planning (WEAP) model developed by the Stockholm Environment Institute. Yates then trained a core technical group drawn from city government departments in setting up and using WEAP to simulate future water resource scenarios for Da Nang under plausible future development and climate conditions and to provide targeted input for a new Asian Development Bank-funded water supply project. The major accomplishment of this project has been the development of a useful water systems model for the evaluation of future water system planning by the City of Da Nang.

### **USAID: Be Secure, Philippines**

RAL is a project partner in the Water Security for Resilient Economic Growth and Stability (Be Secure) Project in support of USAID/Philippines. This effort seeks to support water security in selected sites in the Philippines by increasing sustainable access to water supply services and wastewater services, and increasing resilience to climate-related water stress and hydrologic extremes. In partnership with AECOM and local groups, RAL is providing the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA) with technical and training assistance to improve its ability to share, use and manage weather and climate and hydrometeorological data, forecasts, and future climate projections to improve analysis and data management capacity and enhance regional weather forecasting capabilities in the country.

This is a new project that began in the fall of 2014. A major accomplishment has been the execution of a one-week training on tropical cyclones in Manila in November 2014. PAGASA scientists will be visiting NCAR in the winter of 2015 to participate in the WRF training.

### **USAID: PARA-Agua, Latin America**

Climate change is negatively impacting water resources, agriculture and ecosystems in the Latin America and Caribbean (LAC) region. Increasing temperatures are altering hydrological cycles, affecting crop productivity and biodiversity, changing ocean currents, and causing more frequent and extreme weather events, leading to more intense flooding and drought. Andean glaciers and *páramos*, vital sources of fresh water for tens of millions of people, are under severe threat.

To meet these challenges, a new regional program has been launched by USAID entitled "Partnering for Adaptation and Resilience – Agua" (PARA-Agua) to work directly with scientists, decision-makers, and communities to strengthen watershed resilience to climate change impacts.

RAL contributes to this effort by developing climate information for pilot basin-scale applications. Regional climate data and projections from Global Climate Model results archived through the Inter-Governmental Panel on Climate Change Assessment Report-5 (IPCC-AR5) are being assembled to create a rich data set for use in the evaluation of potential adaptation actions at the watershed scale. Together, these data and data processing techniques will result in a collection of current and future climate projections that are un-biased, and suitable for use in hydrologic and water resources simulation models such as WEAP. Regional climate model results are being generated for the Northern Andes, with the datasets analyzed for their representativeness of the regional climate so that they may be adapted for use in other LAC sub-regions. In addition, RAL scientists are providing technical assistance in the use of the regional and global model scenarios and their associated data to populate WEAP models for future use by regional stakeholders.

A major accomplishment of this project is the development of a dataset that includes global bias corrected climate model output files from version 1 of NCAR's Community Earth System Model (CESM1) that participated in phase 5 of the Coupled Model Intercomparison Experiment (CMIP5), which supported the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5). The dataset contains all the variables needed for the initial and boundary conditions for simulations with the Weather Research and Forecasting model (WRF) or the Model for Prediction Across Scales (MPAS), provided in the Intermediate File Format specific to WRF and MPAS. The data are interpolated to 26 pressure levels and are provided in files at six hourly intervals. The variables have been bias corrected using the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA-Interim) fields for 1981-2005. Files are available for a 20th Century simulation (1951-2005) and three concomitant Representative Concentration Pathway (RCP) future scenarios

(RCP4.5, RCP4.5 and RCP8.5) spanning 2006-2100. An NCAR technote is being written that describes this dataset: “A description of DS316.0, Global 6-hourly Bias-corrected CMIP5 CESM Files in WRF/MPAS Intermediate Format” by A. Monaghan, D. Steinhoff, C. Bruyere, and D. Yates.

**Superstorm Sandy**

In 2013-14 RAL scientists examined the impact of Superstorm Sandy on the electrical power infrastructure in the northeastern U.S. This storm caused loss of electric service to over 90% of the Long Island Power Authority’s 1.1 million customers, and repair costs have approached \$1 billion. This case study brought together researchers and practitioners from the atmospheric and environmental sciences, risk analysis industry, and the electric power sector to explore ways to integrate their respective disciplines to consider how climate change science can be introduced as a design input for electric infrastructure analysis. Analysis focused on surface winds and their impact on storm surge, and on precipitation and associated flooding throughout the region after landfall. These objectives were achieved by simulating, in detail, Superstorm Sandy as it occurred and under future climate conditions, and then using modeling output to conduct hazard and impact analysis. Increased understanding and advanced computer simulation that integrates state-of-the-art weather, impact, and damage models will help in societal and economic analyses for improved storm hardening, enhancing preparedness and planning emergency responses. Results from this study were published in a special issue of the *IEEE Power and Energy* magazine devoted to climate change adaptation (Yates et al, 2014).

**Public Health Benefits of Green House Gas Mitigation: Abu Dhabi**

RAL is working with the Climate Change Research Group to assist the Environmental Agency of Abu Dhabi in developing a climate change research program to assess impacts, vulnerabilities and adaptation at the city, national (UAE), and regional (Arabian Gulf) scales. RAL scientists are conducting regional climate modeling studies aimed at determining how temperature, precipitation, winds, radiation and humidity are expected to change in the region due to increasing concentrations of greenhouse gases. Self-organizing map techniques are being used to identify weather systems that produce the poorest air quality in Abu Dhabi, allowing us to use a small number of highly representative inputs to the air quality model. These inputs, along with pollutant source emissions developed by CCRG, will be used to drive the Community Multi-scale Air Quality model in examining different time periods and emission scenarios. A database for meteorological conditions, source emissions and air quality attributes associated with GHG mitigation strategies is also being produced to ultimately estimate public health co-benefits from differing policy responses to changes in GHG. This project has just begun, but a workshop was held in Abu Dhabi in October 2014, where the methods of analysis were presented. The major accomplishment has been the deployment of air quality models at NCAR, and merging them.

**Regional Atmospheric Modeling under Climate Change for the Arabian Gulf**

This project with the CCRG is conducting a Regional Climate Modeling experiment with the goal of developing projections of regional climate for the Arabian Peninsula at fine spatial and temporal scale, that reflect the large-scale features and temporal trends from Global Climate Model (GCM) simulations (AR5), but also the historical patterns of climate variables at the regional and local scale. To achieve this, a regional climate model (RCM) was deployed that dynamically downscaled the climate of the Arabian Peninsula using GCM data for lateral boundary conditions. Improved topographic representation across the domain reflects the taller topographic features of the region, which potentially increases and re-distributes precipitation due to enhanced lifting. The taller topography also provides a cooler environment for precipitation over places like the Oman Mountains as compared to smoothed topography, which will not resolve warm season convection. The data can be used in support of the other climate change impact, vulnerability and adaptation assessments.

This Regional Atmospheric Modeling sub-project demonstrated the development of a novel, bias-corrected global climate model dataset, based on NCAR’s Community Climate Systems Model (CCSM4). The CCSM4 was one the IPCC AR5 global climate models, which was bias-corrected to be statistically similar to the European Centre for Medium-Range Weather Forecasting (ECMWF) Interim Reanalysis (ERA-Interim; Dee et al. 2011) dataset. The ERA-Interim is considered to be the most accurate atmospheric reanalysis available at the present time (e.g., Lorenz and Kunstmann 2010). The bias-corrected, CCSM4 dataset was then used as the boundary and initial conditions, for simulating the NCAR Weather Research Forecast (WRF) to dynamically downscale the climate of the 20<sup>th</sup> century and the future climate based on the RCP8.5 emission pathway. The WRF model was run at spatial resolutions of 36, 12, and 4-km that included a large portion of the Arabian Peninsula. The 12 and 36 KM domains were run for a longer period, 2006 to 2100, while the 4-km domain (D3) was run for two shorter, 10-year periods.



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WYOMING WEATHER MODIFICATION PROGRAMS

BACKGROUND

Since the completion of the Wyoming Weather Modification Pilot Project (WWMPP) in 2014, the Wyoming Water Development Commission (WWDC) has broadened its focus for cloud seeding research and operations to encompass additional mountain ranges in the State (see Figure 1). The WWMPP had focused on research in the Medicine Bow, Sierra Madre, and Wind River Ranges. Beginning in November 2014, the WWDC implemented an operational cloud seeding program in the Wind River Range under a contract with Weather Modification Inc. (WMI). NCAR was funded by the U.S. Bureau of Reclamation to do a modeling study in parallel with and to complement the Wind River Range program. In May 2014, the WWDC also funded a Phase II Feasibility Study in the Salt River/Wyoming Range of western Wyoming. This area had previously been examined in 2006 to assess the potential for cloud seeding to augment flow into the Green River Basin, and the Phase II study was commissioned in order to update the previous study using new data and modeling technologies developed during the WWMPP. In May 2015, the WWDC funded three new studies, two of which were awarded to NCAR. The two NCAR studies were a Final Design and Permitting study to design an operational cloud seeding program in the Medicine Bow and Sierra Madre Ranges, and a Feasibility Study to assess the potential for cloud seeding in the Big Horn Range in north central Wyoming. This report summarizes the key accomplishments during FY15 of the WWMPP and each of these four new studies led by NCAR (covering five mountain ranges, see Figure 1), as well as plans for the next year.

FY2015 ACCOMPLISHMENTS

Wyoming Weather Modification Pilot Project

The final results of the WWMPP were presented to the Wyoming legislature in early December 2014. The results from physical, modeling, and statistical studies were combined to provide an "accumulation of evidence" to develop the assessed seeding effect estimate (Figure 2). By far the largest impact on the estimated seeding effect from the statistical results was eliminating cases with low numbers of seeding generator hours. The WWMPP final report underwent a detailed review and was revised accordingly. A publication on the results of the cloud seeding evaluation will be submitted once the report has

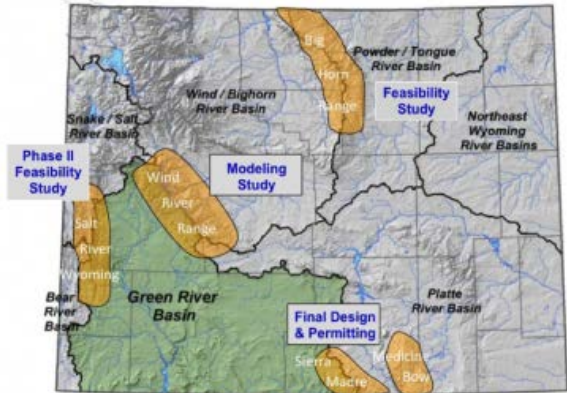


Figure 1. A map of Wyoming with coarse representation of topography and major river basins. Yellow areas denote the five mountain ranges under study related to winter orographic cloud seeding programs: Medicine Bow, Sierra Madre, Wind River, Salt River/Wyoming, and Big Horn Ranges.

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been accepted as final.

Wind River Range Modeling Study

In conjunction with a cloud seeding operational program in the Wind River Range led by the WWDC, the U.S. Bureau of Reclamation funded a cloud seeding modeling study led by NCAR/RAL. The purpose of this project was to utilize numerical cloud models to evaluate the cloud seeding potential and assist forecasters in identifying opportunities for cloud seeding over the Wind River Range. Three tasks were included in this project: 1) a climatological analysis that utilized 8-year high-resolution model output to evaluate the cloud seeding potential of storms in the Wind River Range, 2) real-time forecast modeling activities including adapting a real-time forecast model to identify cloud seeding opportunities over the region and simulate seeding in those cases, and 3) deployment of a microwave radiometer to assist with identifying cloud seeding opportunities and for use in model evaluation.

NCAR developed a climatology of supercooled liquid water (SLW) over the Wind River Range using an 8-year high-resolution modeling dataset produced by the Colorado Headwaters project (Rasmussen et al. 2014). The simulations were verified by comparison to existing SNOTEL gauges and sounding data. This analysis produced an estimate of the percent of time that seedable conditions are present in winter storms impacting the Wind River Range region. A highlight of this analysis was that it indicated airborne seeding would be possible outside of the November–April (winter) period (Figure 3), and therefore the frequency of seeding opportunities was also evaluated over the full year. The full year analysis was conditional on when snow occurred in the mountains, and indicated that airborne seeding year-round can provide on average 100 additional hours of opportunities to augment snowfall beyond the opportunities for seeding in the November–April period. This suggests the possibility to extend snowpack augmentation activities into the beginning of the runoff season.

The NCAR cloud seeding forecast system was adapted for the Wind River Range and incorporated into the Real-time Four Dimensional Data Assimilation (RT-FDDA) numerical forecasting system that ran for the WWMPP. Prior to this, the seeding module was run in a non-real-time system for Wyoming. The model was evaluated with available data, such as that from the radiometer, SNOTEL gauges, and atmospheric soundings launched by the operational cloud seeding program from Pinedale, Wyoming. After the cloud seeding forecast system was developed, it was retrospectively tested by running it for the domain surrounding the Wind River Range for the period of November 15, 2014 – April 15, 2015.

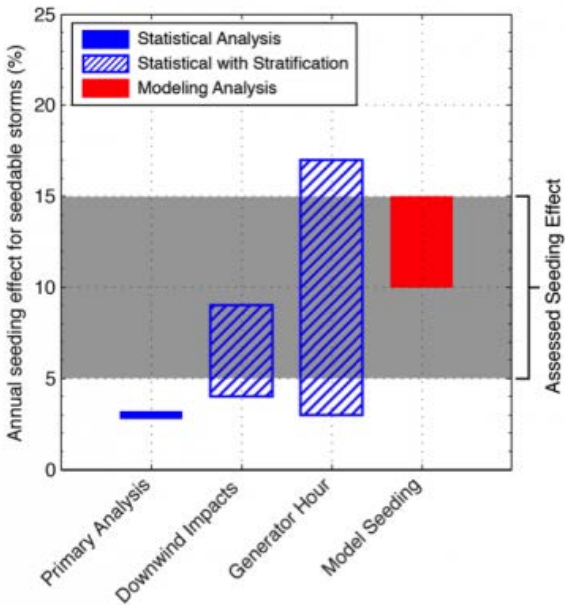


Figure 2. Estimation of seeding impacts on precipitation as determined by various analysis methods. Blue indicates results from the Randomized Statistical Experiment. The solid blue is the primary statistical result, while the hatched blue represent the range achieved through stratification of the statistical data. The red bar represents the range of model seeding results. The accumulation of evidence leads to the assessed seeding effect as indicated by the gray shading.

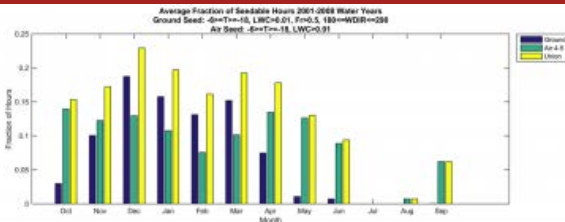


Figure 3. Ground (0–1 km AGL; blue) versus airborne (4–5 km MSL; green) seeding opportunities by month (fraction of hours in the month that meet the designated criteria, listed atop the figure, on average over the 8-year period). The frequency of occurrence of cases from the union of both ground and airborne seeding potential is shown in the yellow bar for each time period.

NCAR also deployed and operated a microwave radiometer near Boulder, Wyoming during the winter 2014-2015 and made the data from the radiometer available to Wind River Range cloud seeding program forecasters in near real-time via a website. The radiometer provided critical liquid water path (LWP) data for the operational cloud seeding program forecasters to call cases and served as verification data for the modeling efforts. NCAR also ran the RT-FDDA real-time forecast model (prior to the cloud seeding system adaptation) for the duration of the operational cloud seeding program to provide forecasters tailored, high-resolution forecasts.

Salt River/Wyoming Range Phase II Feasibility Study

A climatological study of the project area was conducted to determine the characteristics of wintertime precipitation in the Wyoming Range region and estimate how frequently environmental conditions would be amenable to seeding. The study utilized three years of observations recently collected in the region by IPC and results of an 8-year high-resolution model simulation over the region. The typical winds during winter storms impacting the Wyoming Range blow from the west to northwest and occasionally from the southwest. Easterly upslope events on the eastern slopes of the Wyoming Range were very rare, and/or did not produce much, if any, precipitation. Moreover, a spatial mapping analysis of the 8-year model output revealed that liquid water was rarely located over the eastern slopes of the Wyoming Range, and therefore the study concluded that the most feasible conditions for cloud seeding were on the western slopes of the Wyoming and Salt River Ranges. With the goal of targeting precipitation enhancements on the eastern slope of the Wyoming Range, the study then focused on a design that would seed storms that met seeding criteria along the western slopes of the Ranges, but that produced additional precipitation spilling over onto the eastern slope of the Wyoming Range. Airborne seeding potential at 3–4 km MSL had similar frequencies as ground seeding (Figure 4). A combined airborne and ground program could yield roughly 40% more seedable hours per season relative to a ground-based program alone, totaling 27% of the winter season being seedable (Figure 4).

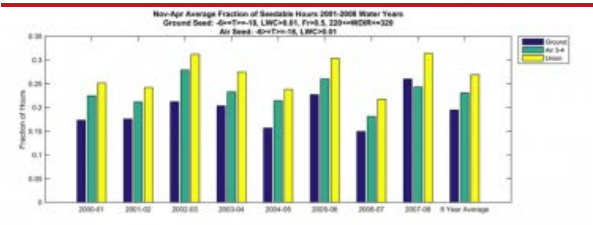


Figure 4. Ground (0–1 km AGL; blue) versus airborne (3–4 km MSL; green) seeding opportunities by Nov–Apr season (fraction of hours in the season that met the designated criteria, listed atop the figure), and the 8-year average. The frequency of occurrence of cases from the union of both ground and airborne seeding potential is shown in the yellow bar for each time period. A year-long Level II, Phase II Feasibility Study was completed to assess the feasibility of conducting an operational weather modification program aimed at increasing precipitation on the eastern slopes of the Wyoming Range in western Wyoming. This study followed a Level II (Phase I) Feasibility Study that was completed in 2006 by North American Weather Consultants (NAWC). The Phase I Feasibility Study focused on the potential for operational cloud seeding in the Salt River and Wyoming Ranges. Since then, Idaho Power Company (IPC) expanded their operational cloud seeding program into the region, particularly the western slope of the Salt River Range targeting the Snake River Basin. The WWDC funded the Level II, Phase II Feasibility Study in order to reexamine operational cloud seeding opportunities in the region, in light of the recent developments by IPC and with a renewed focus on targeting the eastern slopes of the Wyoming Range to enhance streamflow into the Green River Basin. NCAR/RAL led the Phase II study, with collaboration from NAWC and Sunrise Engineering. Sixteen tasks were identified by the WWDC for the study. Highlights from a few of these tasks are presented below.

Based on the results of the climatological analysis, a preliminary project design was developed via an iterative process in which the model was used to evaluate the effectiveness of the design. Specifically, each version of the design was evaluated using the Weather Research and Forecasting (WRF) model coupled with a cloud seeding parameterization that simulates the impact of cloud seeding on precipitation. A field survey consisting of visits to potential generator locations was carried out to assess the suitability of each site for seeding effectiveness, any access issues, and the impacts of land ownership. The design focused on ground-based seeding and an operational season of November through mid-April (e.g. 1 November – 15 April), utilizing silver iodide, or more specifically, a silver iodide-salt compound as the seeding agent. Given that IPC operates a network of remote-controlled ground generators west of the Salt River Range, the design was based upon this existing (or soon-to-be implemented) network.

Operational criteria for the program were developed and a preliminary cost/benefit analysis was also conducted. The draft results were presented at a public meeting and submitted to the WWDC in a written

report in July 2015.

**Medicine Bow/Sierra Madre Final Design and Permitting Study**

Given the results of the WWMPP, the WWDC decided to fund a study to develop a final design for operational cloud seeding in the Medicine Bow and Sierra Madre Ranges in southeast Wyoming. NCAR/RAL leads this program with collaboration from WMI and Heritage Environmental Consultants (HEC). This project began in June 2015 and so far initial public scoping meetings have been held. Additionally, field surveys of potential ground generator sites have been conducted and the initial climatology and model evaluation has begun. A major component of this project is to conduct the permitting activities for the ground generator sites on U.S. Forest Service land, which will be led by HEC. The results will be completed and submitted in a draft report in the fall of 2016.

**Big Horn Range Feasibility Study**

The WWDC also funded a new feasibility study to assess the potential for cloud seeding in the Big Horn Range in north central Wyoming. NCAR/RAL leads this program with collaboration from WMI and HEC. This project began in June 2015 and two initial public scoping meetings have been held since then. Additionally, a preliminary climatology has been conducted in order to site a microwave radiometer and high-resolution snow gauge in the region. These instruments will be deployed to the region in the fall of 2015. This study will be completed and submitted as a draft report in the summer of 2016.

**FY2016 PLANS**

- Submit revised, final report on the Salt River/Wyoming Range Phase II Feasibility Study
- Submit final report on the Wind River Range modeling study
- Deploy a radiometer and snow gauge in the Big Horn Range
- Complete the feasibility study for the Big Horn Range and submit a report on the findings
- Complete the Final Design and Permitting study for the Medicine Bow/Sierra Madre Ranges and submit a report on the findings

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## IDAHO POWER PROJECT

## BACKGROUND

The Idaho Power Company (IPC) conducts a winter cloud seeding program to augment snowfall along the Snake River Basin and its tributaries for hydro-electric generation. . The program has been focused in Payette River basin in western Idaho and the upper Snake River system in eastern Idaho (Figure 5), and has recently expanded into the Boise and Wood basins in western Idaho.

In FY15, RAL conducted a numerical modeling "Phase Four" study to provide real-time and retrospective model-based guidance on the effectiveness of cloud seeding using ground generators and aircraft tracks. The primary goal of Phase Four was to improve a real-time cloud seeding forecast guidance system using the Weather Research and Forecasting (WRF) model developed in Phase Three and continue research and improvements to the cloud seeding module utilized in Phases One and Two. A new goal of Phase Four was to also develop a real-time web-based display to provide IPC forecasters graphical output from the real-time forecast system.

## FY2015 ACCOMPLISHMENTS

In 2015, RAL provided real-time and retrospective model-based guidance on the effectiveness of cloud seeding using ground generators and aircraft tracks. Components of this effort included:

- refining the real-time cloud-seeding decision algorithm;
- collaboration with the University of Arizona (UofA) to incorporate the cloud-seeding module into the UofA real-time WRF model;
- running a research version of WRF on the UofA computing cluster that provided tailored precipitation and cloud-seeding forecasting relevant to the Idaho Power cloud-seeding operations during the 2014-2015 winter season;
- developing a prototype web-based display system for use in the 2014-2015 season;
- simulating cloud-seeding effects for 15 of the 20 cases that were seeded by Idaho Power during the winter season (hereafter, the retrospective cases); and,
- simulating test cases to investigate potential seeding in new target areas and to optimize current cloud-seeding operations.

The retrospective simulations for the 2014-2015 season were run in a "mini-ensemble" mode, using up to three different initialization data sets to drive the model (Figure 6). This resulted in a spread of simulated responses and helped quantify some of the uncertainty in the simulation results. The results

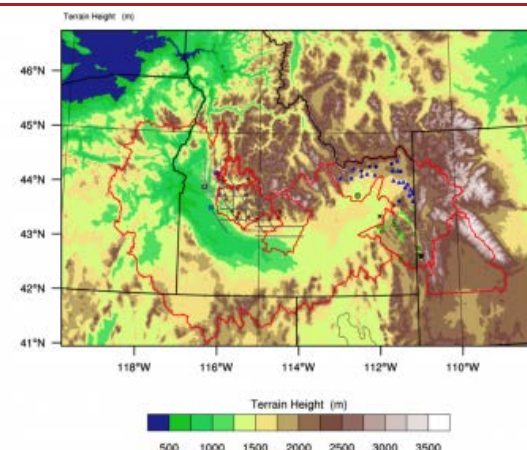


Figure 5. Map of the Snake Watershed in Idaho (large red outline) and existing ground generator and observational facility sites on a map of terrain height (m; color shading). The Payette River Basin, Boise Basin, and Woods Basin target areas are located (north to southeast) in the western Snake watershed, north of Boise and each is also outlined in red. The Upper Snake River Basin target area is located in Eastern Idaho, also outlined in red. Ground generator locations are identified as circle and triangle symbols, and color-coded as red-filled circles (Payette, Boise, Woods), blue (north Eastern Idaho), and green (south Eastern Idaho). The circles are Idaho Power owned generators, and the triangles are generators operated by Let it Snow. Grey lines indicate flight tracks used by the cloud seeding aircraft. Black squares indicate the location of microwave radiometers, black x's for atmospheric sounding sites, open blue and red circles are high-resolution snow gauge sites (located in the western Snake Basin).



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were compared against radiometer, sounding, and precipitation-gauge measurements. The latter is illustrated in Fig. 5, showing the precipitation increase in all three model initializations during the overall simulation period, with the precipitation accumulation in the seeding simulation accumulating more by the second half of the seeding window compared to the control simulation (especially for the RT-FDDA, blue, and NAM, green, initializations). In this example, the NAM captured the observed precipitation accumulation best.

Four modeling experiments were performed to investigate potential seeding in new target areas; to optimize current cloud-seeding operations; and to better understand the current operational design and/or simulated seeding effects produced by the model.

1) The first investigated possible expansion of ground-based seeding into a potential new target area of the Camus Prairie east of Boise. The study indicated only limited additional precipitation in the CP as a result of these new generators. However, there was potential for additional precipitation in the Boise and Woods Basins (BWB) from these new generators when the flow was from the southwest. Similar results were found for simulations of airborne seeding.

2) The second experiment evaluated the impact of seeding from manual versus remote-controlled ground-based generators. As part of this study, an analysis of the inversion characteristics in the area was also conducted using sounding data. When a low-level inversion was present, the dispersion of silver iodide (AgI) particles from manual generators was slightly weaker than those from remote generators. However, the plumes were still able to reach clouds and generate simulated seeding effects.

3) The third experiment investigated whether natural orographic clouds could be “over seeded” by artificial cloud seeding. This study utilized a newly developed bin microphysics scheme with the AgI cloud-seeding parameterization applied to an idealized orographic cloud-seeding situation. The results showed that simulated seeding always increased precipitation relative to natural clouds due to more efficient diffusional growth of the glaciated cloud, but that the effects did tend to “saturate” (or level off) when very large amounts of AgI were simulated to be released.

4) The fourth experiment utilized a Large Eddy Simulation (LES) on a large domain to investigate the simulated airborne seeding effects that extended downwind of the Payette target region. A test case was simulated with high-resolution (600 m) LES and with 1.8-km resolution non-LES, as well as test simulations comparing the number of vertical levels in the non-LES simulations. The results indicated that the AgI vertical dispersion and long-range transport were sensitive to grid spacing and turbulence treatments (i.e. non-LES versus LES). In the high-resolution LES simulation, a more active cloud field was produced compared to the non-LES simulation, leading to more AgI activation and scavenging by hydrometeors, and therefore less downwind transport of AgI.

An NSF proposal (that has been previously submitted in 2014) was revised and submitted to seek funding to conduct a field program called SNOWIE (Seeded and Natural Orographic Wintertime clouds: the Idaho Experiment). This effort involved collaboration with several universities (University of Illinois, University of Wyoming, and University of Colorado). If funded, the proposal aims to conduct the program in winter 2016-2017 and would evaluate ground and airborne cloud seeding using physical and numerical modeling approaches, as well as to validate the cloud seeding module.

Three publications from Phase Four efforts were submitted, two of which are peer-reviewed and currently undergoing revisions and the third was a meeting summary on a panel discussion at the AMS Conference on Planned and Inadvertent Weather Modification that will be in print in December 2015.

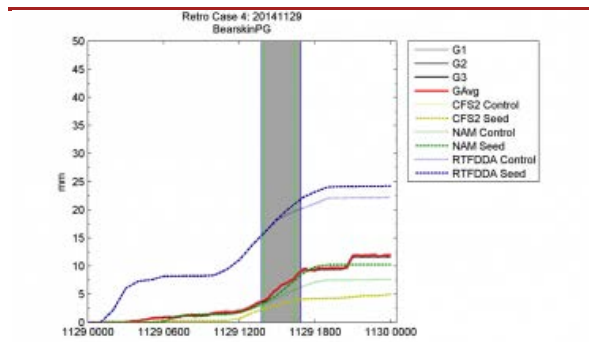


Figure 6. Time series of observed and simulated accumulated precipitation on 29 November 2014 at the Bearskin gauge site in the target area of the Payette basin. Each color represents a different model initialization (blue, green, yellow) and the red and black/grey lines are the observed gauge accumulations (mm). The thick dashed model line is the seeded simulation, while the thin dotted model line is the control simulation accumulation. The gray shading indicates the time when ground seeding was simulated, while the green vertical lines indicate the times when airborne seeding was conducted.

The goals of Phase Five are to complete the development of the real-time cloud seeding modeling system and the real-time web-based display to deliver the model forecast graphics. A new goal in Phase Five is to improve the dispersion of AgI in the model, which was identified as an issue to address based on the Phase Four modeling experiments. So far in 2015, the Phase Five effort has led to additional improvements and new capabilities in the real-time cloud seeding forecast system, as well as new features and integration of model and observational data in the web-based display. These new real-time model and display features will be demonstrated beginning 1 Nov 2015 for the 2015-2016 winter season.

**FY2016 PLANS**

- Run the newly updated seeding case-calling algorithm in real time for the 2015-2016 season.
- Complete the development of the web-based display system to display the real-time model graphics, along with IPC observations in real time
- Conduct retrospective simulations of seeded cases and for alternative seeding scenarios, such as investigating the potential seeding impact of current/planned seeding facilities on the Boise and Wood Basins or for aircraft in the Eastern Idaho region.
- Improve the dispersion of AgI in the model with detailed and high-resolution modeling studies.
- Publish journal papers on the major findings from these studies.

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# WMO SOLID PRECIPITATION INTER-COMPARISON EXPERIMENT (SPICE)

## BACKGROUND

### Evaluation of Solid Precipitation gauges at the Marshall Field site and numerical modeling as part of the WMO Solid Precipitation Inter-comparison Experiment (SPICE)

Precipitation is one of the most important atmospheric variables for ecosystem research, hydrological and weather forecasting and climate monitoring. Despite its importance, accurate measurements of precipitation remain a challenge. Measurement errors for solid precipitation, which are often ignored for automated systems, frequently range from 20% to 70% due to under-catch in windy conditions. While solid precipitation measurements have been the subject of many studies, there have been only a limited number of coordinated assessments on the accuracy, reliability, and repeatability of automatic precipitation measurements. The most recent comprehensive study, the “WMO Solid Precipitation Measurement Intercomparison” concluded in 1998 and focused on manual techniques of solid precipitation measurement.

### FY2015 Accomplishments

Precipitation gauge technology has advanced considerably in the last 12 years and the focus has shifted to automated techniques. The Marshall Field Site, located southwest of Boulder, Colorado, is a collaboration between NOAA, NCAR, NWS, and FAA to assess various solid precipitation measurement techniques. This site is being used to test new gauges and other solid precipitation measurement techniques in comparison to reference measurements made by a Double Fence

Intercomparison Reference gauge (DFIR) as part of the WMO Solid Precipitation Inter-Comparison Experiment (SPICE) program. Data has been collected at the Marshall site for the SPICE program during the past three winter seasons. SPICE also hosts 14 other data collection sites world-wide, and NCAR is archiving the data from all 15 sites and making it available to SPICE scientists for analysis.

FY2016 Plans

In FY2015 NCAR scientists are evaluating the performance of the instruments under testing relative to the DFIR at the Marshall Field Site, as well as conducting numerical model simulations. The use of a single Alter Shield snow gauge and unshielded snow gauge to establish a reference system is also being examined. Future activities include writing a final report on the SPICE program by September 2016.

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CLIMATE, WEATHER AND SOCIETY

*Promote societal welfare by conducting interdisciplinary research on the interactions between society and weather and climate in order to increase societal resilience to the associated risks and to support decision making.*

<ul style="list-style-type: none"><li>• Socio-ecological Systems in a Changing Climate: Governance and Adaptation</li><li>• Urban Futures</li><li>• Weather, Climate and Health</li><li>• Geographic Information System (GIS) Program</li><li>• Regional Climate Science</li></ul>		
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## SOCIO-ECOLOGICAL SYSTEMS IN A CHANGING CLIMATE: GOVERNANCE AND ADAPTATION

### 2015 ACCOMPLISHMENTS

In FY 2015 Kathleen Miller completed work on a book entitled: *Water Policy and Planning in a Variable and Changing Climate* (In press, CRC Press - Taylor and Francis Group). This is an edited volume that will serve as a comprehensive resource for both students and practitioners in fields related to water policy and environmental management in the Western United States. The 480 page volume includes 21 chapters written by highly-regarded experts on their respective topics. The book describes the physical, socioeconomic and institutional setting for water resource planning and policy development in the western United States. It explains the processes driving climate variability in the region as well the potential impacts of climate change on water availability, water quality and water-related hazards. It highlights the relevance of climate variability and change for addressing the major ongoing water policy challenges confronting western water planners and policy makers, and provides case studies that document both emerging challenges and creative approaches to planning for managing climate-related risks. Publication is scheduled for April 2016.

Other work focused on examining policy alternatives for reducing the impacts of Georgia’s groundwater and surface water extractions on drought-year flows in the Flint River. Such reductions may be required pending the outcome of a current complaint filed by the state of Florida in the U.S. Supreme Court. Dr. Miller is working with a team of researchers at Albany State University, GA and Auburn University, AL on methods for estimating the impacts of alternative drought-response policies on Georgia’s agricultural economy. In FY15, Dr. Miller collaborated with Dr. Mark Masters at Albany State University to identify techniques for estimating irrigation water demands by farms in the Flint River Basin. She supervised the work of a graduate student assistant to survey literature on irrigation water demand as function of production costs, crop prices and climate state. Certain data that would be useful for such an analysis are currently embargoed due to the ongoing litigation. The team is thus exploring approaches for overcoming the data limitations, including using experimental agricultural station data to estimate impacts of proposed irrigation restrictions on crop yields and farm-level economic returns. The project is primarily supported by the NOAA-SARP program, with NSF co-sponsorship of part of Dr. Miller’s time.

She also completed work with Dr. David Yates, RAL-HAP, Dr. Robert Wilby, Loughborough University, UK, and Larna Kaatz, Denver Water, on a paper published in the peer-reviewed journal: *Climate Risk Management*. The paper describes Denver’s Upper Colorado River Basin reservoirs and transbasin water diversions as conditioned by the existing legal definitions of their water rights, and the agreements and management protocols that govern storage operations and downstream water release obligations. A WEAP-based model was developed and applied under a range of plausible scenarios of future climate change and associated changes in watershed conditions to simulate the performance of the water management system with and without a specific drought mitigation policy, the Shoshone Call Relaxation Agreement, in place. It was found that while the policy would be beneficial in a warmer and drier future climate, its impact would be very small and would do little to offset the impacts of the scenario itself. That work dovetailed closely with work on a USDA-NSF-Water Sustainability and Climate project: “Snowpack and Ecosystem Dynamics: The Sustainability of Inter-basin Water Transfers under a Changing Climate.” For that project, Dr. Miller worked on documenting the history and current institutional arrangements governing the major transbasin water diversion projects in Colorado.

References

Miller, Kathleen A., Alan F. Hamlet, Douglas S. Kenney, and Kelly T. Redmond (Eds.), In Press. *Water Policy and Planning in a Variable and Changing Climate*. CRC Press - Taylor & Francis Group (Boca Raton, FL).

Yates, David N., Kathleen A. Miller, Robert L. Wilby and Lurna Kaatz, 2015. Decision-centric adaptation appraisal for water management across Colorado’s Continental Divide, *Climate Risk Management*.  
<http://dx.doi.org/10.1016/j.crm.2015.06.001>.

FY2016 PLANS

Dr. Miller is currently working on a chapter entitled “Extreme drought and California's water economy: Lessons for building resilience.” This will be included in a book edited by K N Ninan (Centre for Economics, Environment and Society, Bangalore, India) and Makoto Inoue (University of Tokyo, Japan). The book is entitled: *Building a Climate Resilient Economy and Society – Challenges and Opportunities*. It is to be published by Edward Elgar Press. This chapter describes the factors that have caused different groups of water users to face very different vulnerabilities to the extreme drought now gripping California. These factors include the state’s complex geography, the configuration of its water storage and delivery infrastructure, and its imperfectly-administered mixture of prior appropriation and riparian surface water rights coupled with limited regulation of groundwater withdrawals. The chapter highlights innovative water management strategies that have emerged over the course of the current drought and the lessons that California’s drought experience suggests for other areas that may face increasing drought risks in a warmer future climate.

Work will continue on the Georgia water policy and drought risk management project. In particular Dr. Miller will work with Dr. Mark Masters, Albany State University Georgia in supervising the work of the graduate student assistant on irrigation water demand modelling and policy-impact estimation. Research will continue to focus on the design of incentive systems for drought year water withdrawal reductions that are spatially-differentiated to best protect streamflows in the Flint River Basin while minimizing economic disruption.

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# URBAN FUTURES

## BACKGROUND

Urban areas play crucial roles in the arena of climate and environmental change, not only as key sources of carbon and other air pollutants, but also as hotspots of vulnerability to water scarcity, floods, heat waves, and other hazards that climate change is expected to aggravate. These roles create a unique opportunity for urban centers to prove their talents as sources of innovations, and laboratories for responses that help transition to more sustainable and more resilient pathways of urban development. The main goal of *Urban Futures* is to integrate different disciplinary domains within NCAR and with other national and international organizations to:

- Explore the dynamics of urbanization and urban systems that shape urban emissions, vulnerabilities and risks
- Investigate urban populations' and decision makers' capacity to respond to climatic and non-climatic hazards and stresses
- Research how particular cities attempt to meet the challenges of reducing emissions (sustainability) while improving their response capacity (resilience) to environmental impacts
- Build capacity to foster urban sustainability and resilience through educational, mentoring and outreach activities at the science-policy interface

## 2015 ACCOMPLISHMENTS

### Explore the dynamics of urbanization and urban systems that shape urban risk

Scholarship on the links between urbanization and vulnerability has focused mostly on the global and national distributions of the current and future exposure of urban areas to climate hazards. However, other dimensions of urban vulnerability, such as sensitivity and capacity, have been insufficiently explored. To address the gap, Paty and colleagues applied national level data to ten country groups sharing similar patterns of urbanization and socio-economic development to explore the associations between these country groups and selected indicators of exposure, sensitivity, coping capacity and adaptive capacity. They find that while country groups are at similar risks from exposure to hazards, countries with rapid urbanization and economic growth face greater challenges with respect to sensitivity and lack of capacity. For instance, country groups with rapid urban growth (which are mainly in Asia and Africa) have the highest levels of sensitivity and the lowest capacity levels. In fact, these countries show significantly higher sensitivity and lower capacity values than the groups with similar current income and urbanization levels, but less dynamic urban growth (notably groups seven and nine).

These correlative findings, however, should not lead one to conclude that rapid urbanization is a sufficient condition to cause high sensitivity and low capacity. A series of capacity-enhancing effects of urbanization exist, particularly among emerging economies and transition countries. Yet, in cases where rapid urbanization is not matched by inclusive economic growth and governance structures, the challenge of building response capacity can be overwhelming. Furthermore, urbanization may also offer opportunities for disaster risk reduction, and urban population density can be utilized for increasing the efficiency and effectiveness of emergency response programs, hydraulic infrastructure or risk-sensitive land use zoning. Conversely, slower urbanization processes can bring forth tremendous challenges for designing and financing efficient adaptation strategies, as observed mostly among ex-members or successor states of the Soviet Union and features

a high proportion of shrinking cities with decreasing densities.

Investigate capacity to respond to climatic and non-climatic hazards and stresses

Greenhouse gas emissions and climate risks in cities are not only local governmental concerns; they challenge a range of actors across sectors to create coalitions for climate governance in order to mitigate emissions and adapt to climate risks. Urban climate change governance occurs within a broader socio-economic and political context, with actors and institutions at a multitude of scales shaping the effectiveness of urban-scale interventions. These interventions may be particularly powerful if co-benefits with other development priorities are explored, creating urban systems (both built and institutional) that are able to withstand, adapt to, and recover from climate related hazards. Collaborative, equitable, and informed decision-making is needed in order to enable the transformative responses to climate change, as well as fundamental changes in energy and land use regimes, growth ethos, production and consumption, lifestyles and worldviews. Leadership, legal frameworks, public participation mechanisms, information sharing, and financial resources all work to shape the form and effectiveness of urban climate change governance.

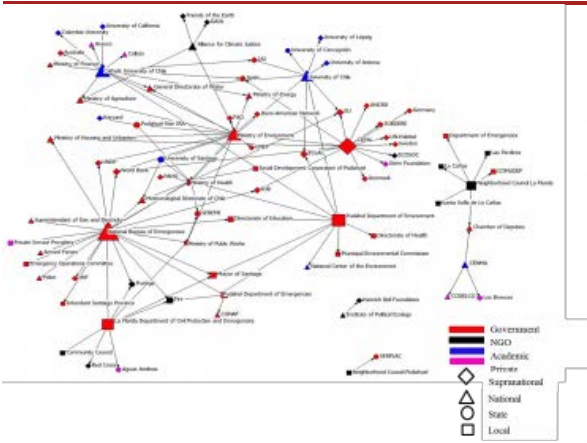


Figure 1: Santiago Chile actor network. Size of nodes is proportional to the number of ties. Note the peripheral not connected to the main network

While jurisdiction over many dimensions of climate change adaptation and mitigation resides at the national level, along with the relevant technical and financial capacities, comprehensive national climate change policy is often lacking. This is equally true in high-, middle-, and low-income countries. Despite this gap, municipal, state, and provincial governmental and non-governmental actors are taking action to address climate change.

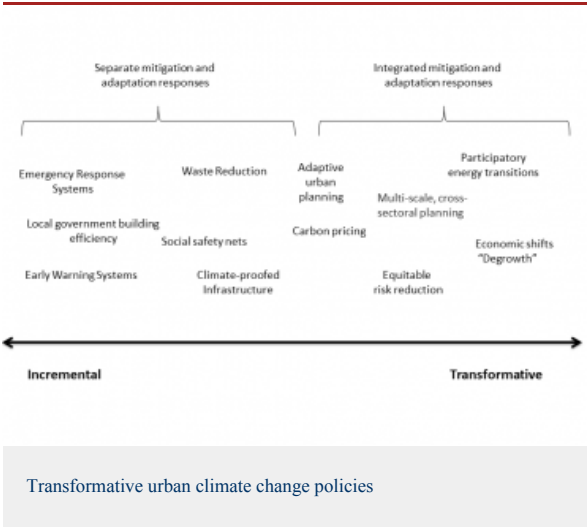
The Urban Futures team has conducted comparative studies and synthesis research dealing with urban governance as the set of formal and informal rules, rule-making systems, and actor-networks at all levels, both in and outside of government, established to steer cities towards mitigating and adapting to climate change. Since 2000, they have designed and applied a framework to examine the dimensions of the capacity to develop governance solutions for carbon and climate change in cities from Latin America, Asia and more recently the U.S. (including:

- a) The types of mitigation and adaptation policy actions;
- b) The actors and networks at multiple levels;
- c) The opportunities, barriers and limits that multi-level governance poses to effective local climate policy; and
- d) The factors explaining the gaps between the policy discourse and the reality of challenges to local climate action.

While climate change mitigation and adaptation have become a pressing issue for cities, governance challenges have led to policy responses that are incremental and fragmented (see Figure 1). Some cities are integrating mitigation and adaptation, but fewer are embarking on the more transformative strategies required to trigger a fundamental change towards sustainable and climate-resilient urban development pathways.

The drivers, dynamics, and consequences of climate change cut across jurisdictional boundaries and require collaborative governance across governmental and non-governmental sectors, actors, administrative boundaries, and jurisdictions. Although there is no single governance solution to climate change, longer planning timescales, coordination and participation among multiple actors, and flexible, adaptive governance arrangements may lead to more effective urban climate governance.

Urban climate change governance consists not only of decisions made by government actors, but also by non-governmental and civil society actors in the city. Participatory processes that engage these interests around a common aim hold the potential to create legitimate, effective response strategies.



Transformative urban climate change policies

Challenges to developing effective governance strategies contribute to a disconnect between the commitments made by cities to address climate change and the effectiveness of their responses. The results often lead to incremental and fragmented mitigation and adaptation responses. Governance capacity to respond to climate change varies widely within and between low- and high-income cities, creating different needs and opportunities.

The challenge of coordinating across the governmental and non-governmental sectors, jurisdictions and actors that is necessary for transformative urban climate change policies often leads to smaller scale, incremental actions controlled by local jurisdictions, or single institutions, or private and community actors (See Figure 2). While scientific information is necessary for effective urban climate change governance, it is not sufficient to trigger action on its own. Even when produced with policy outcomes in mind, scientific information often fails to meet the needs of urban decision-makers.

#### Relevant recent publications

Solecki, W., Seto, K. C., Balk, D., Bigio, A., Boone, C. G., Creutzig, F., ... & Zwickel, T. (2015). A conceptual framework for an urban areas typology to integrate climate change mitigation and adaptation. *Urban Climate*.

Qin, H., Romero-Lankao, P., Hardoy, J., & Rosas-Huerta, A. (2015). Household responses to climate-related hazards in four Latin American cities: A conceptual framework and exploratory analysis. *Urban Climate*.

Romero-Lankao, P., Hardoy, J., Hughes, S., Rosas-Huerta, A., Borquez, R., Gnatz, D., "Multilevel governance and institutional capacity for climate change responses in

Latin American cities"(2015) The Urban Climate Challenge Rethinking the Role of Cities in the Global Climate Regime, edited by Johnson, Toly and Schroeder,

Romero-Lankao, P., S. Hughes, et al. (2014). "Scale, urban risk and adaptation capacity in neighborhoods of Latin American cities." *Habitat International* 42(0): 224-235.

Romero-Lankao, P., and Gnatz, D., (2016) "Urbanization, Vulnerability and Risk", UGEC Handbook on Urbanization and Global Environmental Change, Seto, K., Solecki, W., Griffith, C., (Eds), pp.213-228 (in press).

Romero-Lankao, P., Burch, S., Hughes, S., Auty, K., Aylett, A., Krellenberg, K., Nakano, N., Simon, D., Ziervogel, G., Wejs, A., Governing Carbon and Climate in Cities, in Rosenzweig, C., Solecki, W., Romero-Lankao, P. Mehrotra, S., Dhakal, S., (Eds), *Cities and Climate Change, Second Assessment Report of the of the Urban Climate Change Research Network*, University of Cambridge (in press)

Rosenzweig, C., Solecki, W., Romero-Lankao, P. Mehrotra, S., Dhakal, S., 2015: "Introduction", in *Climate Change and Cities: Second Assessment Report of the of the Urban Climate Change Research Network*, Rosenzweig, C., et al., (Eds) University of Cambridge (in press).

Build capacity to foster urban sustainability and resilience

NCAR social scientist Paty Romero-Lankao served as a contributing author for the Intergovernmental Panel on Climate Change's Fifth Assessment Report. She contributed to the IPCC Working Group II's findings, reported in "Climate Change 2014: Impacts, Adaptation, and Vulnerability." This report focuses on the potential impacts of climate change and how society can adapt.

Romero-Lankao is a member of the Urban Climate Change Research Network (UCCRN) and co-editor of the Second Assessment Report on Climate Change and Cities published by University Cambridge to be launched at the COP in Paris in December 2015. Watch the UCCRN Video

For more info on outreach and capacity building see links to Videos and TV and radio interviews

1. <http://www.pbs.org/newshour/bb/closing-window-action-climate-change-offers-conse...>
2. <http://ucarconnect.ucar.edu/multimedia/videos/climate-change-social-perspective#...>
3. <http://www.kqed.org/a/forum/R201404010900>
4. "UCCRN: Preparing Local Leaders for Tomorrow" <http://t.co/i2FI1mPsSd>
5. Presentation IPCC-AR5 Report: Lessons Learned  
[http://video.ucar.edu/mms/ral/ipcc\\_wg\\_II\\_seminar.mp4](http://video.ucar.edu/mms/ral/ipcc_wg_II_seminar.mp4)
6. Interview on Climate Change Adaptation, channel 8, Boulder View <http://vimeo.com/97607385>
7. Interview on three boulder scientists don't let climate change get them down, CPR  
<http://www.cpr.org/news/story/three-boulder-scientists-dont-let-climate-...>



PLANS FOR 2016

In 2016 Romero-Lankao will conduct further research, outreach and education in the three areas described above both at the city and global level.

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# WEATHER, CLIMATE AND HEALTH

## BACKGROUND

There is widespread scientific consensus that the world's climate is changing and that there will be a broad range of impacts on health through a variety of factors, including greater heat stress, air pollution, respiratory disease exacerbation, and changes in the geographic distribution of vector-, food- and water-borne disease. The complexity of such influences requires a multi-disciplinary approach to address climate-related public health challenges. The overall goal of this work is to research the complex interactions among weather and climate processes, ecosystems, and human health in order to improve our knowledge of climate impacts on human health and the health of the planet. Through collaboration within RAL (Barlage, Delle Monache, Hopson, Steinhof, Wilhelmi), with other laboratories in NCAR (Morss, Demuth - MMM, Oleson - CGD, Wiedinmyer -- ACD), university partners (CSU, CU, KU, U of Veracruz, U of AZ), federal agencies (CDC, NASA, NIH, Environment Canada), and state and local agencies (AZ Department of Health Services, Maricopa County Health Department, Office of Border Health (AZ), Toronto Public Health (Canada), Monroe County Health Dept. (Key West, FL) and Houston Department of Health) the research has and will continue to focus on:

- Investigating the complex relationships among weather, climate, human health and ecosystems
- Researching population vulnerability to human health threats
- Focusing on solutions-oriented scalable research with appropriate adaptation and mitigation strategies to tackle critical health issues
- Educating the next generation of scientists in these complex, yet interconnected areas

## FY 2015 ACCOMPLISHMENTS

### Health Risks from Extreme Heat and Indoor Air Pollution

Changing climate is predicted to increase the intensity and impacts of heat waves prompting the need to develop preparedness and adaptation strategies that reduce societal vulnerability. Work was completed in FY 2014 on a NASA-funded project to develop a System for Integrated Modeling of Metropolitan heat Risk (SIMMER), but RAL scientists continued to address extreme heat issues in 2015. GIS-based maps are being launched that are tailored for both public health officials and the general public toward reducing vulnerability to extreme heat in Houston, TX. Several manuscripts addressing various aspects of the SIMMER project were submitted or published in peer-reviewed journals in FY15. One paper investigated how future climate and land use changes may impact heat exposure in Houston, finding that the impacts of land use change on future heat stress are on par with climate change, and that the number of high heat stress days may increase four-fold by 2050. Another study explores how climate and population changes may influence heat-related mortality in Houston, finding that population and demographic changes may be stronger drivers of future heat vulnerability than climate change. Recent funding from EPA will support a new investigation of the combined role of heat and indoor air pollution in increasing vulnerability among the elderly in Houston.

### Toward Malaria reduction

Dr. Mary Hayden and Dr. Kacey Ernst from the University of Arizona received funding from the Bill and Melinda Gates Foundation to determine avenues for empowering women to control the mosquito vectors of malaria in Indonesia and Kenya. Work is underway using a mixed methods approach including focus group discussions, key informant interviews and

household surveys to better understand ways to include more women in vector-control at a household, regional and national scale.

### 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.

RAL scientists continued to participate in a four-year NIH-funded project led by the University of Arizona. Efforts in the final year have focused on extending the collection of adult *Ae. aegypti* (the dengue virus vector mosquito) into cities south of Hermosillo where the burden of dengue is high. Modeling efforts will extend into these areas as well as continue along the original transect from Tucson, AZ to Hermosillo, Sonora, Mexico to determine transmission dynamics in the region. NCAR scientists plan participate in the submission of a follow-on proposal in Feb. 2015 to determine how the interactions among climate, *Ae. aegypti* survival, and the extrinsic incubation period influence the risk and transmission of dengue virus and a newly emerging virus in the western hemisphere, chikungunya virus, in an arid area at periphery of transmission in the southern US and northern MX. Additional research in 2015 was focused on the future range of *Ae. Aegypti* under climate change scenarios; a manuscript detailing this work is under review.

### Lyme Disease in the United States

NCAR is working with CDC to better understand the meteorological drivers of Lyme disease ecology. Dr. Andrew Monaghan led a research effort that employed global climate model projections to investigate the impacts of climate change on the annual onset of Lyme disease cases in the U.S. The resulting paper suggests that the Lyme disease season will become earlier in the future due to warmer winter and springtime temperatures in the U.S. (Fig. 1). This work was featured in a forthcoming report on climate change and health by the U.S. Global Change Research Program.

### CDC-NCAR Postdoctoral Fellowship

Two postdoctoral fellows will complete their second year of a two-year program in fall of 2015. The goal of this program is to train the next generation of researchers in a multidisciplinary setting so that they are qualified to address the challenges of integrating health and weather/climate data. Both postdocs had successful and productive tenures at NCAR/CDC. Micah Hahn made substantial progress (including the publication of a paper) toward the development of an early-warning system for West Nile Virus in the United States in collaboration with CDC's Division of Vector-Borne Diseases, where she has been hired upon completion of her postdoc. Katie Conlon submitted a paper investigating the impact of future changes in climate and land use on extreme heat exposure in Houston; she has collaborated with CDC's National Center for Environmental Health to help prepare cities and states for climate-related risks and has been hired by CDC upon completion of her postdoc.

### Community Outreach

- This year RAL hosted Cory Morin, a postdoc at the University of Arizona (currently at NASA), for a one-month visit. A model-based investigation conducted during the visit is now under review. It explores meteorological influences on dengue transmission in the AZ-Sonora, MX border region and addresses the question of why transmission only occurs in certain regions despite the ubiquitous presence of the dengue mosquito *Ae. aegypti*. RAL also hosted Kacey Ernst, an infectious disease epidemiologist from the University of Arizona, to work on proposal development and manuscripts.
- Monaghan worked with a high-school student from Nederland on her senior year capstone project, in which she ran a mosquito model for current and future climatic conditions to determine the potential impacts of climate change on the dengue vector *Ae. aegypti* in Mexico.
- Hayden has been an invited lecturer at multiple universities along the Front Range of Colorado as well as elsewhere in the U.S., Rotary International, ESPOL University in Guayaquil, Ecuador, and the NAS in Washington, DC.

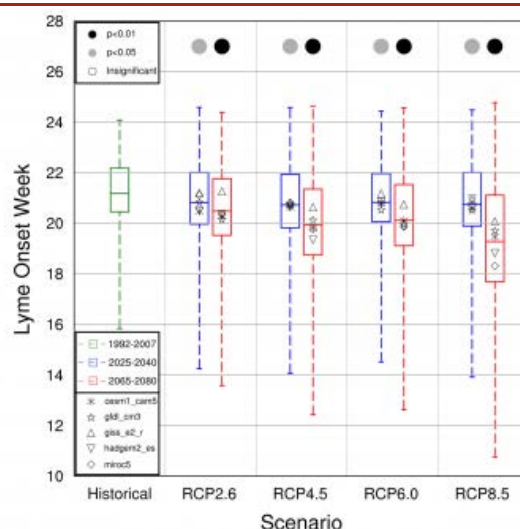


Figure 1. Box plots comparing the distributions of the national-level historical data for annual Lyme Onset Week (LOW) with the atmosphere-ocean global climate model (AOGCM) multi-model mean distributions of LOW for each of the four RCP scenarios and two future periods. Each box plot shows the values of LOW for the maximum (top of dashed line), 75th percentile (top of box), mean (line through middle of box), 25th percentile (bottom of box) and minimum (bottom of dashed line) of the distribution. All distributions are comprised of values for the 12 states where >90% of Lyme cases occur, and over 16 years (N=192). Circles along the top of each panel indicate whether the AOGCM multi-model mean is significantly different from the mean of the historical mean (see top legend). Box plot colors indicate different time periods (see middle legend). Black symbols on each box plot indicate the mean value of LOW from each individual AOGCM that contributes to the multi-model ensemble (see bottom legend).

- Hayden and CDC collaborator, Ben Beard, put considerable effort into planning and hosting a successful Climate and Health Workshop focused on vector-borne diseases in July 2015. Approximately 45 people attended the workshop including graduate students, postdocs, early career faculty and colleagues from academia and government.
- Hayden and Monaghan contributed as authors to a forthcoming report on climate change and health by the U.S. Global Change Research Program.

FY 2016 PLANS

Work will continue on the NIH-funded dengue project, on new CDC research efforts focused on Lyme disease and human plague, and on enhancing the role of women in malaria control funded by the BMGF. They also anticipate working with CDC on a project aimed at better understanding the ecology of monkeypox in the Democratic Republic of Congo. A major focus in FY 2016 will be to continue writing proposals to secure additional grants for further climate-and-health research. In addition to the NIH renewal proposal, Monaghan and Hayden are submitting multiple proposals to assess risk of dengue/chikungunya virus transmission that will augment their current dengue work. These include:

- a proposal to investigate community adoption of a novel intervention to control *Ae. aegypti* in the Florida Keys
- a proposal to use NASA soil moisture products to improve estimates of near-surface humidity and temperature in order to develop realistic simulations of the *Ae. aegypti* mosquito life cycle in an arid region along the US-MX border
- a proposal to investigate the role of travel in the emergence of dengue in the Galapagos Islands

Hayden and Monaghan will mentor a new NCAR/CDC postdoc slated to begin in December 2015; her research will focus on West Nile virus transmission and climate.

Publications

Five articles were published in peer-reviewed journals; one is in press; five have been accepted for publication; and six more have been submitted for publication.

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GEOGRAPHIC INFORMATION SYSTEM (GIS) PROGRAM

BACKGROUND

The Geographic Information System (GIS) program at the National Center for Atmospheric Research (NCAR) is an interdisciplinary effort to foster collaborative science, spatial data interoperability, and knowledge sharing using GIS. Working toward the definition, standards and interoperability of atmospheric information for usable science, the GIS program is: 1) conducting research integrating the Earth system and social sciences through spatial analysis and interoperability of georeferenced information; 2) supporting the use of GIS as both an analysis, and an infrastructure tool in atmospheric research; 3) improving usable science and knowledge sharing between science groups, educators and stakeholders; and 4) addressing broader issues of spatial data management, interoperability, and geoinformatics within the geosciences. Research progress in integration of geographic and atmospheric information allows GIS staff to lead and participate in a variety of research projects at NCAR, where spatial analysis and accurate georeferenced data are critical to answering complex interdisciplinary questions. With more than one hundred GIS users in all NCAR laboratories, the projects range from atmospheric chemistry to societal impacts of climate change to homeland security.

Current research activities in the GIS program occur in three thematic areas:

- Integrating physical and social science data in GIS
- Improving spatial accuracy and usability of atmospheric models for terrestrial and societal applications,
- Conducting GIS-focused educational activities at the science-society interface.

2014 ACCOMPLISHMENTS

Integrating physical and social science data in GIS

In 2014, the NASA-funded SIMMER project: System for Integrated Modeling of Metropolitan Extreme Heat Risk was successfully completed. The project addressed the critical need for information at regional to local scales that are pertinent to public health decision-making in the context of global change. Through the SIMMER project our research team advanced a methodology for assessing current and future urban vulnerability to extreme heat through integration of physical and social science models, research results, and NASA data, and developed tools for building local capacity for heat hazard mitigation and climate change adaptation in the public health sector. A series of publications highlight our research findings and new methods for integrating physical and social science data (see Publications). Several manuscripts are in preparation and will be submitted to peer-reviewed journals in 2015. SIMMER GIS tools illustrate the integration of diverse datasets and models into a platform for decision-making at various spatial scales. For example, our team developed the "Beat the Heat" online GIS tool for the

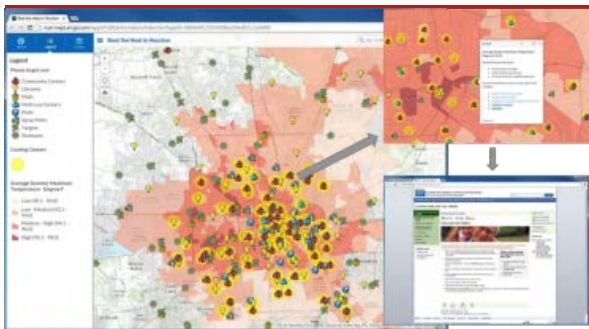


Figure 1. Beat the Heat online GIS tool provides information about average summer maximum temperature in Houston neighborhoods and guides the user to multiple strategies for staying safe and healthy in hot weather.



general public in Houston. (Figure 1).

### Publications

Hart, H., Gower S., Wilhelmi, O. and Yagouti A. 2013. Integrated Models For Heat-Health Decision Making: Linking Complex Science to Policy for Heat-Health Decision Making. SIMMER Workshop Report, Toronto (Canada), 40 pp. online at: <http://ral.ucar.edu/csap/events/heat-health-decision-making/>

Monaghan, A.J., Hu, L. N.A. Brunsell, M.P. Barlage, and O.V. Wilhelmi, 2014. Evaluating the impact of urban morphology configurations on the accuracy of urban canopy model temperature simulations with MODIS. *Journal of Geophysical Research: Atmospheres*, conditionally accepted.

Hu, L., N.A. Brunsell, A.J. Monaghan, M. Barlage, O. V. Wilhelmi, 2014. How can we use MODIS land surface temperature to validate long-term urban model simulations? *Journal of Geophysical Research: Atmospheres*, 119 (6): 3185–3201

Heaton, M.J., S. R. Sain, A. J. Monaghan, O.V. Wilhelmi, and M. H. Hayden, 2013. An Analysis of an Incomplete Marked Point Pattern of Heat-Related 911 Calls, *Journal of the American Statistical Association*, in review.

Heaton, M. J. , S. R. Sain, T. Greasby, C. K. Ueijo, M. H. Hayden, A. J. Monaghan, J. Boehnert, K. Sampson, D. Banerjee, V. Nepal, and O. V. Wilhelmi, 2014. Identifying vulnerability to heat-related mortality using a spatially-varying coefficient model, *Spatial and Spatio-temporal Epidemiology*, 8, 23-33.

In 2014, the GIS program contributed to an edited volume “Mapping and Modeling Weather and Climate with GIS” (Figure 2). This book is a result of a multi-year working dialog between Esri and the weather and climate research, educational and operational communities. The GIS program contributed to this community effort. Several chapters highlight examples from the GIS Program research projects and data interoperability experiments (see publications)

### Publications

Wilhelmi, O., K. Sampson, and J. Boehnert, 2015 Exploring Future Climates in a GIS, In: *Mapping and Modeling Weather/Climate with GIS* (Armstrong et al. Eds.), Esri Press, Redlands, California, in press.

Wilhelmi, O., K. Sampson, and J. Boehnert, J. and O. Wilhelmi, 2015. Meteorological data in a geodatabase, In: *Mapping and Modeling Weather/Climate with GIS* (Armstrong et al. Eds.), Esri Press, Redlands, California, in press.

Boehnert, J., A. Monaghan, and O. Wilhelmi, 2015. The Shape of Earth: Spatial Referencing in Weather and Climate Models, In: *Mapping and Modeling Weather/Climate with GIS* (Armstrong et al. Eds.), Esri Press, Redlands, California, in press.

### Improving spatial accuracy and usability of atmospheric models for terrestrial and societal applications

The NCAR GIS Program serves a large community of GIS users interested in global climate change. The GIS Climate Change Scenarios portal was the first internet gateway in which users are able to access global climate model data in GIS formats. This data portal provides access to global and downscaled data sets of climate change scenarios generated for the IPCC by the Community Earth System Model (CESM). Users can access climate change analysis products such as seasonal and annual averages, climate anomalies, and statistically downscaled climate change data for the continental United States. The model outputs can be downloaded and added to any GIS application, thus allowing for easy integration of climate projections with environmental and socio-economic datasets. The GIS Program released the Climate Inspector in 2014, which allows for the visualization of climate change in space and time through a web application. The app displays anomaly temperature and precipitation values from the IPCC AR5 runs of the NCAR CCSM4 model

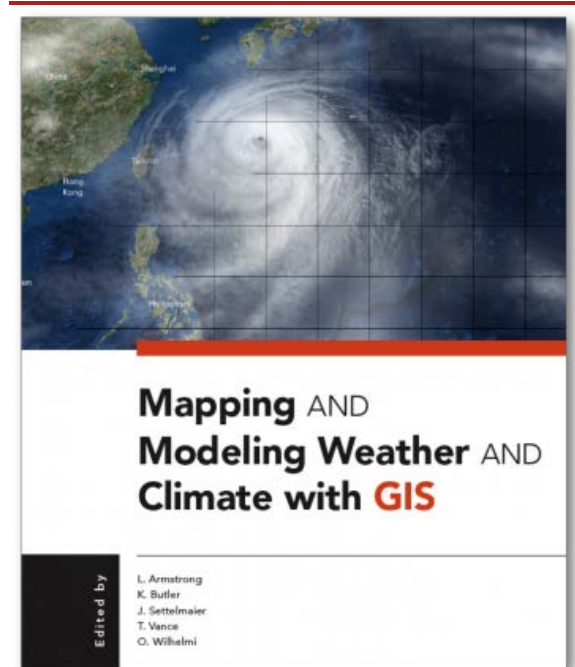
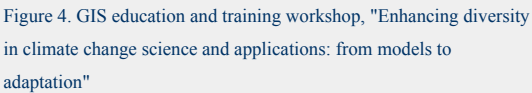


Figure 2. Book cover (draft) of the upcoming publication: Armstrong, L., K. Butler, J. Settelmaier, T. Vance and O. Wilhelmi, 2015. “Mapping and Modeling Weather/Climate with GIS”. Esri Press, Redlands, CA, in press.

Work will continue in the three focus areas described above. Progress will be made in developing research frameworks and spatial methods for integration of diverse, multidisciplinary datasets, which are both quantitative and qualitative and exist at different spatial and temporal scales. Ongoing, externally funded projects in this area of research are focused on extreme heat, air quality and human health, as well as on drought and water use, hurricanes and social vulnerability. Previously developed educational materials that link GIS, climate science and societal vulnerability and adaptation will be adjusted for a variety of training programs and workshops. A lab manual for meteorology departments on the use of GIS is currently in development.



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REGIONAL CLIMATE SCIENCE

BACKGROUND

The objective of the Regional Climate Science for Applications (RC4A) group is to generate, evaluate, translate and deliver sound climate science to decision makers to identify and address adaptation needs, to promote sustainability, and to reduce human system vulnerability to regional climate variability/change. The activities broadly fall into four categories: (1) Perform and advance climate data evaluation looking across time scales and integrating past, present and future, (2) make climate science usable, (3) explore climate scenarios for a more comprehensive view of impacts, vulnerabilities and adaptation, and finally (4) engage in translation and climate change capacity building.

FY2015 ACCOMPLISHMENTS

**Advanced Climate and Regional Model Validation for Societal Applications (funded by an Earth System Modeling [EaSM] grant from NSF)**

In collaboration with Iowa State University and Denver Water, the EaSM team at RAL develops novel methods to validate climate models. This project assesses the real world needs from climate model predictions and projections by testing the output for fidelity with regards to water sector needs to adequately inform decisions towards these needs. By developing informative diagnostics that are built on advanced tools originally designed for weather forecast verification, such a use-driven perspective of validation of models can also be directly incorporated into other EaSM projects and model development processes, and in particular the community-driven NCAR CESM effort. This project is conducted under the auspices of NCAR’s Community Earth System Model/Societal Dimensions Working Group, yet its products are more broadly applicable. Model output from sub-seasonal to seasonal or decadal forecasts can now be evaluated as readily as climate change projections. Thus the EaSM Advanced Climate and Regional Model Validation effort is forming one part of the research base for an increasing number of RAL activities.

With support from the EaSM project, MET/MODE tools (developed at RAL and in broad use across the weather forecast verification community) have been undergoing an expansion into the time-domain. MET/MODE version 5.1 was released in October 2015. The tools contain now the capability for a time-evolving perspective of weather sequences. These are now actively being applied to different climate problems ranging from seasonal phenomena, such as mountain snowpack, summer drought or Arctic sea ice, to interannual and longer climate anomalies, such as multi-year droughts for the US West, decadal variability in the Pacific, or variations in Atlantic overturning. This is a welcome expansion of the more static assessment of the traditional tools that compare two states. This approach is particularly useful since climate simulations cannot reproduce specific time sequences seen in observations but rather are supposed to generate similar statistics and spatio-temporal relationships. MODE-TD now helps EaSM leap into that new 3D perspective facilitating a more intuitive and quantitative, yet engaging



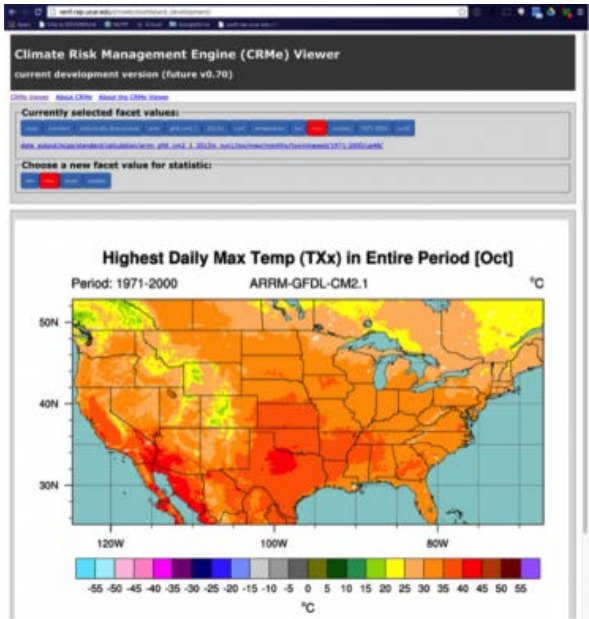


Figure 1: Interface for access to climate indices in downscaled climate model archives. Example of the CLIMDEX index TXx – highest daily maximum temperature – for the downscaled GFDL-CM2.1 model for the period 1971-2000 using the ARR-M (asynchronous regional regression model) downscaling method.

way of analysis useful for modelers and translation to users.

Direct interactions with planners at Denver Water headquarters led to a new exercise that is assessing why water managers currently don't use available seasonal forecasts in their streamflow estimates but rather use the climatology and its variability over the past 30 years as a guide when planning the upcoming melt season in the Colorado high country. RAL's EaSM team is determining the quality of these global-model-based forecasts to test if such forward looking information actually provides sufficient additional information that it would alter decisions in what is traditionally a rather risk-averse planning environment.

With supplemental funds from the NCAR Weather and Climate Impact Assessment Science Program led by L. Mearns (CISL-IMAGE), RAL scientists have been evaluating the spatio-temporal behavior of extreme convective activity as represented by the joint occurrence of high vertical convective potential energy (CAPE) and high wind shear over the lower half of the atmosphere, the key ingredients for tornadic development. A study of the field behavior conditioned on the presence of extreme conditions was based on reanalysis data. In a follow-up, the team is assessing the ability of regional climate models used in the North American Regional Climate Change Assessment Program to reproduce these observed spatio-temporal characteristics of severe convective weather events to determine the role of model resolution, the influence of boundary conditions derived from the driving models, and the robustness of changes between the present and projected future across the different model ensembles. This work is directly related to EaSM model validation as it focuses both on extreme conditions and takes into account spatio-temporal characteristics of a phenomenon with high societal impact.

Evaluation of Downscaled Climate Data

The final year of the National Climate Predictions and Projections (NCP) platform funded through the NOAA Climate Program Office, has advanced the access and delivery of a large set of downscaled climate data diagnostics. Led by the NCP core team consisting of PI R. Rood (Univ. of Michigan), J. Barsugli (NOAA/Univ. of Colorado-CIRES) as well as C. Ammann and G. Guentchev (NCAR), both statistically downscaled climate dataset for the US (BCCA from Maurer et al. 2004, 2007; and ARR-M from Stoner et al. 2012) and dynamically downscaled experiments from NARCCAP (Mearns et al. 2014) have been analyzed. Diagnostics focus not only on climatological means of the primary downscaled fields of temperature and precipitation, but on application-oriented indices with their ranges, extremes and sequencing. This work was done in close collaboration with public and private partners at the regional, national, and international levels to determine how well downscaled climate products can reproduce observations and thus how well-suited these commonly used products are for application and decision-making. NCP strives to ingest evaluation as a critical step into the data dissemination process through enriching raw climate data with diagnostics and extensive, standardized metadata.

Emerging Heat Threats in South Asia

In collaboration with ISET (Institute for Societal and Environmental Transition), a climate study was performed that focused on the emergence of heat threat to social and economic development in mid-sized cities in South Asia (i.e., India and Pakistan). The cities studied, located in the Ganges and Indus Valleys, are generally used to flooding as a potential environmental threat. But over recent years, the issue of excessively high temperatures during high humidity has risen. This project funded through a Rockefeller Foundation grant brought together physical and social scientists and local

stakeholders to quantify current and future heat threats to largely poor populations that rely on natural ventilation and ambient cooling. Looking at projections of future heat indices in these cities, the research demonstrated how focusing on physiological thresholds might bring a different perspective and impetus to the climate change problem than the analysis of temperature changes alone. Relentless heat that exceeds the physiological threshold for cooling of the human body over consecutive days, weeks and months, will form a threat in regions where no active cooling through air-conditioning is available.

USDA Climate Change Support

CSAP/RC4A assisted USDA’s Climate Change Program Office in carrying out assessments of the effects of climate change on U.S. Agriculture. This process included review, analysis, synthesis of current research in climate and agricultural science, providing scientific input, holding author meetings and providing logistical support for the now released USDA report: “*Climate Change, Global Food Security, and the U.S. Food System*” and working with the new USDA Climate Hubs for risk Adaptation and Mitigation to Climate Change. In addition, a workshop associated with this project titled: “Agriculture in a Changing Climate across Scales: Broadening Participation in Research and Decision-Making”, led by the CSAP/GIS group, provided an opportunity for the participants to embrace an interdisciplinary approach to these scientific and societal challenges by offering the variety of daily sessions focused on topics ranging from fundamental climate science to vulnerability of agroecosystems and farm communities. The workshop focused on topics of weather and climate-related impacts, vulnerability, and decision-making across spatial scales with an emphasis on the agricultural sector in the U.S. With the help of geospatial technologies (i.e., GIS and remote sensing) the participants learned how to integrate spatial information about weather, climate change, agriculture, and society in a meaningful and innovative way.

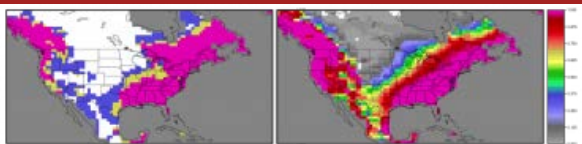


Figure 2: MODE analysis of winter precipitation frequency of more than 100mm over North America in years with positive El Niño conditions (NINO3.4 >1). Left panel shows that frequency for observations (CRU TS3.21), and the right panel for the CESM-1 35 member Large Ensemble collection.

FY 2016 PLANS

In 2016 the RC4A effort will further develop the tools necessary for an integrated climate risk management capability. This will require expanding climate datasets and collections into useful and usable ensembles that anticipate both non-scientist and specialist use of the information. Through application dashboards, climate information will be collected and visualized for different audiences. These dashboards will also serve as templates for work with the World Bank and the InterAmerican Development Bank to assist in climate change risk screening. In close collaboration with the USGCRP, the research done under EaSM and NCPP will be put to use in helping advance access to and use of National Climate Assessment data by the public and decision-makers. Using this perspective, further advances in the evaluation and validation of model data and model-based ensembles of data will be embedded in work-flow capabilities that improve efficiency and flexibility to work with different user groups. Aligning, and at times embedding, these tools within the NCAR CESM effort is expected to bring clear benefits to an increasing number of model developers, application scientists and users.



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