2016 NCAR ANNUAL REPORT

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40 Earths: NCAR's Large Ensemble reveals staggering climate variability ›

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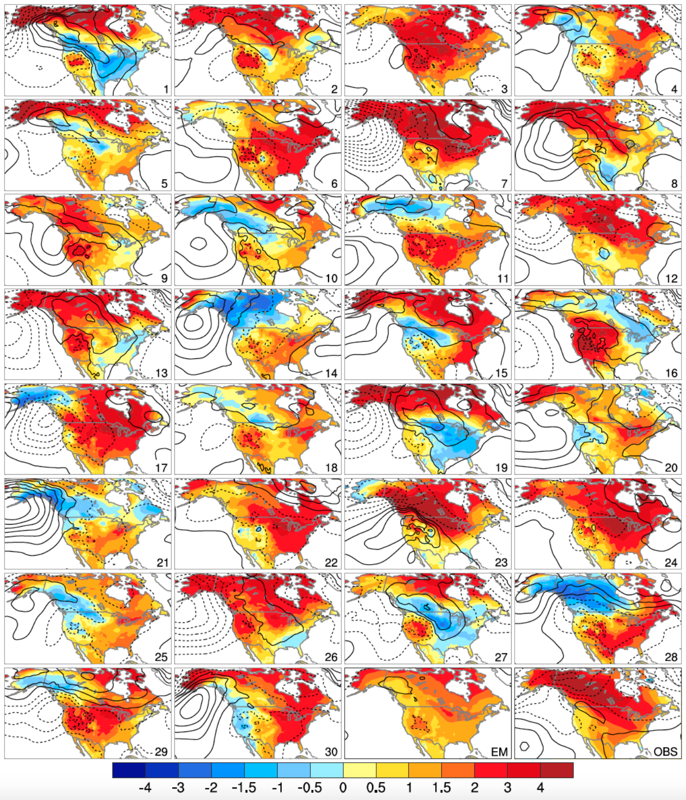
40 EARTHS: NCAR’S LARGE ENSEMBLE REVEALS STAGGERING CLIMATE VARIABILITY

Over the last century, Earth's climate has had its natural ups and downs. Against the backdrop of human-caused climate change, fluctuating atmosphere and ocean circulation patterns have caused the melting of Arctic sea ice to sometimes speed up and sometimes slow down, for example. And the back-and-forth formation of El Niño and La Niña events in the Pacific has caused some parts of the world to get wetter or drier while some parts get warmer or cooler, depending on the year.

But what if the sequence of variability that actually occurred over the last century was just one way that Earth's climate story could have plausibly unfolded? What if tiny — even imperceptible — changes in Earth's atmosphere had kicked off an entirely different sequence of naturally occurring climate events?



Winter temperature trends (in degrees Celsius) for North America between 1963 and 2012 for each of 30 members of the CESM Large Ensemble. The variations in warming and cooling in the 30 members illustrate the far-reaching effects of natural variability superimposed on human-induced climate change. The ensemble mean (EM; bottom, second image from right) averages out the natural variability, leaving only the warming trend attributed to human-caused climate change. The image at bottom right (OBS) shows actual observations from the same time period. By comparing the ensemble mean to the observations, the science team was able to parse how much of the warming over North America was due to natural variability and how much was due to human-caused climate change. Read the full study in the American Meteorological Society's Journal of Climate. (© 2016 AMS.)

"It's the proverbial butterfly effect," said Clara Deser, a senior climate scientist at the National Center for Atmospheric Research (NCAR). "Could a butterfly flapping its wings in Mexico set off these little motions in the atmosphere that cascade into large-scale changes to atmospheric circulation?"

To explore the possible impact of miniscule perturbations to the climate — and gain a fuller understanding of the range of climate variability that could occur — Deser and her colleague Jennifer Kay, an assistant professor at the University of Colorado Boulder and an NCAR visiting scientist, led a project to run the NCAR-based Community Earth System Model (CESM) 40 times from 1920 forward to 2100. With each simulation, the scientists modified the model's starting conditions ever so slightly by adjusting the global atmospheric temperature by less than one-trillionth of one degree, touching off a unique and chaotic chain of climate events.

The result, called the CESM Large Ensemble, is a staggering display of Earth climates that could have been along with a rich look at future climates that could potentially be.

"We gave the temperature in the atmosphere the tiniest tickle in the model — you could never measure it — and the resulting diversity of climate projections is astounding," Deser said. "It's been really eye-opening for people."

The dataset generated during the project, which is freely available, has already proven to be a tremendous resource for researchers across the globe who are interested in how natural climate variability and human-caused climate change interact. So far, more than 100 peer-reviewed scientific journal articles have used data from the CESM Large Ensemble.

A COMMUNITY EFFORT

Running a complex climate model like the CESM several dozen times takes a vast amount of computing resources, which makes such projects rare and difficult to pull off. With that in mind, Deser and Kay wanted to make sure that the data resulting from the Large Ensemble were as useful as possible. To do that, they queried scientists from across the community who might make use of the project results — oceanographers, geochemists, atmospheric scientists, biologists, socioeconomic researchers — about what they really wanted.

"It took a village to make this ensemble happen and for it to be useful to and usable by the broad climate community," Kay said. "The result is a large number of ensemble members, in a state-of-the-art climate model, with outputs asked for by

the community, that is publicly available and relatively easy to access — it's no wonder it's getting so much use."

Scientists have so far relied on the CESM Large Ensemble to study everything from oxygen levels in the ocean to potential geoengineering scenarios to possible changes in the frequency of moisture-laden atmospheric rivers making landfall. In fact, so many researchers have found the Large Ensemble so useful that Kay and Deser were honored with the 2016 CESM Distinguished Achievement Award, which recognizes significant contributions to the climate modeling community.

The award citation noted the pair was chosen because "the Large Ensemble represents one of NCAR's most significant contributions to the U.S. climate research community. ... At a scientific level, the utility of the Large Ensemble cannot be overstated."

THE POWER OF MULTIPLE RUNS: LOOKING FORWARD -- AND BACKWARD

Clearly, the CESM Large Ensemble is useful for looking forward: What is the range of possible futures we might expect in the face of a changing climate? How much warmer will summers become? When will summer Arctic sea ice disappear? How will climate change affect ocean life?

But the Large Ensemble is also an extremely valuable tool for understanding our past. This vast storehouse of data helps scientists evaluate observations and put them in context: How unusual is a particular heat wave? Is a recent change in rainfall patterns the result of global warming or could it be from solely natural causes?

With only a single model run, scientists are limited in what they can conclude when an observation doesn't match up with a model's projection. For example, if the Arctic sea ice extent were to expand, even though the model projected a decline, what would that mean? Is the physics underlying the model wrong? Or does the model incorrectly capture the natural variability? In other words, if you ran the model more times, with slightly different starting conditions, would one of the model runs correctly project the growth in sea ice?

The Large Ensemble helps answer that question. Armed with 40 different simulations, scientists can characterize the range of historic natural variability. With this information, they can determine if observations fit within the envelope of natural variability outlined in the model, instead of comparing them to a single run.

Creating an envelope of what can be considered natural also makes it possible to see when the signal of human-caused climate change has pushed an observation beyond the natural variability. The Large Ensemble can also clarify the climate change "signal" in the model. That's because averaging together the 40 ensemble members can effectively cancel out the natural variability — a La Niña in one model run might cancel out an El Niño in another, for example — leaving behind only changes due to climate change.

"This new ability to separate natural internal variability from externally driven trends is absolutely critical for moving forward our understanding of climate and climate change," said Galen McKinley, a professor of atmospheric and oceanic sciences at the University of Wisconsin–Madison.

McKinley used the Large Ensemble — which she called a "transformative tool" — to study changes in the ocean's ability to take up carbon dioxide in a warming climate.

THE TWO COMPONENTS OF THE CLIMATE SYSTEM

The CESM Large Ensemble is not the first ensemble of climate simulations, though it is perhaps the most comprehensive and widely used. Scientists have long understood that it makes sense to look at more than one model run. Frequently,

however, scientists have done this by comparing simulations from different climate models, collectively called a multi-model ensemble.

This method gives a feel for the diversity of possible outcomes, but it doesn't allow researchers to determine why two model simulations might differ: Is it because the models themselves represent the physics of the Earth system differently? Or is it because the models have different representations of the natural variability or different sensitivities to changing carbon dioxide concentrations?

The Large Ensemble helps resolve this dilemma. Because each member is run using the same model, the differences between runs can be attributed to differences in natural variability alone. The Large Ensemble also offers context for comparing simulations in a multi-model ensemble. If the simulations appear to disagree about what the future may look like—but they still fit within the envelope of natural variability characterized by the Large Ensemble—that could be a clue that the models do not actually disagree on the fundamentals. Instead, they may just be representing different sequences of natural variability.

This ability to put model results in context is important, not just for scientists but for policy makers, according to Noah Diffenbaugh, a climate scientist at Stanford University who has used the Large Ensemble in several studies, including one that looks at the contribution of climate change to the recent, severe California drought.

“It’s pretty common for real-world decision makers to look at the different simulations from different models, and throw up their hands and say, 'These models don't agree so I can't make decisions,'" he said. "In reality, it may not be that the models are disagreeing. Instead, we may be seeing the actual uncertainty of the climate system. There is some amount of natural uncertainty that we can't reduce — that information is really important for making robust decisions, and the Large Ensemble is giving us a window that we haven’t had before.”

Deser agrees that it's important to communicate to the public that, in the climate system, there will always be this "irreducible" uncertainty.

"We’re always going to have these two components to the climate system: human-induced changes and natural variability. You always have to take both into account," Deser said. "In the future, it will all depend on how the human-induced component is either offset — or augmented — by the sequence of natural variability that unfolds."

ABOUT THE ARTICLE

Title: The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability

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‹ 2016 NCAR Annual Report up NCAR gets a powerful new supercomputer ›

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NCAR GETS A POWERFUL NEW SUPERCOMPUTER

In September, the National Center for Atmospheric Research (NCAR) installed its next supercomputer for advancing atmospheric and Earth science. The new machine will help scientists lay the groundwork for improved predictions of a range of phenomena, from hour-by-hour risks associated with thunderstorm outbreaks to the timing of the 11-year solar cycle and its potential impacts on GPS and other sensitive technologies.

The new system, named Cheyenne, was installed at the NCAR-Wyoming Supercomputing Center (NWSC) and will begin running Advanced Scientific Discovery projects, proposed by NCAR researchers and university partners, in early 2017.

Cheyenne was built by Silicon Graphics International Corp. (SGI) in conjunction with centralized file system and data storage components provided by DataDirect Networks (DDN). The SGI high-performance computer is a 5.34-petaflop system, meaning it can carry out 5.34

In September, staff from SGI and NCAR worked to install Cheyenne at the NCAR-Wyoming Supercomputing Center. (©UCAR. Photos by Carlye Calvin. This image is freely available for media & nonprofit use.)

quadrillion calculations per second. It is capable of more than three times the amount of scientific computing performed by Yellowstone, the NCAR's previous supercomputer.

Funded by the National Science Foundation and the state of Wyoming through an appropriation to the University of Wyoming, Cheyenne will be a critical tool for researchers across the country studying climate change, severe weather, geomagnetic storms, seismic activity, air quality, wildfires, and other important geoscience topics. Since the supercomputing facility in Wyoming opened its doors in 2012, more than 2,200 scientists from more than 300 universities and federal labs have used its resources.

"We're excited to bring more supercomputing power to the scientific community," said Anke Kamrath, interim director of NCAR's Computational and Information Systems Laboratory. "Whether it's the threat of solar storms or a heightened risk in certain severe weather events, this new system will help lead to improved predictions and strengthen society's resilience to potential disasters."

"Researchers at the University of Wyoming will make great use of the new system as they continue their work into better understanding such areas as the surface and subsurface flows of water and other liquids, cloud processes, and the design of wind energy plants," said William Gern, vice president of research and economic development at the University of Wyoming. "UW's relationship with NCAR through the NWSC has greatly strengthened our scientific computing and data-centric research. It's helping us introduce the next generation of scientists and engineers to these endeavors."

The NWSC is located in Cheyenne, and the name of the new system was chosen to honor the support that it has received from the people of that city. It also commemorates the upcoming 150th anniversary of the city, which was founded in 1867 and named for the American Indian Cheyenne nation.

INCREASED POWER, GREATER EFFICIENCY

The new data storage system for Cheyenne is integrated with NCAR's existing GLADE file system. The DDN storage will provide an initial capacity of 20 petabytes, expandable to 40 petabytes with the addition of extra drives. This, combined with the current 16 petabytes of GLADE, totals 36 petabytes of high-speed storage. The new DDN system can also transfer data at the rate of 200 gigabytes per second, which is more than twice as fast as the old file system's rate of 90 gigabytes per second.

The system includes powerful Intel Xeon processors, whose performance is augmented through optimization work that has been done by NCAR and the University of Colorado Boulder. NCAR and the university performed this work through their participation in the Intel Parallel Computing Centers program.

Even with its increased power, Cheyenne is three times more energy efficient (in floating point operations per second, or flops, per watt) than Yellowstone, its predecessor, which is itself highly efficient.

“The new system will have a peak computation rate of over 3 billion calculations per second for every watt of power consumed," said NCAR’s Irfan Elahi, project manager of Cheyenne and section manager for high-end supercomputing services.

MORE DETAILED PREDICTIONS

High-performance computers such as Cheyenne allow researchers to run increasingly detailed models that simulate complex processes and how they might unfold in the future. These predictions give resource managers and policy experts valuable information for planning ahead and mitigating risk.

Some of the areas in which Cheyenne is expected to accelerate research include the following:

Streamflow. Year-ahead predictions of streamflows and associated reservoir levels at a greater level of detail will provide water managers, farmers, and other decision makers with vital information about likely water availability and the potential for drought or flood impacts.

Severe weather. By conducting multiple simultaneous runs (or ensembles) of high-resolution forecast models, scientists will lay the groundwork for more specific predictions of severe weather events, such as the probability that a cluster of intense thunderstorms with the risk of hail or flooding will strike a county at a particular hour.

Solar energy. Specialized models of solar irradiance and cloud cover will be run more frequently and at higher resolution, producing research that will help utilities predict how much energy will be generated by major solar arrays hours to days in advance.

Regional climate change. Scientists will conduct multiple simulations with detailed climate models, predicting how particular regions around the world will experience changing patterns of precipitation and temperature, along with potential impacts from sea level rise, streamflow, and runoff.

Decadal prediction. Ensembles of detailed climate models will also help scientists predict the likelihood of certain climate patterns over a 10-year period, such as the risk of drought for a certain region or changes in Arctic sea ice extent.

Air quality. Scientists will be able to simulate the movement and evolution of air pollutants in far more detail, thereby better understanding the potential health effects of particular types of emissions and working toward improved forecasts of air quality.

Subsurface flows. More accurate and detailed models will enable researchers to better simulate the subsurface flows of water, oil, and gas, leading to a greater understanding of these resources.

Solar storms. Innovative, three-dimensional models of the Sun will lay the groundwork for predictions of the timing and strength of the Sun’s 11-year cycle as well as for days-ahead forecasts of solar disturbances that can generate geomagnetic storms in Earth’s upper atmosphere.

"Supercomputing is vital to NCAR’s scientific research and applications, giving us a virtual laboratory in which we run experiments that would otherwise be impractical or impossible to do,” said NCAR Director James Hurrell. “Cheyenne will be a key component of the research infrastructure of the United States through its provision of supercomputing specifically tailored for the atmospheric, geospace, and related sciences. The capabilities of this new system will be central to the continued improvement of our ability to understand and predict changes in weather, climate, air quality, and space

weather, as well as their impacts on people, ecosystems, and society."

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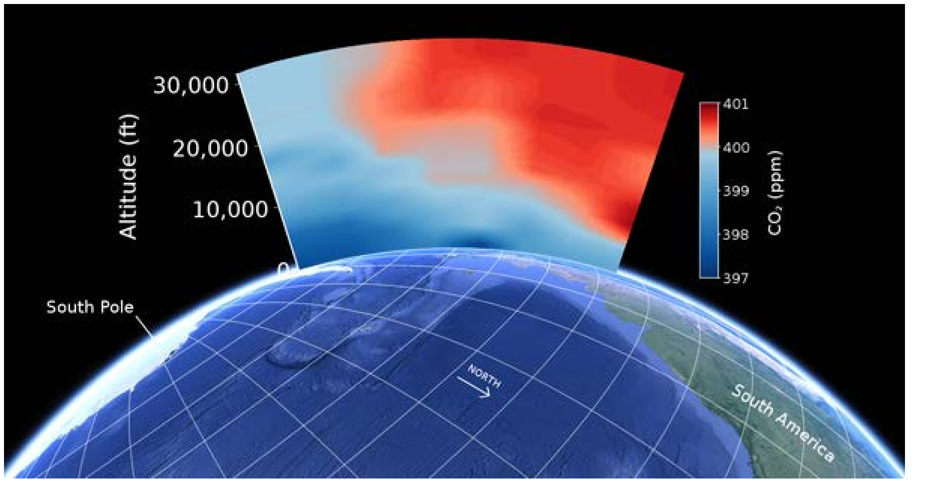
FLYING LAB INVESTIGATED SOUTHERN OCEAN’S APPETITE FOR CARBON

In early 2016, a team of scientists flew 19 research flights over the remote Southern Ocean in an effort to better understand just how much carbon dioxide the icy waters are able to lock away.

The ORCAS field campaign — led by the National Center for Atmospheric Research (NCAR) — gave scientists a rare look at how oxygen and carbon dioxide are exchanged between the air and the seas surrounding Antarctica. The data they collected will help illuminate the role the Southern Ocean plays in soaking up excess carbon dioxide emitted into the atmosphere by humans.

If we want to better predict the temperature in 50 years, we have to know how much carbon dioxide the oceans and terrestrial ecosystems are going to take up," said NCAR scientist Britton Stephens, co-lead principal investigator for



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This illustration, based on data collected during the ORCAS field campaign, shows the atmosphere near Antarctica in January 2016, just as air masses over the Southern Ocean began to exceed 400 parts per million of CO2. The 400 ppm level is regarded as a milestone by climate scientists, as the last time concentrations of the heat-trapping gas reached such a point was millions of years ago, when temperatures and sea levels were far higher. (Illustration by Eric Morgan, Scripps Institution of Oceanography.)

ORCAS. "Understanding the Southern Ocean's role is important because ocean circulation there provides a major opportunity for the exchange of carbon between the atmosphere and the vast reservoir of the deep ocean."

ORCAS was funded by the National Science Foundation’s Division of Polar Programs.

"Building on decades of U.S. Antarctic Program research, new questions of global significance continue to emerge," said Peter Milne, program director of Ocean and Atmospheric Sciences in the Division of Polar Programs. "ORCAS addresses one of those questions: how the Southern Ocean affects global climate by storing, or releasing, carbon dioxide, water vapor, and heat.”

Carbon dioxide, the main greenhouse gas contributing to human-caused climate change, is continually transferred back and forth between the atmosphere, plants on land, and the oceans. As more carbon dioxide has been released into the atmosphere by the burning of fossil fuels, oceans have stepped up the amount they absorb. But it's unclear whether oceans have the ability to keep pace with continued emissions.

In the Southern Ocean, studies have disagreed about whether the ocean's ability to act as a carbon sink by taking up carbon dioxide is speeding up or slowing down. Measurements and air samples collected by ORCAS — which stands for the O2/N2 Ratio and CO2 Airborne Southern Ocean Study — will give scientists critical data to help clarify what's actually happening in the remote and difficult-to-study region.

TRACKING CARBON BY AIR

The ORCAS field campaign operated out of Punta Arenas, near the southern tip of Chile. The researchers flew the NSF/NCAR HIAPER research aircraft for 98 hours across parts of the Southern Ocean between Jan. 15 and Feb. 28. A suite of instruments on the modified Gulfstream V measured the distribution of oxygen and carbon dioxide as well as other gases produced by marine microorganisms, plus aerosol and cloud characteristics in the atmosphere.

The flights also observed the ocean color — which can indicate how much and what type of phytoplankton is growing in the water — using NASA's Portable Remote Imaging Spectrometer (PRISM). The addition of the PRISM instrument to the ORCAS campaign was funded by NASA.

The science campaign was led by Stephens and NCAR scientist Matthew Long. Other principal investigators include Elliot Atlas (University of Miami), Michelle Gierach (NASA's Jet Propulsion Laboratory), Ralph Keeling (Scripps Institution of Oceanography), Eric Kort (University of Michigan), and Colm Sweeney (Cooperative Institute for Research in Environmental Sciences).

CIRES is a partnership of the National Oceanic and Atmospheric Administration and the University of Colorado Boulder.

The management of the field campaign was handled by NCAR. Logistics included everything from obtaining diplomatic clearances from multiple countries to fly through their airspaces to providing housing and workspace for project scientists in South America.

CARBON, OXYGEN, AND PHYTOPLANKTON

Measuring oxygen alongside carbon dioxide can give scientists a clearer picture of the ocean processes affecting carbon dioxide than they would get from measuring carbon dioxide alone.

"The air-sea exchange of carbon dioxide is controlled not just by physics but also by biology," Long said. "There's a nice relationship between the fluxes of oxygen and the fluxes of carbon dioxide that can be exploited to gain insight into these processes."

Carbon dioxide in the ocean is drawn into a chain of chemical reactions that buffer the impact of biological and physical ocean processes on carbon dioxide in the overlying atmosphere. Oxygen air-sea fluxes, however, are more directly tied to these same biological and physical factors. So if scientists know what's going on with oxygen, they can better understand the processes affecting carbon dioxide as well.

Additionally, if scientists know how the concentrations of the two gases change relative to one another with location and time, they can disentangle how biology and physics separately affect the ocean's ability to absorb carbon dioxide.

Physics and biology affect the ratio of carbon dioxide to oxygen in the air in different ways. In the austral spring the warmth of the returning Sun drives both carbon dioxide and oxygen out of the Southern Ocean surface and into the atmosphere. But the sunlight also triggers the growth of phytoplankton in the water. As the organisms begin to flourish, they take in carbon dioxide and release oxygen, causing the relative amounts of those two gases in the atmosphere to shift in opposite directions. Observations of these shifts can ultimately tell scientists how much carbon is going where and, more importantly, why.

A WINDOW INTO THE DEEP OCEAN

The Southern Ocean is unique among Earth's oceans. Unimpeded by continental landmasses, and driven by a westerly wind, the Southern Ocean is able to form a circular current around Antarctica. This huge flow, the largest current on the planet, connects the adjacent Atlantic, Pacific, and Indian oceans. The complex interactions between this Antarctic Circumpolar Current and currents flowing in from other ocean basins creates an overturning circulation that brings deep water to the surface where it can exchange gases with the atmosphere before it is returned to depth.

Once it dives toward the ocean floor, that surface water — and any carbon dioxide it takes with it — can stay sequestered in the deep ocean for hundreds or even thousands of years. Data collected by the ORCAS flights will help determine how much carbon dioxide goes along for the ride.

"The Southern Ocean provides a window into the deep ocean, but it's a difficult system to simulate in our Earth system models," Long said. "It's remote, and so there has been a paucity of observations that can be used to improve the models we have."

The data generated during the field campaign will be used by the ORCAS team to improve these global computer models so they do a better job representing the complexities of the Southern Ocean. The data set, which is managed by NCAR, is publicly available.

The NSF’s Division of Polar Programs manages the U.S. Antarctic Program, through which it funds researchers, coordinates all U.S. government research on the southernmost continent, and provides logistical support needed to make the science possible.

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Laura Snider, Senior Science Writer and Public Information Officer

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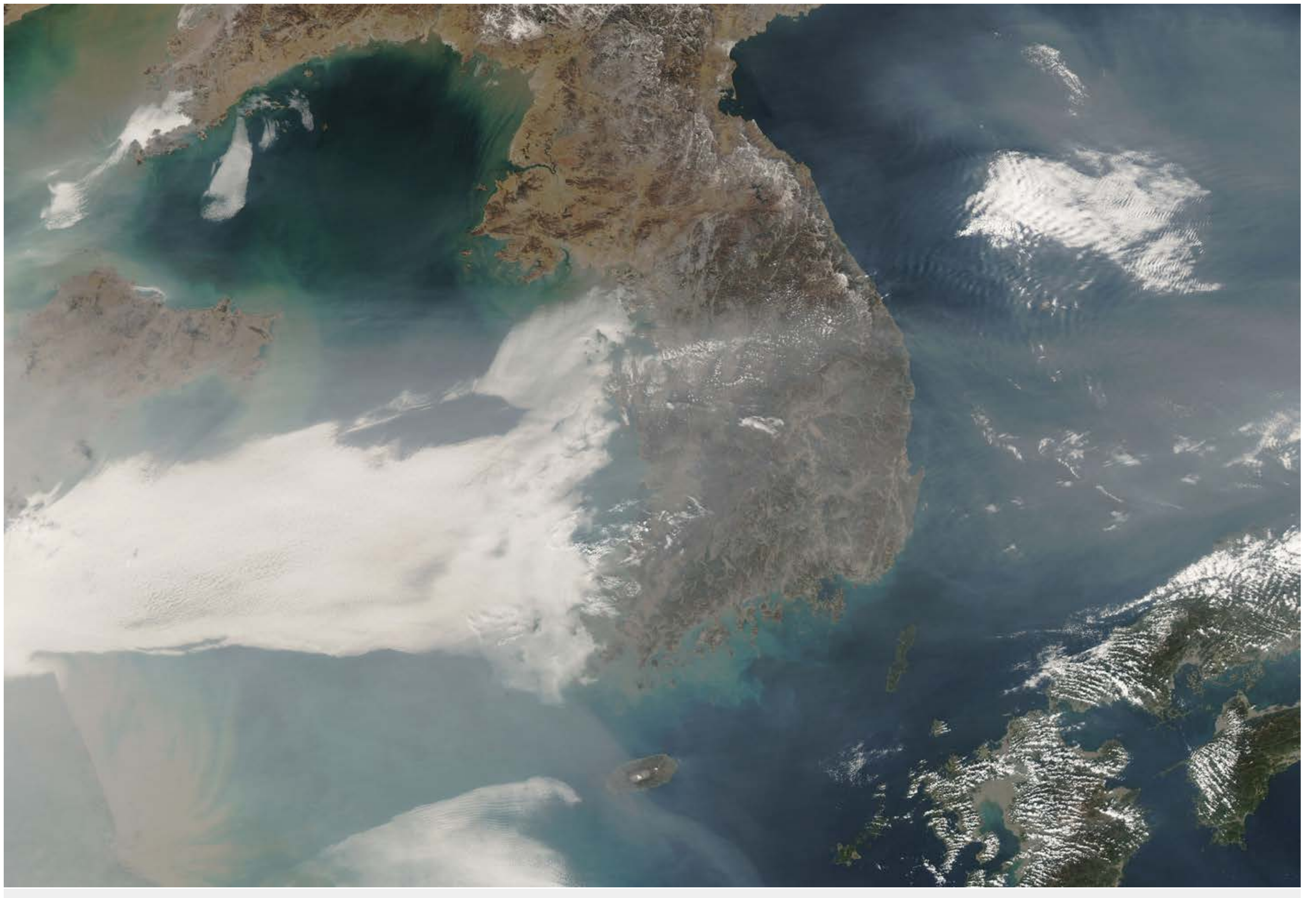
PLANES, SHIPS, AND SATELLITES: INVESTIGATING AIR QUALITY IN KOREA

Scientists from the National Center for Atmospheric Research traveled to South Korea last spring as part of a field campaign to investigate the region's air quality.

Between May 1 and June 12, NCAR scientists and their colleagues from NASA, U.S. and South Korean universities, and South Korea’s National Institute of Environmental Research



This 2007 NASA satellite image shows a swath of air pollution sweeping east across the Korean peninsula to Japan. (Image courtesy NASA.)

(NIER) collected observations from airborne labs, ships, satellites, and ground-based instruments. The campaign, which involved more than 580 researchers from 72 institutions, was called KORUS-AQ (Korea U.S.-Air Quality study).

"These observations will help us develop a much better understanding of the various complex factors controlling air quality over the Korean Peninsula," said NCAR scientist Louisa Emmons. "The observations will help improve air quality models, and in turn, those models will help us interpret the current, as well as future, observations."

South Korea offers a rare opportunity to separate the diverse factors that contribute to air quality. For example, Seoul, the capital of South Korea, is one of the world's five most-populated metropolitan areas, but it is surrounded by rural, forested land. This stark separation gives scientists the ability to differentiate the components of pollution that originate from factories, tailpipes, and other human-related sources of pollution from those that originate from natural areas, including volatile organic compounds emitted by vegetation.

Because the Korean Peninsula is largely isolated by bodies of water, scientists can also more easily determine what kinds of pollution blow into the region — dust and industrial pollution from China, for example — as well as what kinds of pollution blow out of the region toward Japan.

NCAR scientists contributed to the effort in several ways. A team led by Emmons issued chemical forecasts of pollution transport and formation so that the scientists taking airborne measurements can decide where, or whether, to fly. The planes used during KORUS-AQ included a NASA DC-8, a NASA King Air, and a Korean King Air operated by Hanseo University and NIER.

Two NCAR research groups from the Atmospheric Chemistry Observations and Modeling lab also flew instruments onboard the DC-8, which made 20 flights during the campaign. One team, led by NCAR scientist Sam Hall, measured the amount of

light available to break down compounds in the atmosphere. The second, led by NCAR scientist Andy Weinheimer, measured ozone and nitrogen oxides in the atmosphere. In combination with other instruments on the aircraft, these helped to characterize the photochemical history, processes, and evolution of air pollution along the flight path.

WRITER/CONTACT:

Laura Snider, Senior Science Writer and Public Information Officer

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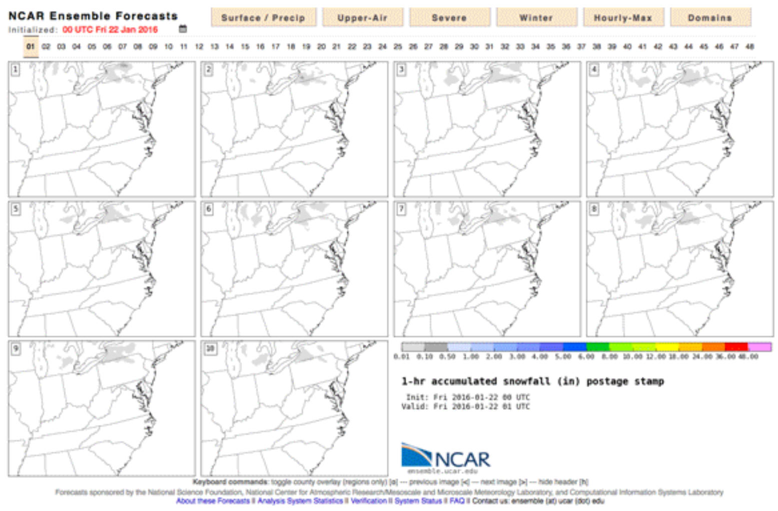
NCAR WEATHER ENSEMBLE OFFERS GLIMPSE AT FORECASTING’S FUTURE

NCAR WEATHER ENSEMBLE OFFERS GLIMPSE AT FORECASTING’S FUTURE

In the spring of 2015, scientists at the National Center for Atmospheric Research (NCAR) flipped the switch on a first-of-its-kind weather forecasting system. Since then, NCAR's high-resolution, real-time ensemble forecasting system has been ingesting 50,000 to 70,000 observations every six hours and creating a whopping 90,000 weather maps each day.

The system has become a favorite among professional forecasters and casual weather wonks: Typically more than 200 people check out the site each day with more than a thousand coming during major weather events.

During this experimental period, the NCAR ensemble has also become a popular source of guidance within the National Weather



This animation shows the forecast for accumulated snowfall made by each of the NCAR ensemble's 10 members for the 48-hour period beginning on Jan. 22, 2016. In the run-up to the blizzard, which ultimately dropped more than 30 inches of snow on parts of the Mid-Atlantic, more than 1,000 people visited the NCAR ensemble's website. (©UCAR. This animation is freely available for media & nonprofit use.)

Service, where it has already been referenced several hundred times by forecasters at more than 50 different offices.

But perhaps more important, the data accumulated from running the system daily — and there is lots of it — is being used by researchers at universities across the country to study a range of topics, from predicting hail size to anticipating power outages for utilities.

"We wanted to demonstrate that a real-time system of this scale was feasible," said NCAR scientist Craig Schwartz. "But it's also a research project that can help the community learn more about the predictability of different kinds of weather events."

Schwartz is a member of the team that designed and operates the system, along with NCAR colleagues Glen Romine, Ryan Sobash, and Kate Fossell.

TESTING A UNIQUE TOOL

NCAR's high-resolution ensemble forecasting system is unique in the country for a couple of reasons, both of which are revealed in its name: It's an ensemble, and it's high resolution.

Instead of producing a single forecast, the system produces an "ensemble" of 10 forecasts, each with slightly different (but equally likely) starting conditions. The degree to which the forecasts look the same or different tells scientists something about the probability that a weather event, like rain, hail, or wind, will actually occur.

By comparing the actual outcomes to the forecasted probabilities, scientists can study the predictability of particular weather events under different circumstances.

The forecasting system's high resolution (the grid points are just 3 kilometers apart) allows it to simulate small-scale weather phenomena, like the creation of individual storms from convection — the process of moist, warm air rising and then condensing into clouds.

The combination of fine grid spacing and ensemble predictions in the NCAR system offers a sneak peek at what the future of weather forecasting might look like, and weather researchers across the country have noticed.

Cliff Mass, a professor of atmospheric sciences at the University of Washington whose specialty is forecasting, said: "It's extremely important for the United States to have a convection-allowing ensemble system to push our forecasting capabilities forward. We were delighted that NCAR demonstrated that this could be done."

‘THE CAT’S MEOW’

The treasure trove of accruing weather data generated by running the NCAR ensemble is already being used by researchers both at NCAR and in the broader community. Jim Steenburgh, for instance, is a researcher at the University of Utah who is using the system to understand the predictability of mountain snowstorms.

"NCAR's ensemble not only permits the 'formation' of clouds, it can also capture the topography of the western United States," he said. "The mountains control the weather to some degree, so you need to be able to resolve the mountains' effects on precipitation."

Steenburgh has also been using the ensemble with his students. "We’re teaching the next generation of weather forecasters," he said. "In the future, these high-resolution ensemble forecasts will be the tools they need to use, and this gives them early, hands-on experience."

Like Steenburgh, Lance Bosart, an atmospheric researcher at the University of Albany, State University of New York, has used the ensemble both in his own research — studying the variability of convective events — and with his students. He said having 10 members in the ensemble forecast helps students easily see the great spread of possibilities, and the visual emphasis of the user interface makes it easy for students to absorb the information.

"What makes it an invaluable tool is the graphical display," he said. "It's visually compelling. You don't have to take a lot of time to explain what you're looking at; you can get right into explaining the science. I like to say it's the cat's meow."

SETTING AN EXAMPLE

The NCAR ensemble is also enabling the researchers running it to further their own research.

"We're collecting statistics on the misfit between the model predictions and observations and then we're trying to use that to improve our model physics," Romine said.

The ensemble project is also teaching the team about the strengths and weaknesses of the way they've chosen to kick off, or "initialize," each of the ensemble members.

"The NCAR ensemble happens to produce a pretty good forecast, but we realize there are some shortcomings," Schwartz said. "For example, if we were trying to make the best forecast in the world, we would probably not be initializing the model the way we are. But then we wouldn’t learn as much from a research perspective."

The NCAR ensemble began as a yearlong trial, but the project is continuing to run for now, and the research team plans to keep it up and running through June 2017.

WRITER/CONTACT:

Laura Snider, Senior Science Writer and Public Information Officer

‹ Planes, ships, and satellites: Investigating air quality in Korea | up | Working in UNEION together ›

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WORKING IN UNEION TOGETHER

The UNEION (UCAR|NCAR Equity and Inclusion) training series has been such a success that the NCAR Office for Diversity, Education & Outreach plans to run a third session in the spring. The program has also spun off a UNEION Journal Club, which meets once a month, as well as an online forum where UNEION graduates can discuss diversity and inclusion issues.

“The sessions have gone so well—it was brilliant how much the cohorts participated, shared, and learned,” said Carolyn Brinkworth, Director of NCAR Diversity, Education and Outreach. “The feedback from the courses has been wonderful, and they said it best: Our scientific excellence depends on the equal participation and inclusion of all of us, with everyone empowered to bring our unique viewpoints to our work. This course really empowers participants to fully support our whole community, including our students and visitors.”

The UNEION initiative was designed to help staff learn and talk about diversity, equity, and inclusion in a safe and interactive learning

The first UNEION cohort during one of its regular meetings.
Front row (from left): Silvia Agnona (CISL), Marissa Miller (DEO), Cheryl Harrison (CGD), and Helen Moshak (NCAR Directorate).
Back row (from left): Rebecca Morss (MMM), Esther Brady (CGD), Justin Young (Unidata), Mike Daniels (EOL), Geoff Cheeseman (NCAR Directorate), Diane Thompson (CGD), David Sundvall (General Counsel), and Carolyn Brinkworth (DEO). (Photo by Rebecca Swisher, ©UCAR.)

environment. The inaugural session — completed by 18 staff members in the spring of 2015 — was comprised of four intensive training sessions on topics spanning bias and privilege, race, gender, and how to create a workplace environment where everyone can thrive.

UNEION is a grassroots program organized by staff in collaboration with the NCAR Office for Diversity, Education and Outreach (DEO). Early on, Josh Young (Unidata), Mike Daniels (EOL), and Diane Thompson (CGD) approached Carolyn Brinkworth (DEO) to brainstorm about how to create and support a community to talk about diversity, and UNEION was born. Young, Daniels, and Thompson led the sessions for the first cohort, with support from Brinkworth and Marissa Miller (DEO).

Cohort members read articles and listen to podcasts and video clips before each session. In the sessions, they engage in a mix of group exercises and discussions designed to bring out the themes of the readings and relate them to our work and science community as a whole. One member said she really enjoyed the opportunity to share stories, experiences, struggles, and successes together. Another member said, "UNEION increased my overall knowledge on the issues surrounding diversity, equity, and inclusion and increased my awareness of the concept of privilege."

Another community member explained, "Educating ourselves about bias and how it affects our organization should be considered part of our mission at NCAR|UCAR and is the key for increasing and sustaining diversity. This is especially true for an organization that focuses on societal effects of climate. Building diversity will only increase the effectiveness of our scientific and outreach efforts as an organization."

The first two UNEION sessions were so successful, the group is considering a UNEION-Level 2 series in the future.

WRITER/CONTACT:

Jeff Smith, Science Writer and Public Information Officer

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3D-PRINTED WEATHER STATIONS FILL GAPS IN DEVELOPING WORLD

Scientists have successfully installed the first wave of low-cost weather stations that are designed to provide critically needed information to farmers and other residents in developing countries.

The stations are built largely with 3D-printed parts that can be easily replaced if they wear out in the field. They were created by weather experts at the National Center for Atmospheric Research (NCAR) and its managing entity, the University Corporation for Atmospheric Research (UCAR).

The first five stations were installed in Zambia last summer, and additional stations were installed at four schools in Kenya this fall. The stations can transmit information about temperature, rainfall, winds, and other weather parameters. These measurements and the resulting forecasts can provide weather information for local subsistence farmers deciding when to plant and fertilize crops. They can also alert communities about floods and other potential disasters.

NCAR scientist Paul Kucera at a weather station newly installed in Kenya. (Image courtesy Kristin Wegner.)

"It's a major opportunity to provide weather information that farmers have never had before," said NCAR scientist Paul Kucera, one of the project leaders. "This can literally make the difference when it comes to being able to feed their families."

The project is funded by the U.S. Agency for International Development's Office of Foreign Disaster Assistance and the U.S. National Weather Service.

"The bottom line is that 3D-printing will help to save lives," said Sezin Tokar, a hydrometeorologist with U.S. AID. "Not only can they provide countries with the ability to more accurately monitor for weather-related disasters, the data they produce can also help reduce the economic impact of disasters."

LACK OF OBSERVATIONS

Like many developing countries, Zambia and Kenya do not have detailed forecasts, partly because weather stations are scarce. The density of stations in Africa is eight times lower than recommended by the World Meteorological Organization. Building out a network can be prohibitively expensive, with a single commercial weather station often costing $10,000 to $20,000, plus ongoing funding for maintenance and replacing worn-out parts.

To fill this need, UCAR and NCAR scientists have worked for years to come up with a weather station that is cheap and easy to fix, and can be adapted to the needs of the host country. The resulting stations are constructed out of plastic parts that are custom designed and can be run off a 3D printer, along with off-the-shelf sensors and a basic, credit card-sized computer developed for schoolchildren.

Total cost: about $300 per station. Best of all, the host country can easily print replacement parts.

"If you want a different kind of wind direction gauge or anemometer, or you just need to replace a broken part, you can just print it out yourself," said project co-lead Martin Steinson of UCAR. "Our role is to make this as accessible as possible. This is entirely conceived as an open-source project."

BUILDING OUT A NETWORK

Working with the Zambian Meteorological Department and other agencies, Kucera and Steinson installed the first stations earlier this year—three next to radio stations that will broadcast the information to local communities, one by a rural hospital, and one by the headquarters of the meteorological department.

The meteorological office will take over the project later this year, with a goal of building out a network of 100 weather stations across Zambia. They will also have the 3D printers, materials, and training to maintain or upgrade the network.

The weather station measurements are accessible to local meteorologists and also transmitted over wireless networks in real time to NCAR. After all the weather stations have been installed, scientists will develop a system of one- to three-day regional forecasts for Zambia using the NCAR-based Weather Research and Forecast (WRF) computer model. The forecasts, in addition to helping farmers and other residents, can also alert the country to the threat of impending floods or other weather-related disasters.

The system will ultimately be transferred to the Zambian Meteorological Department to run the forecasts.

"The objective of the project is to transfer the technology so this will be run by Zambia," Kucera said.

In Kenya, the weather stations were installed at four schools as a partnership with the Global Learning and Observations to Benefit the Environment (GLOBE) program, an international science and education initiative that encompasses tens of thousands of schools.

Students will learn about local weather and climate by comparing their weather observations to those taken at other schools using science protocols established by GLOBE. They can also assess the impacts of climate change on society and the environment, as well as see how the observations help with farming, flood prediction, and other applications.

WRITER/CONTACT:

David Hosansky, Manager of Media Relations

‹ Working in UNEION together up Super-resolution solar model achieves order out of chaos ›

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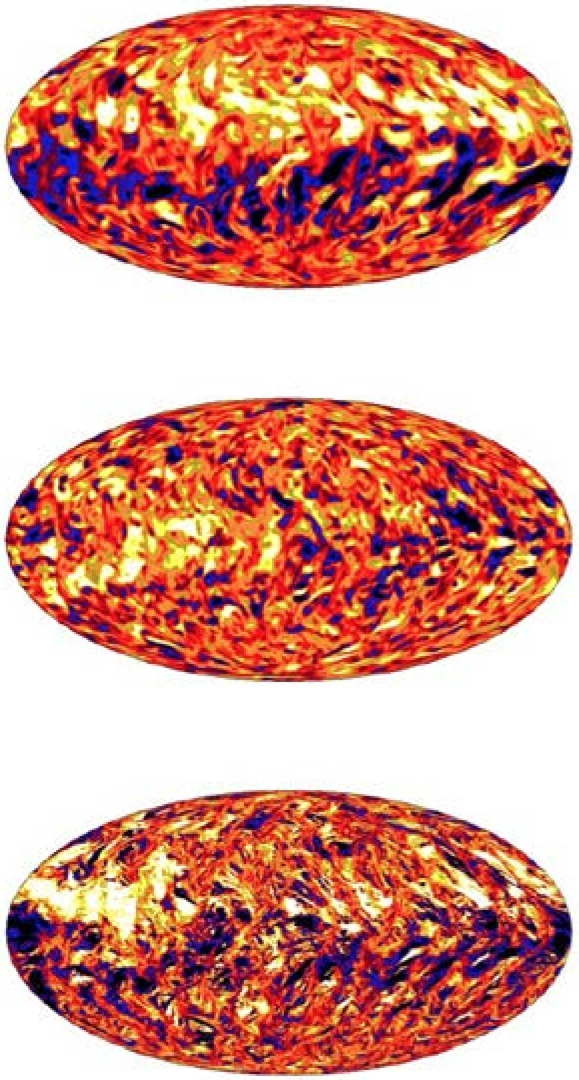
SUPER-RESOLUTION SOLAR MODEL ACHIEVES ORDER OUT OF CHAOS

Over the past few decades, computer models of the Sun’s interior have matured, showing that turbulent flows of plasma create a chaotic magnetic tangle. And after observing the Sun's surface for hundreds of years, scientists know that order emerges from that tangle in the form of the solar cycle.

When run at relatively low resolution, three-dimensional models of the Sun have been able to capture the solar cycle, which includes a predictable flip-flopping of the Sun's magnetic field about every 11 years. But something puzzling would happen when researchers increased model resolution in an effort to explore smaller-scale magnetic processes: the large-scale patterns associated with the solar cycle could no longer be seen.

A study published in 2016 in the journal Science, shows that, for the first time,



The images show simulations of the Sun's longitudinal magnetic field at the base of the convective zone at low resolution (top), medium resolution (middle), and high resolution (bottom). (Image courtesy of Matthias Rempel, NCAR. This image is freely available for media & nonprofit use.)

the Sun's large-scale patterns can re-emerge when a model's resolution is pushed even further, to a scale finer than any ever attempted. To perform the pioneering experiment, the research team — led by Hideyuki Hotta, of Chiba University in Japan, and including Matthias Rempel, of the National Center for Atmospheric Research (NCAR), and Takaaki Yokoyama, of the University of Tokyo — harnessed two of the world's most powerful supercomputers: NCAR's Yellowstone and the K computer at Japan's RIKEN Advanced Institute for Computational Science.

The experimental results give scientists important insight into how the Sun's magnetic fields, both tiny and massive, can co-exist and interact without destroying the solar cycle.

"It's like our model has to travel through this valley to get to the other side," said Rempel, a senior scientist at NCAR's High Altitude Observatory and a co-author of the paper. "Many other models of the same type are still on their way into the valley."

The existence of this conceptual valley is likely related to the fact that solar dynamos — the process by which the energy of turbulent flows of plasma is converted into magnetism — occur on both large and small scales inside the Sun. The large-scale solar dynamo is thought to be responsible for the solar cycle. But small-scale solar dynamos also exist, though their effects on the global scale are not well understood.

"There is a lot of small-scale turbulence on the Sun. The smallest eddies, or magnetic whirlpools, you find can be just meters, or even centimeters, in size," Rempel said. "The question is, when you have both large-scale and small-scale dynamos operating at the same time, how do they influence each other?"

Scientists have tried to answer this question by increasing the resolution of their solar models so that the large-scale and small-scale processes could be "seen" at the same time. But in these earlier simulations, the small-scale turbulence appeared to interfere with the large-scale dynamo, and the solar cycle pattern dissipated.

In the new study, the researchers attacked the problem by pushing the model resolution even further. The result was that the model established connections between the small and large magnetic fields, allowing the solar cycle pattern to re-emerge.

Essentially, the models used in previous attempts could see the small-scale phenomena, but it may be that they couldn't

see them well enough.

"In the past, the resolution was not high enough to really grow the small-scale component and see its full impact," Rempel said.

VISCOSITY AND COMPUTING POWER

Rempel thinks the key to building the large-scale patterns may be found in how models of differing resolution represent the apparent viscosity of the Sun's plasma. At low resolution, models assume that the plasma is more viscous—flowing more like honey than water—which allows order to emerge in the model system.

But as the resolution increases, the equations that govern the model actively lower the plasma's viscosity. This allows small-scale interactions to begin to play out, but makes it more difficult for large-scale patterns to form.

When the model was pushed to much higher resolution for the new study—about four times higher than previous attempts—the model's viscosity was dropped further still. But because the small-scale dynamos were able to fully evolve in the simulation, the model was able to let new magnetic fields form and grow, something that didn't happen before. The result was that the snarl of new magnetic fields created a level of magnetic stress that caused the plasma to act as if it was more viscous, even though it wasn't.

While some innovative modeling code allowed the scientists to go to a higher resolution using fewer computing resources than would normally be required, the effort still demanded a lot of computing power. The sheer amount of computing resources needed—and the scarcity and expense of those resources—mean that, practically speaking, many solar physicists may not be able to run their models at a resolution high enough to maintain the Sun's large-scale pattern.

The results of the new study offer at least a stop-gap solution for scientists trying to better understand the complicated interplay of the Sun's dynamos. The study suggests that researchers who can't go to an extremely high resolution may be able to get similar results by artificially increasing the model's viscosity.

More important, the new study offers a look at why increasing the viscosity would work.

"The Sun is magnetic on all scales," Rempel said. "We have shown that it's really important to understand this and account for how those magnetic fields interact."

H. Hotta, M. Rempel, and T. Yokoyama, Large-scale magnetic fields at high Reynolds numbers in magnetohydrodynamic simulations, Science, doi: 10.1126/science.aad1893

WRITER/CONTACT:

Laura Snider, Senior Science Writer and Public Information Officer

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US TAPS NCAR TECHNOLOGY FOR NEW WATER RESOURCES FORECASTS

The National Oceanic and Atmospheric Administration (NOAA) launched a comprehensive system for forecasting water resources in the United States in August that is built around technology developed by the National Center for Atmospheric Research (NCAR) and its university and agency collaborators.

WRF-Hydro, a powerful NCAR-based computer model, is the first nationwide operational system to provide continuous predictions of water levels and potential flooding in rivers and streams from coast to coast. NOAA's new Office of Water Prediction selected it last year as the core of the agency's new National Water Model.

"WRF-Hydro gives us a continuous picture of all of the waterways in the contiguous United States," said NCAR scientist David Gochis, who helped lead its development. "By generating detailed forecast guidance that is hours to weeks ahead, it will help officials make more informed decisions about reservoir levels and river navigation, as well as alerting them to dangerous events like flash floods."

WRF-Hydro (WRF stands for Weather Research and Forecasting) is part of a major Office of Water Prediction initiative to bolster U.S. capabilities in predicting and managing water resources. By teaming with NCAR and the research community, NOAA's National Water Center is developing a new national water intelligence capability, enabling better impacts-based forecasts for management and decision making.

Unlike past streamflow models, which provided forecasts every few hours and only for specific points along major river systems, WRF-Hydro provides continuous forecasts of millions of points along rivers, streams, and their tributaries across the contiguous United States. To accomplish this, it simulates the entire hydrologic system — including snowpack, soil moisture, local ponded water, and evapotranspiration — and rapidly generates output on some of the nation's most powerful supercomputers.

WRF-Hydro was developed in collaboration with NOAA and university and agency scientists through the Consortium of Universities for the Advancement of Hydrologic Science, the U.S. Geological Survey, Israel Hydrologic Service, and Baron Advanced Meteorological Services. Funding came from NOAA, NASA, and the National Science Foundation, which is NCAR's sponsor.

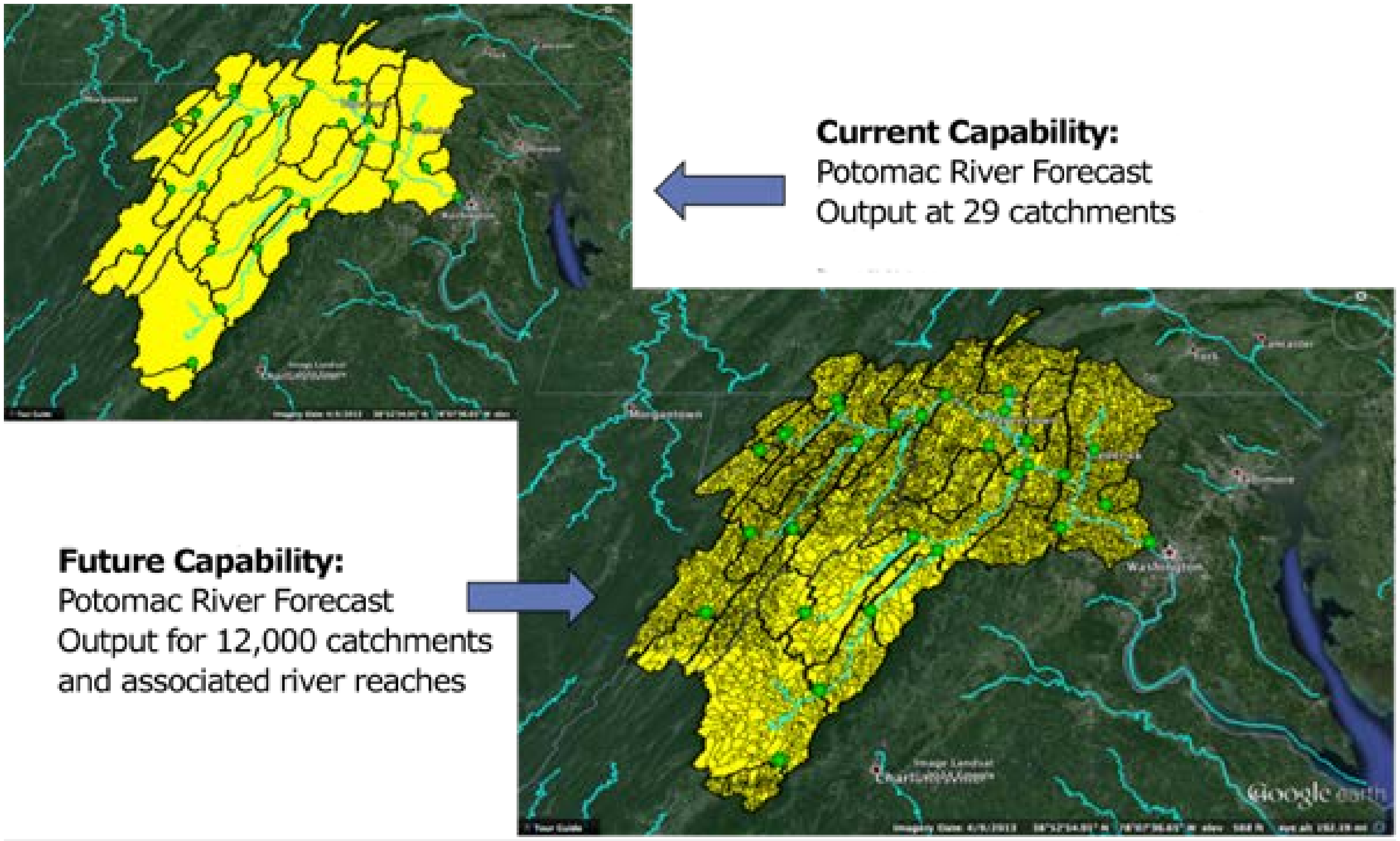
"WRF-Hydro is a perfect example of the transition from research to operations," said Antonio J. Busalacchi, president of the University Corporation for Atmospheric Research, which manages NCAR on behalf of the National Science Foundation (NSF). "It builds on the NSF investment in basic research in partnership with other agencies, helps to accelerate collaboration with the larger research community, and culminates in support of a mission agency such as NOAA. The use of WRF-Hydro in an operational setting will also allow for feedback from operations to research. In the end this is a win-win situation for all parties involved, chief among them the U.S. taxpayers."

"Through our partnership with NCAR and the academic and federal water community, we are bringing the state of the science in water forecasting and prediction to bear operationally," said Thomas Graziano, director of NOAA's new Office of Water Prediction at the National Weather Service.

FILLING IN THE WATER PICTURE

The continental United States has a vast network of rivers and streams, from major navigable waterways such as the Mississippi and Columbia to the remote mountain brooks flowing from the high Adirondacks into the Hudson River. The levels and flow rates of these watercourses have far-reaching implications for water availability, water quality, and public safety.

Until now, however, it has not been possible to predict conditions at all points in the nation's waterways. Instead, computer models have produced a limited picture by incorporating observations from about 4,000 gauges, generally on the country's bigger rivers. Smaller streams and channels are largely



The new WRF-Hydro computer model simulates streams and other aspects of the hydrologic system in far more detail than previously possible. (Image by NOAA Office of Water Prediction.)

left out of these forecast models, and stretches of major rivers for tens of miles are often not predicted — meaning that schools, bridges, and even entire towns can be vulnerable to unexpected changes in river levels.

To fill in the picture, NCAR scientists have worked for the past several years with their colleagues within NOAA, other federal agencies, and universities to combine a range of atmospheric, hydrologic, and soil data into a single forecasting system.

The resulting National Water Model, based on WRF-Hydro, simulates current and future conditions on rivers and streams along points two miles apart across the contiguous United States. Along with an hourly analysis of current hydrologic conditions, the National Water Model generates three predictions: an hourly 0- to 15-hour short-range forecast, a daily 0- to 10-day medium-range forecast, and a daily 0- to 30-day long-range water resource forecast.

The National Water Model predictions using WRF-Hydro offer a wide array of benefits for society. They will help local, state, and federal officials better manage reservoirs, improve navigation along major rivers, plan for droughts, anticipate water quality problems caused by lower flows, and monitor ecosystems for issues such as whether conditions are favorable for fish spawning. By providing a national view, this will also help the Federal Emergency Management Agency deploy resources more effectively in cases of simultaneous emergencies, such as a hurricane in the Gulf Coast and flooding in California.

"We've never had such a comprehensive system before," Gochis said. "In some ways, the value of this is a blank page yet to be written.

A BROAD SPECTRUM OF OBSERVATIONS

WRF-Hydro is a powerful forecasting system that incorporates advanced meteorological and streamflow observations, including data from nearly 8,000 U.S. Geological Survey streamflow gauges across the country. Using advanced

mathematical techniques, the model then simulates current and future conditions for millions of points on every significant river, stream, tributary, and catchment in the United States.

In time, scientists will add additional observations to the model, including snowpack conditions, lake and reservoir levels, subsurface flows, soil moisture, and land-atmosphere interactions such as evapotranspiration, the process by which water in soil, plants, and other land surfaces evaporates into the atmosphere.

Scientists over the last year have demonstrated the accuracy of WRF-Hydro by comparing its simulations to observations of streamflow, snowpack, and other variables. They will continue to assess and expand the system as the National Water Model begins operational forecasts.

NCAR scientists maintain and update the open-source code of WRF-Hydro, which is available to the academic community and others. WRF-Hydro is widely used by researchers, both to better understand water resources and floods in the United States and other countries such as Norway, Germany, Romania, Turkey, and Israel, and to project the possible impacts of climate change.

"At any point in time, forecasts from the new National Water Model have the potential to impact 300 million people," Gochis said. "What NOAA and its collaborator community are doing is trying to usher in a new era of bringing in better physics and better data into forecast models for improving situational awareness and hydrologic decision making."

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David Hosansky, Manager of Media Relations

Collaborators
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Consortium of Universities for the Advancement of Hydrologic Science
Israel Hydrologic Service
National Center for Atmospheric Research
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RISING VOICES MELDS INDIGENOUS, WESTERN SCIENCE PERSPECTIVES

Indigenous people around the world are often among the first to experience the consequences of extreme weather and climate change. The effects on their lives and livelihoods of sea level rise, changes in farming and fishing seasons, and other environmental impacts often are dramatic. Yet their perspectives are rarely considered in public policy discussions. In many tribal communities, climate change exacerbates a situation already marked by economic hardship, resource loss, and discrimination.

Now in its fourth year, a program hosted by NCAR called Rising Voices brings social and physical scientists and engineers together with Native American community members to build bonds that lead to collaboration on research proposals and projects. The premise is that indigenous peoples experience and understand the changes occurring in their communities, while scientists can provide insight on the underlying causes and how those changes might be managed.

"We need to appreciate the experience and knowledge that has been transferred from generation to generation to

generation in Native American communities," said Bob Gough, a founding member of Rising Voices, an attorney, and a descendant of the Leni Lenape tribe of Delaware.

For NCAR Director Jim Hurrell, indigenous knowledge systems are critical to understanding the current and future impacts of climate variability and change, and "they are especially central to discussions around adaptation strategies. Rising Voices has been tremendously successful in bringing the indigenous and scientific communities together on these issues, and the collaborative efforts that are emerging are going to pay tremendous dividends."

Students attending the Rising Voices workshop in Waimea, Hawaii, in 2016, visited a food garden planted according to traditional Hawaiian techniques to learn about climate change and phenology – the study of the seasonality of plants and animals. (Photo courtesy Craig Elevitch.)

Many of the indigenous communities involved in Rising Voices are already contending with significant impacts. In January 2016, the U.S. Department of Housing and Urban Development announced it would fund a proposal to resettle the Isle de Jean Charles Band of the Biloxi-Chitimacha-Choctaw tribe, a Louisiana Bayou community that has lost virtually all its land due to rising sea levels and to erosion caused by extreme weather as well as human activities such as oil and gas development. This is believed to be the first resettlement in the United States related to climate change.

A Native American village in Kivalina, Alaska, is expected to soon face a similar fate, while many tribes in the Southwest are struggling with severe drought and scarce water. Members of both the Isle de Jean Charles and Kivalina tribes participate in Rising Voices.

Bull Bennett, an ecologist, Mi'kmaq tribal member in North Dakota, and Rising Voices participant gave a vivid example of just one problem facing cold-climate communities during a video interview last summer for a new climate exhibit at NCAR's Mesa Lab.

"Imagine you carve out your cellar in the permafrost and that's how you store your meat in the lean times," Bennett said. "And now imagine the permafrost thaws and your basement is full of water and the structure isn't supported and it falls in. That's what communities in Alaska are dealing with in the interior, with profound permafrost thaw. And it's only going to get worse."

UN PANEL URGES SCIENTISTS TO TAP INDIGENOUS KNOWLEDGE

Rising Voices comes at a time of increasing recognition of the role indigenous people play worldwide in climate issues. In 2014, the United Nation's Intergovernmental Panel on Climate Change highlighted how indigenous knowledge and practice, including the "holistic view of community and environment, are a major resource for adapting to climate change."

The Rising Voices program grew out of a hallway coffee conversation three years ago between Gough and Heather Lazrus, an NCAR environmental anthropologist. At the time, Gough was involved in a project to improve wind-energy predictions and map Indian reservations for potential renewable energy projects. Initially intended as a one-time workshop, Rising Voices received additional funding for subsequent workshops which have been organized by Lazrus, Gough, and Julie

Maldonado of the Livelihoods Knowledge Exchange Network. The NCAR Director's Office is the primary funder. Rising Voices has grown from 45 participants at the first workshop to more than 110 at the third annual workshop last July. (NCAR hosted a similar meeting in 2008).

Gough, who grew up clamming and fishing on former tribal homelands on the New Jersey Coast, has been involved in tribal climate and energy issues for several decades. He said that while there are academic efforts to include indigenous people, Rising Voices fills a niche as a community-oriented group that connects tribes to each other and to scientists. Participants have also come from the U.S. National Climate Assessment and the Department of Interior's Climate Science Centers.

In a survey of the 2015 workshop participants, nearly two-thirds of respondents said they came away with a stronger appreciation of cultural protocols and knowledge required for partnerships in key areas, including water, relocation, climate cycles, and health and livelihood hazards. More than three-quarters said the workshop supported collaborative scientific-indigenous partnerships "extremely well" or "a lot."

Lazrus said the ultimate goal is for indigenous perspectives to inform science. For example, Rising Voices is a formal partner in NCAR's Engineering for Climate Extremes Partnership, which is developing tools that help communities adapt and build resilience to extreme weather events.

But while outcomes are important, the primary benefits of Rising Voices right now are to encourage connections and collaboration, and to support indigenous science students and early-career scientists. "In those respects," Lazrus said, "Rising Voices is succeeding."

WRITER/CONTACT

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North Central Climate Science Center
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Collaborators
Intertribal Council on Utility Policy
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STRATEGIC PLANS

NCAR Strategic Plan

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NCAR 2016 METRICS & PUBLICATIONS

FISCAL YEARS 2014-2015 NCAR 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. They are based on data reported in the Metrics Database and iVantage HR system as of April 4, 2016 for the current NSF Cooperative Agreement fiscal years 2014 and 2015 (October 1, 2013-September 30, 2015). Staff contribute to this Database on a voluntary basis, and they continue to update their entries and expand their contributions throughout the year. Thus, please visit the Metrics Database (https://www.ncar.ucar.edu/apps/metrics) for the most current data.

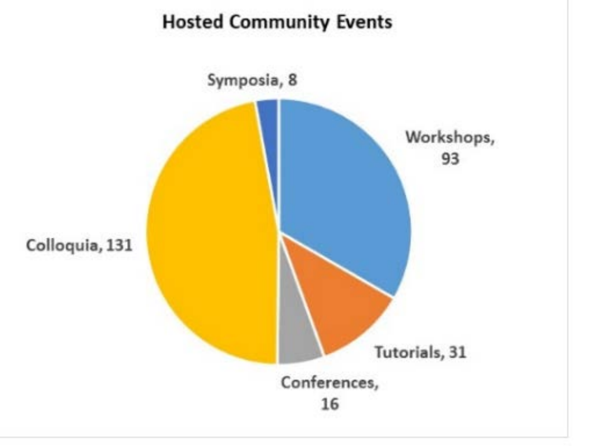
LAB/OBSERVATORY/PROGRAM-LEVEL METRICS

NCAR-Hosted Community Events

Date Range	Total Hosted Events	Workshops	Tutorials	Symposia	Conferences	Colloquia
FY14-FY15	279	93	31	8	16	131

NCAR hosts a variety of community events every year, including colloquia, conferences, symposia, tutorials, and workshops.

In FY2014 and 2015, a total of 279 events were hosted with an average audience of 52 colleagues per event and estimated total audience of over 14,400. Event co-sponsors included the National Business Aviation Association, the Climate Corporation, the Molina Center for Energy and the Environment, the Department of Energy, the Climate and Cryosphere Group, and various universities including the University of Washington STATMOS Group, Pennsylvania State University, Newcastle University and the University of Ljubljana (Slovenia).



FIELD CAMPAIGNS

Date Range	Total Campaigns	Institutions	PIs	Undergraduate Students	Graduate Students
FY14-FY15	24	327	335	169	281

In FY14 and 15, NCAR participated in 24 field campaigns ranging in duration from 5 to 2,283 operational field days. A total of 327 institutions, including 132 UCAR member institutions, participated in these campaigns. The projects involved 335 investigators, 169 undergraduate students, and 281 graduate students.NCAR's geosciences research facilities, instrumentation and field support services support field campaigns around the globe.

For example, the 2014 Biogenic Aerosols-Effects on Clouds and Climate (BAECC) field campaign is a collaboration with Finnish scientists to measure biogenic aerosols emitted from forests in order to determine their effects on clouds, precipitation, and climate. BAECC placed the second ARM Mobile Facility (AMF2) in a Scots pine forest in southern Finland from February through September 2014 to

Locations of Field Campaigns for FY14-FY15

obtain surface-based measurements of biogenic aerosols and gases. These measurements were augmented by aircraft observations of aerosol microphysics, as well as measurements from the University of Helsinki's Station for Measuring Ecosystem-Atmosphere Relations (SMEAR-II).

The 2015 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.

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
CSET	Cloud System Evolution in the Trades
Nor'easter	Nor'easter
MASCRAD	Multi-Angle Snow Camera and Radar experiment - Accurate Characterization of Winter Precipitation Using Multi-Angle Snowflake Camera, Visual Hull, Advanced Scattering Methods and Polarimetric Radar
FRAPPE	The Front Range Air Pollution and Photochemistry Experiment
STEP	STEP Hydromet Experiment
LATTE	Lower Atmospheric Thermodynamics and Turbulence Experiment
FRONT-DE	Front Range Observational Network Testbed - Demonstration Project
OWLES	Ontario Winter Lake-effects Systems
HS3 2014	Hurricane and Severe Storm Sentinel 2014
IFRACS	Isotopic Fractionation in SNOW
DEEPWAVE	Deep Propagating Gravity Wave Experiment over New Zealand
CONTRAST	Convective Transport of Active Species in the Tropics
METCRAX II	Meteor Crater Experiment II
FIXCIT	Focused Isoprene Experiment at California Institute of Technology
GO AMAZON 2014/15	Green Ocean Amazon 2014-15
BAECC	Biogenic Aerosols-Effects on Clouds and Climate
DISCOVER AQ	Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality

NCAR-WYOMING SUPERCOMPUTER CENTER SELF-GUIDED PUBLIC TOURS

Date Range	Walk-in Public Visitors	Visitors per Month
FY14-FY15	1650	69

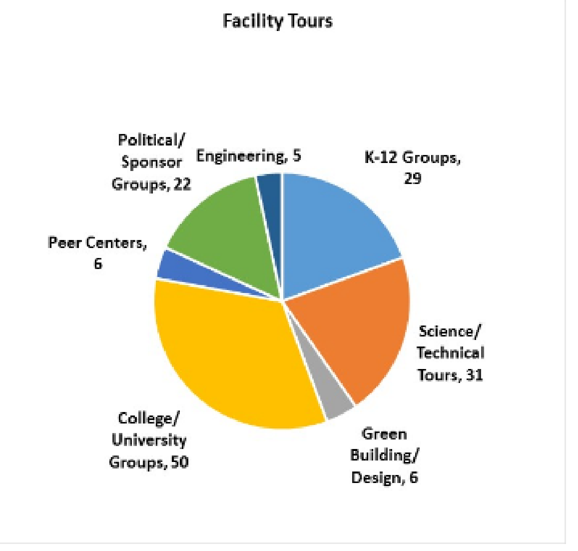
The NCAR-Wyoming Supercomputer Center is based in Cheyenne, Wyoming. The Center provides advanced computing services to scientists studying a broad range of disciplines, including weather, climate, oceanography, air pollution, space weather, computational science, energy production, and carbon sequestration. The Center is open to the public for self-

guided tours, field trips for school groups, and non-school group special tours. In FY14-15, the Center received 1650 walk-in public visitors, and averaged 69 visitors per month.

GUIDED FACILITY TOURS AT THE NCAR-WYOMING SUPERCOMPUTER CENTER AND NCAR RESEARCH AVIATION FACILITY

Date Range	Total Hosted Tours	K-12 Groups	Science/ Technical Tours	College/ University Groups	Political/ Sponsor Groups	Peer Centers	Engineering	Green Building/ Design
FY14-FY15	149	29	31	50	22	6	5	6

Every year, NCAR facilities host a number of participants for tours organized for a specific organization or group. This year, NCAR hosted a total of 149 tours.



The NCAR-Wyoming Supercomputer Center (NWSC) hosted 102 tours in this period, for groups ranging in size from 1 to 80 people and averaging 17. K-12 groups included the Boy Scouts of Douglas, Wyoming and various local high school visits. The science/technical group included a tour for colleagues from the Australian Bureau of Meteorology. The Front Range Community College in Fort Collins and the Western Wyoming Community College in Rock Springs, WY are examples from the college/university group. Green building and engineering tours were provided to groups such as I Phelps Construction and the Black Hills Corporation. Tours to political/sponsor groups included the Denver Federal Reserve, the South Korean Consulate and WYDOT. There were also six peer centers whoreceived tours including the San Diego Supercomputing Center, Penn State Data Center Project Team and the USGS Powell Center.

Our NCAR Research Aviation Facility (RAF) team at the Rocky Mountain Metropolitan Airport hosted a total of 47 tours in FY14-15. College and university groups toured the facility and airplanes including Embry-Riddle Aeronautical University, Front Range Community College and Colorado State University. Science and technical groups included the US Air Force, NOAA and colleagues participating in the AMS Measurement Symposium. Seven tours were made by political/sponsor groups, including Senator Thom Till's Office and James Change, Congressional Staffer for Brian Schatz of Hawaii.

INDIVIDUAL STAFF METRICS

Contributions to Individual Graduate Student Education

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

Date Range	Total Committee Service	Total Students	International Service	U.S. Service
FY14-FY15	331	309	27%	73%

Of the 309 graduate students that have one or more NCAR staff serving as graduate advisors or committee members, 73% hail from U.S. universities such as the University of Puerto Rico, Howard University, Yale and the University of Virginia in 31 states. Twenty-

Locations of Graduate Students Globally FY14-FY15

seven percent study at schools in 26 countries around the world, including a student from Addis Ababa University in Ethiopia.

Editorships

Date Range	Total Editorships	Different Editorial Roles	Different Publications/ Journals
FY14-FY15	88	139	95

NCAR staff members 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.

Eighty-eight NCAR staff served across 139 different editorial roles on 95 different publications or journals. Publications included top-tier journals such as AMS Journal of Hydrometeorology, Geoscience Data Journal, and the Bulletin of the American Meteorological Society.

External Awards

Date Range	Total External Awards
FY14-FY15	63

Every year a significant number of NCAR Staff are honored for their scientific excellence and community contributions to the Atmospheric and related sciences. Some examples are given below.

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

In FY 2014-2015 Vanda Grubišić (EOL) and Matthias Steiner (RAL) were named as American Meteorology Society Fellows. 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. This past January, seven more NCAR scientists were named AMS Fellows. These distinguished fellows are Jeffrey Anderson, Christopher Davis, Roland Garcia, James Moore, Bette Otto-Bliesner, Chris Snyder, and Jothiram Vivekanandan.

AMS American Meteorological Society

Warren Washington, Jerry Meehl, Clara Deser and Gordon Bonan were named as Fellows of the American

Geophysical Union, a tribute to those AGU members who have made exceptional contributions to Earth and space sciences as valued by their peers and vetted by section and focus group committees. Three more NCAR staff members were named AGU Fellows this past December: Michael Thompson, Better Otto-Bliesner, and William Randel.

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.

Lisa Kaser (ASP) received an Award of Excellence for outstanding Dissertations from the Austrian Federal Ministry of Science and Research. During her work as a PhD student at the University of Innsbruck, she participated in the NCAR/ACD-led BEACHON ROCS and ROMBAS field campaigns at the Manitou Experimental Forest (close to Woodland Park, Colorado). She studied the biosphere-atmosphere exchange of volatile organic compounds (VOCs) in this Ponderosa Pine ecosystem using the eddy covariance technique and a newly developed instrument (PTR-TOF-MS).

William Mahoney, Sue Ellen Haupt, and Brako Kosovic (Principal Investigators) and the Windpower Forecasting Team (RAL) received the 2014 Colorado Governor's Award for High-Impact Research for their project "Optimizing Integration of Renewable Energy into the Power Grid in Colorado." This award was in the in the Sustainability category as well as an honorable mention in Public-Private Partnerships, for work on a cutting-edge wind and solar energy forecasting system. 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.

Fellowships

Date Range	Total Fellowships
FY14-FY15	9

Nine NCAR staff received fellowships in FY 2014-2015. Among the highlights: Tanya Peevey (ACOM) was awarded a place in the International Research Fellowship Program (IRFP) offered by the National Science Foundation (NSF) and Gerald Meehl was appointed a Visiting Senior Fellow at the University of Hawaii. Mari Tye (MMM) was awarded a visiting research associate position by Colorado State University (CSU). At CSU, she is working with two Professors in the Statistics department on research covering statistical analysis relating to tropical cyclones, and extremes. The goals of the research include developing spatial statistical techniques applicable to extreme precipitation and use in adaptation planning and resilient design.A fellowship is typically a special appointment granting support for a term for advanced research or study.

K-12 Outreach

Date Range	Total K-12 Outreach	Schools/ Events	Communities Reached
FY14-FY15	160	108	39

During this time period, 160 NCAR Staff worked with K-12 students at 108 different schools or events. Activities included a career fair, helping teachers, mentoring, and field trips reaching 39 different communities. Staff members also take the opportunity to work with young students and teachers while on field campaigns or collaborating internationally. 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 and contributing as a consultant and contributor to the Solar Superstorms

Planetarium show in New York. Among the highlights: Tara Jensen built an automated weather station for Mead Elementary School in Mead, Colorado; and Thomas Cram taught Bubbles on Bottle classroom kit to a second-grade class at Laurel Elementary School in Fort Collins, Colorado.Staff members 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.

K-12 Global Outreach for FY14-FY15

Mentoring

Date Range	Total Mentoring	Institutions
FY15	149	95

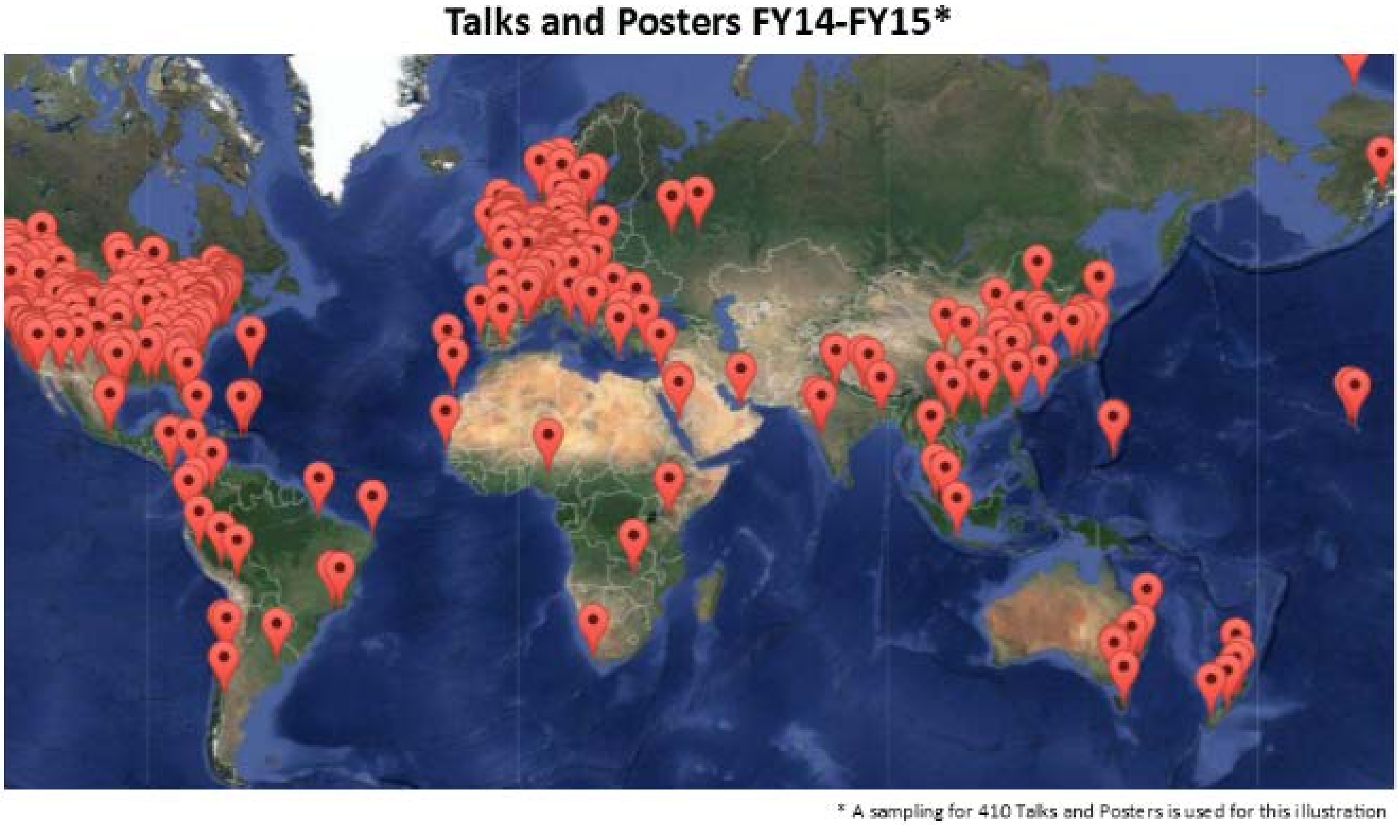
Talks and PostersMentoring is a new report category in FY2015 so we are just starting to capture these data. As of early April, 2016, NCAR staff report mentoring 149 colleagues at 95 different institutions in disciplines ranging from Hydrology to Computer Science to Aerospace Engineering across the United States and around the world. The mentoring occurred both inside and outside of NCAR. John Ortega mentored a student from the National Space Research and Development Agency 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.

Talks and Posters

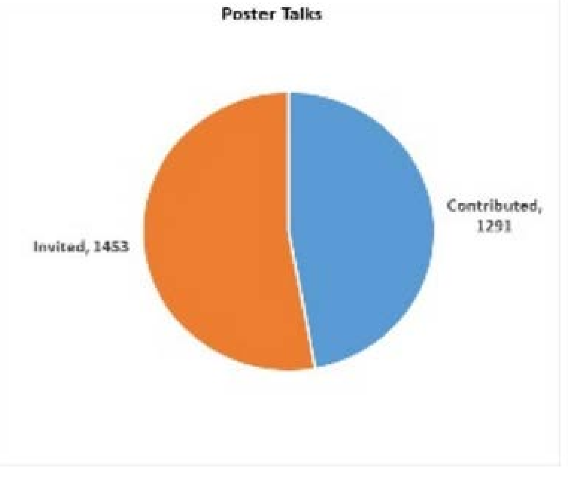
Date Range	Total Talks	NCAR Staff Talks	Total Poster Presentations	NCAR Staff – Poster Presentations
FY14-FY15	2,386	313	358	165

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

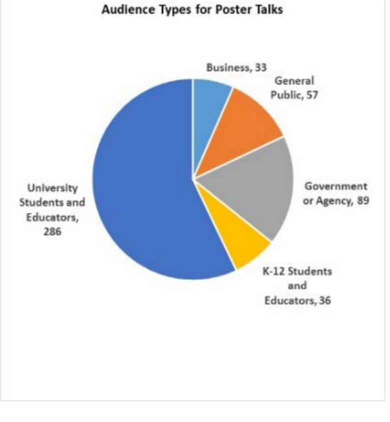
Talks: Many thousands of people were in the audience when 313 NCAR staff gave more than 2,386 (1,431 invited) talks across the country and around world, from Biddeford Maine to Amsterdam, Netherlands.



Examples range from Matthias Rempel's talk on "Magnetoconvection - the Global and the Local Dynamo" at the Conference on Coupling and Dynamics of the Solar Atmosphere in Pune, India to Wojciech Grabowski's talk "Untangling microphysical impacts on deep convection applying a novel modeling methodology" in La Jolla, California.



Qian Wu's gave his talk on "Upper Atmosphere Observation" at Embry-Riddle Aeronautical University in Daytona, Florida and Bette Otto-Bliesner presented her talk entitled "Working Group Report: Quaternary Interglacials" in Namur, Belgium. Sheldon Drobot gate a TEDx talk in Boulder, "The Promise of Connected Vehicles," to 2200 people.



Posters: One hundred sixty-five NCAR staff made more than 358 poster presentations across the country and around world, from Madison, Wisconsin to Montpellier, France. Examples include Peisang Tsai's 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 Gibson's poster "Coronal Magnetism and FORWARD IDL SolarSoft Package" in Punta Leona, Costa Rica at the IAU Symposium 305.

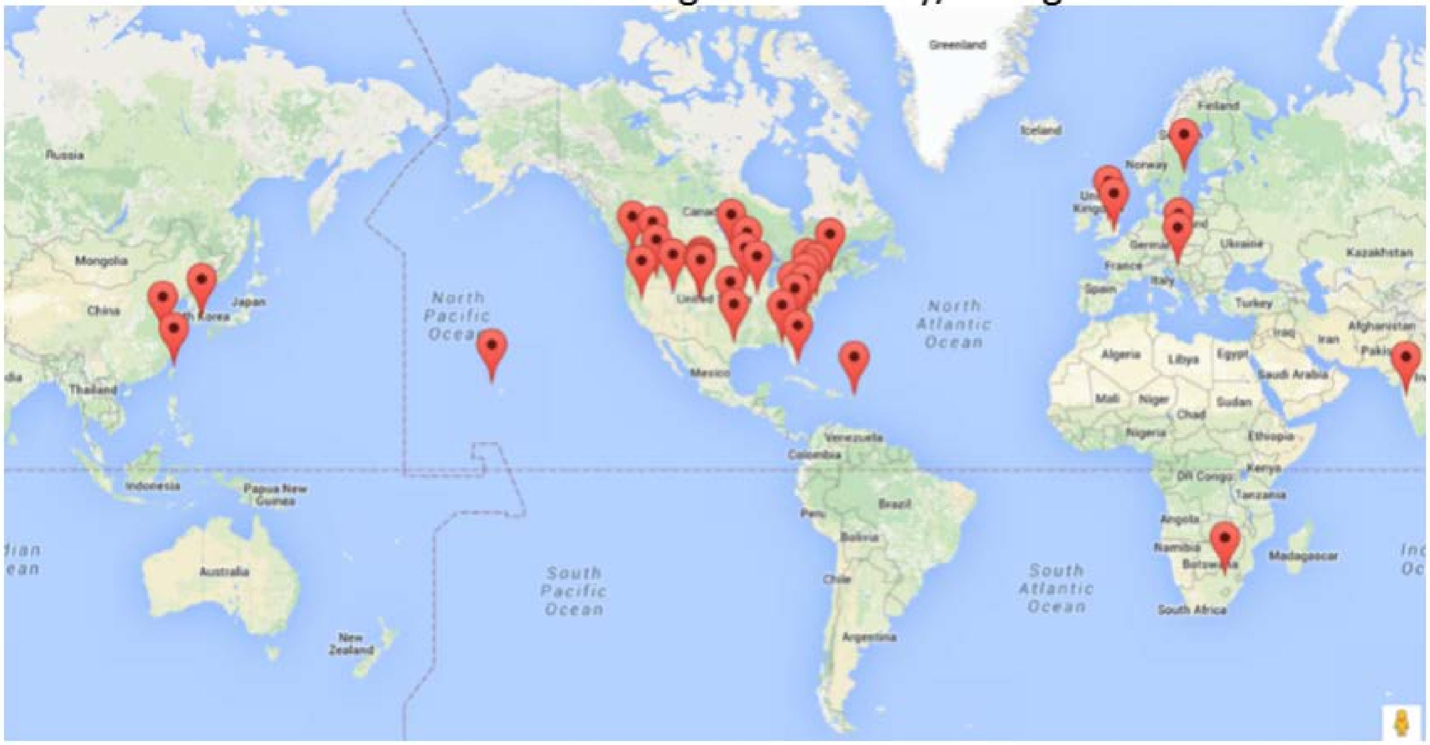
Don Stott contributed his poster "The Pacific Marine Arctic Regional Synthesis (PacMARS) Data Archive" in Anchorage, Alaska at the Alaska Marine Science Symposium and Joseph Plowman shared his poster "Automated Coalignment of Multi-instrument Data" in La Roche-en-Ardenne, Belgium at the 7th Solar Information Processing Workshop.

Teaching in University/College Classroom

Date Range	Total Teaching Appointments	Countries	U.S. States
FY14-FY15	85	9	21

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

Classroom Teaching in University/College



Teaching ppointments at institutions of higher education currently number 85. Thirteen percent of these appointments occurred in 9 countries around the world; 87% took place in 21 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

Date Range	Total Teaching Opportunities	Workshops/ Tutorials/ Colloquia	Classes	Countries	U.S. States
FY14-FY15	102	223	1115	28	11

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

Teaching or Training at Workshops/Tutorials/Colloquia FY14-FY15

During this year, 102 staff members taught at a total of 223 workshops, tutorials, and colloquia. In all, 1115 individual classes were taught, with class sizes ranging from small groups to 100 people. Seventeen percent of these events occurred in 28 countries around the world including Seychelles and Croatia; 83% took place in 11 U.S. states, from Maine to California. Examples range from Mary Barth's contributions at the “Atmospheric Composition and the Asian Monsoon Training School” in Bangkok, Thailand to Mary Haley’s teaching at the Visualization with NCL - Hands on Workshop Fall 2014 in Hamburg, Germany. More examples include Simone Tilmes' contributions at the “1st West African Workshop on Air Quality” in Abuja, Nigeria to Qian Wu’s teaching at the CEDAR workshop in Seattle, Washington.

External Committee Service

Date Range	Total External Committees	NCAR Staff Served	Service on more than one committee
FY14-FY15	705	188	65%

Over this two-year period, 188 NCAR staff served in a multitude of roles on 705 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. Other examples include the Green Enterprise IT Awards for the Uptime Institute, the Committee on Probability and Statistics for the American Meteorological Society, and the Committee on Solar and Space Physics for The National Research Council. More than 65% served on more than one committee.NCAR staff members 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.

Staff Collaboration Visits to Universities

Date Range	Total Leaves	NCAR Staff Members	Institutions
FY14-FY15	30	23	26

Over this period, institution visits ranged from the University of Leeds to the Korean Institute of Atmospheric Prediction Systems (KIAPS). Among the highlights: Paul Kucera, a Project Scientist II, visited the University of Hamburg to engage in collaborative research and Steven Massie, a Scientist III, visited Florida State University to teach a graduate course in atmospheric chemistry, and engage in collaborative research with the chemistry programs of the geology and oceanography departments.NCAR staff members 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.

APPOINTMENT METRICS

Special Appointments

NCAR Affiliate Scientists: Select university and research-community scientists are invited to carry out long-term, highly interactive, collaborative work with NCAR 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.

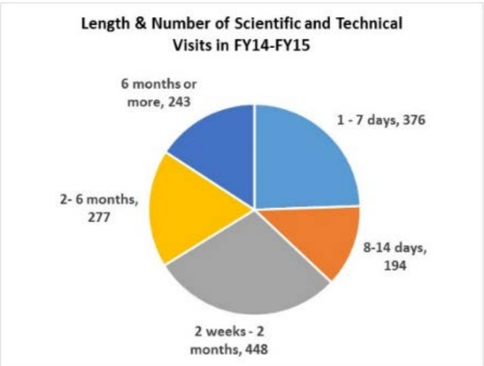
NCAR Affiliate Scientist	Home Institution
Dr. Elliot Atlas	University of Miami
Dr. Ed Balistreri	Colorado School of Mines
Dr. Dale Barker	United Kingdom Meteorological Office
Dr. Alan Blyth	University of Leeds
Prof. Lance Bosart	State University of New York Albany
Dr. Natalia Calvo	Universidad Complutense de Madrid
Dr. Guido Cervone	Pennsylvania State University
Dr. Paul Charbonneau	University of Montreal
Dr. Shuyi Chen	University of Miami
Prof. Philip Chilson	University of Oklahoma
Prof. Cathy Clerbaux	CNRS
Dr. Enrique Curchitser	Rutgers University
Dr. Ineke deMoortel	University of St. Andrews
Dr. Leo J. Donner	NOAA GFDL
Dr. Veronika Eyring	German Aerospace Center
Dr. Jerome Fast	Pacific Northwest National Laboratory
Dr. Michael Ferrari	aWhere
Dr. Paul Field	Met Office
Dr. Silvano Fineschi	Osservatorio Astrofisico di Torino
Dr. John Finnigan	CSIRO, Australia
Prof. Viggo Hansteen	University of Oslo
Dr. Song-You Hong	Yonsei University
Dr. Joseph Huba	Naval Research Laboratory
Dr. Mary Hudson	Dartmouth College
Dr. Harm Jonker	Delft University of Technology
Dr. Reto Knutti	ETH Zurich, Switzerland
Dr. Hao-Sheng Lin	University of Hawai'i Manoa
Dr. Elisabeth Lloyd	Indiana University
Dr. William Lotko	Dartmouth College
Dr. Larry Mahrt	Oregon State University
Dr. Marty Mlynczak	NASA Langley Research Center
Dr. Antonio Navarra	Instituto Nazionale di Geofiica e Vulcanologia
Prof. Lorenzo Polvani	Columbia University
Dr. Mark Rast	University of Colorado
Dr. Kevin Repasky	Montana State University
Dr. Alfonso Saiz-Lopez	Ministerio de Ciencia e Innovaction, Madrid
Prof. Gunilla Svensson	University of Stockholm
Dr. Laurent Terray	CERFACS
Prof. Javier Trujillo-Bueno	Instituto de Astrofisica de Canarias
Dr. Lian-Ping Wang	University of Delaware
Prof. Mei Zhang	Chinese Academy of Sciences

Emeritus/Emeritae: 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.

Emeritus/Emerita	Year of Appointment
Jackson Herring	1998
Bob Serafin	2001
Jack Calvert	2002
Roland Madden	2002
James Dye	2003
William Mankin	2003
Brian Ridley	2007
Fred Eisele	2009
Peter Gilman	2009
Margaret LeMone	2009
Raymond Roble	2009
Donald Lenschow	2011
Al Cooper	2013
Roy Jenne	2013
Richard Katz	2013
Charles Knight	2013
Bruce Lites	2013
Annick Pouquet	2013
David Williamson	2014
Jim Wilson	2014
John Gille	2015
Maura Hagan	2015

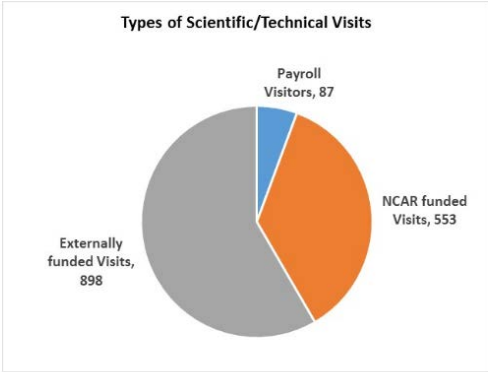
SCIENTIFIC AND TECHNICAL VISITS TO NCAR

Date Range	Total Scientific/ Technical Visits	1-7 days	8-14 days	2 weeks-2 months	2-6 months	6 months or longer
FY14-FY15	1538	376	194	448	277	243



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 1,538 times and hailed from 517 institutions, located in all 50 U.S. states and 49 different countries.



‹ Rising voices melds indigenous, Western science perspectives up

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ACOM DIRECTOR'S MESSAGE

ACOM Director David Edwards

Welcome to the 2016 Laboratory Annual Report (LAR) for the Atmospheric Chemistry Observations and Modeling (ACOM) Laboratory. This report highlights some examples of the exceptional work and scientific community leadership carried out by ACOM staff during the last fiscal year. This research significantly furthers the ACOM mission of developing predictive capability for atmospheric composition, through advances in understanding of chemistry and related processes.

The report is organized according to the six Imperatives of the NCAR Strategic Plan. The research in ACOM particularly emphasizes the quantitative integration of atmospheric chemistry observations and modeling across scales, to identify impacts on weather, climate and air quality, and to assess the role of chemistry within the coupled Earth system. As such, the Laboratory makes important contributions to Imperative 2, that concentrates on observations, and Imperative 3, focused on modeling atmospheric chemistry, data assimilation and developing capability for predicting composition. On the observations side, activities related to ACCORD (Atmospheric Chemistry Center for Observational Research and Data) are discussed, along with highlights of this year's ACOM participation in field campaigns such as ATom, PROPHET, ORCAS

and KORUS-AQ. With respect to modeling, there have been advances across scales, from the process level with TUV, through regional scale atmospheric chemistry described with WRF-Chem, to the whole-atmosphere representation in WACCM.

Many of the important scientific advances that ACOM contributes to Imperative 1 on fundamental research come from the analysis of measurements using models and the improvement and development of model parameterizations based on observations. This report discusses some recent model comparisons of measurements from past field campaigns, such as MILAGRO in 2006 (*1.4 Non-linear partitioning and organic volatility distributions of urban aerosols*) and DC3 in 2012 (*1.5 Transport of Soluble Trace Gases in Thunderstorms*). Other examples, such as *1.6 Evaluating stratospheric temperature trends in WACCM* and *1.8 Emergence of healing in the Antarctic ozone layer* illustrate work from ACOM's model analysis of satellite data.

ACOM scientists work closely with national and international researchers, teachers, students and decision makers, providing intellectual leadership and support for community measurement capabilities, laboratory and field experiments, and atmospheric chemistry models. In this way, the Laboratory acts as a nexus for the community, welcoming collaborators for short and extended visits, and hosting meetings. The latter are exemplified by descriptions of just a few of the workshops organized by ACOM this year. Some of these, such as the *6.3 NCAR/ASP 2016 Summer Colloquium* focus on educational aspects of our program, while others demonstrate scientific leadership in bringing together researchers at the forefront of a particular topic.

In the coming year, ACOM will continue to work closely with the other NCAR laboratories, UCAR, and our external stakeholders to ensure that our research and facility support is optimally positioned to provide leadership and meet the needs of the wider community. To this end, ACOM is embarking on an intensive period of strategic planning. This is motivated in part by the dismantling the NCAR Earth System Laboratory (NESL) in 2015, and the promotion of the former Atmospheric Chemistry Division (ACD) to the status of an NCAR Laboratory in the form of ACOM. ACOM is also embracing the charge set forth in the recently published National Academies report on the *Future of Atmospheric Chemistry Research*. This report called on NCAR/ACOM to define a new strategy such "*that the research capabilities and facilities at NCAR serve a unique and essential role to the NSF atmospheric chemistry community*". By the Summer of 2017, ACOM will have a new Strategic Plan that will guide our program for the next several years.

David Edwards

‹ 2016 ACOM Annual Report | up | NCAR Imperative 1: Conduct innovative fundamental research to advance the atmospheric and related sciences. ›

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1.1 THE O2/N2 RATIO AND CO2 AIRBORNE SOUTHERN OCEAN (ORCAS) STUDY

The O_2/N_2 Ratio and CO_2 Airborne Southern Ocean (ORCAS) Study was an NSF sponsored airborne field campaign conducted with the NCAR/NSF GV aircraft with research flights from Punta Arenas, Chile during January and February 2016. A major goal of ORCAS is to gain a more quantitative understanding of the dominant role that the Southern Ocean plays in the uptake of anthropogenic carbon and to provide the basis for a better representation of this process in global atmospheric models. ACOM scientists provided key measurements of a wide range of VOCs (Apel, Hornbrook, and Hills) using the Trace Organic Gas Analyzer (TOGA).

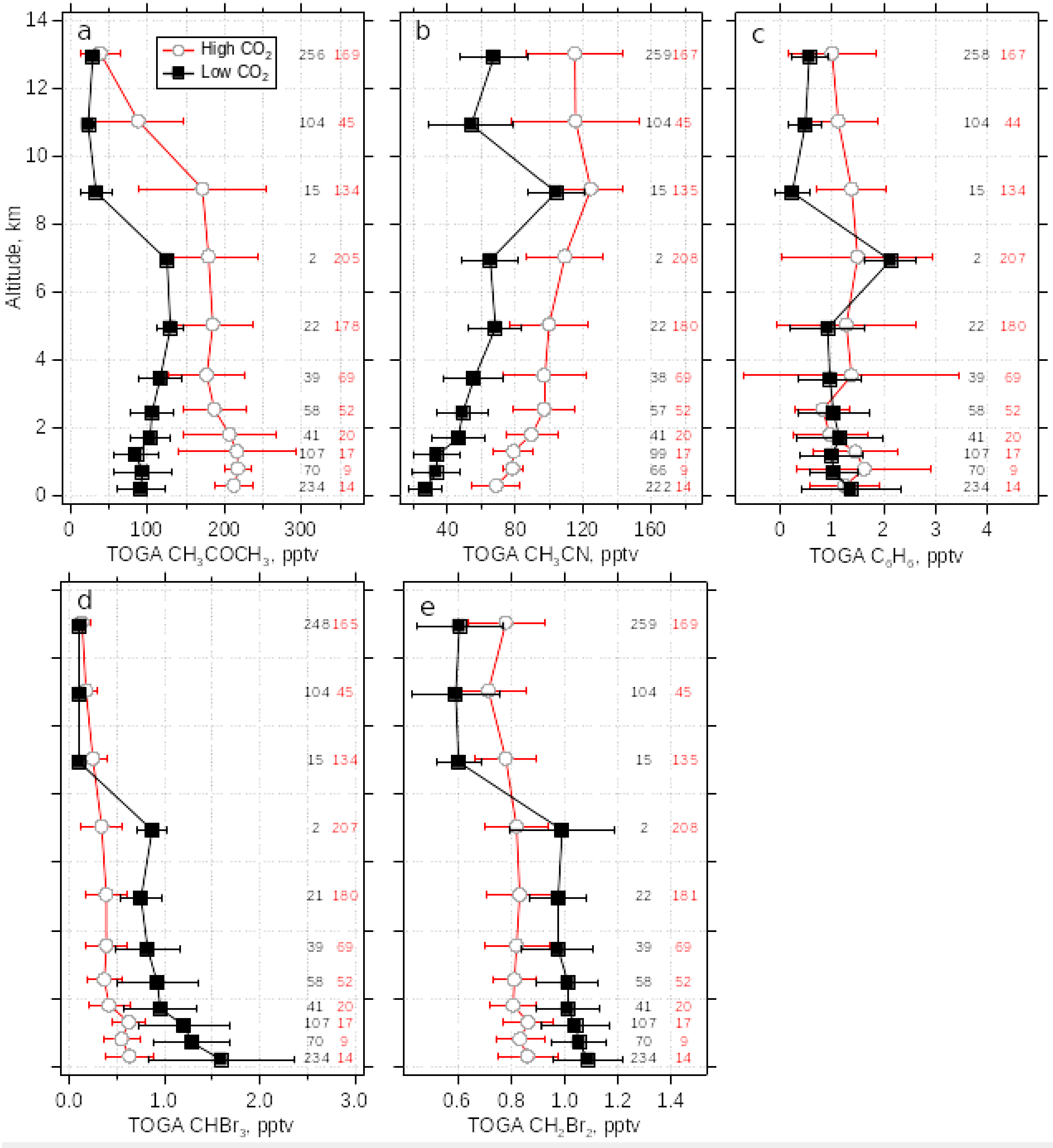

Figure 1. ORCAS observations.

Figure 1 shows a subset of the ORCAS observations as binned altitude profiles of VOC mixing ratios observed by TOGA. The data in each altitude bin are also separated by the corresponding observed CO_2 mixing ratio (high CO_2 ≥ 399 ppm > low CO_2) according to the CO_2 averaged over the timescale of the respective VOC measurement. In Figure 1(a and b), the vertical profiles of acetone and acetonitrile show higher mixing ratios were observed in air with higher CO_2. NMHC less susceptible to ocean uptake such as benzene (Figure 1c), indicate no correlation with CO_2 in the lower troposphere and marine boundary layer, and a small correlation in the mid- and upper troposphere with CO_2. The findings are consistent with continental emissions and interhemispheric transport influencing the mixing ratios of both longer- and shorter-lived gases in the middle and upper troposphere, and loss to the oceans impacting mixing ratios of more soluble gases in the middle and lower troposphere.

The ocean is a primary source for bromoform ($CHBr_3$) and dibromomethane (CH_2Br_2) [e.g., Goodwin et al., 1997], species that have a large impact on natural stratospheric ozone destruction. Figure 1(d and e) shows that bromoform and dibromomethane were anticorrelated with CO_2 in the ORCAS domain in the boundary layer and mid-troposphere to ≈ 6 km. This anticorrelation of ocean-emitted species with CO_2 in the lower atmosphere is consistent with increased ocean uptake of CO_2 in air that has had more interaction with the ocean surface. The ORCAS dataset provides a means to identify biological processes responsible for the emissions and uptake of reactive (VOCs) and non-reactive (CO_2, O_2) gases and explore the relationships and commonalities between the two.

The relationships shown between CO_2 and reactive VOCs demonstrate that the air masses sampled in the ORCAS domain are not uniformly influenced by continental sources or air-sea exchange in marine environments, and provide a mechanism to constrain the relative influence of the ocean surface and long-range transport on the observations of longer-lived gases measured during ORCAS.

‹ NCAR Imperative 1: Conduct innovative fundamental research to advance the atmospheric and related sciences.   up   1.2 Reactions of NO3 Radicals with Some Alkenes ›

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1.2 REACTIONS OF NO3 RADICALS WITH SOME ALKENES

The nitrate radical, NO_3, is a fascinating species. As a result of its rapid photolysis, it is typically only present in very small amounts during the daytime, but can build up to significant concentrations at night. NO_3 is known to react with alkenes by addition to the double bond, and to abstract weakly-bound hydrogen atoms, such as those in aldehydes. The rate constants for NO_3 addition to alkenes increase with the size of the organic molecule, and can become quite rapid with large, biogenic alkenes such as terpenes. Recent field studies in forested areas have suggested that the products of the NO_3-terpene reactions can lead to secondary aerosol formation, and act as a loss for NO_x in these regions. However, the mechanisms of these reactions have not been thoroughly studied. Following addition of NO_3 to the alkene, a series of reactions can lead to the production of alkoxy radicals. The fate of these radicals determines whether the NO_x is released back to the atmosphere, or remains in the organic products, which can enhance the rate of secondary aerosol production.

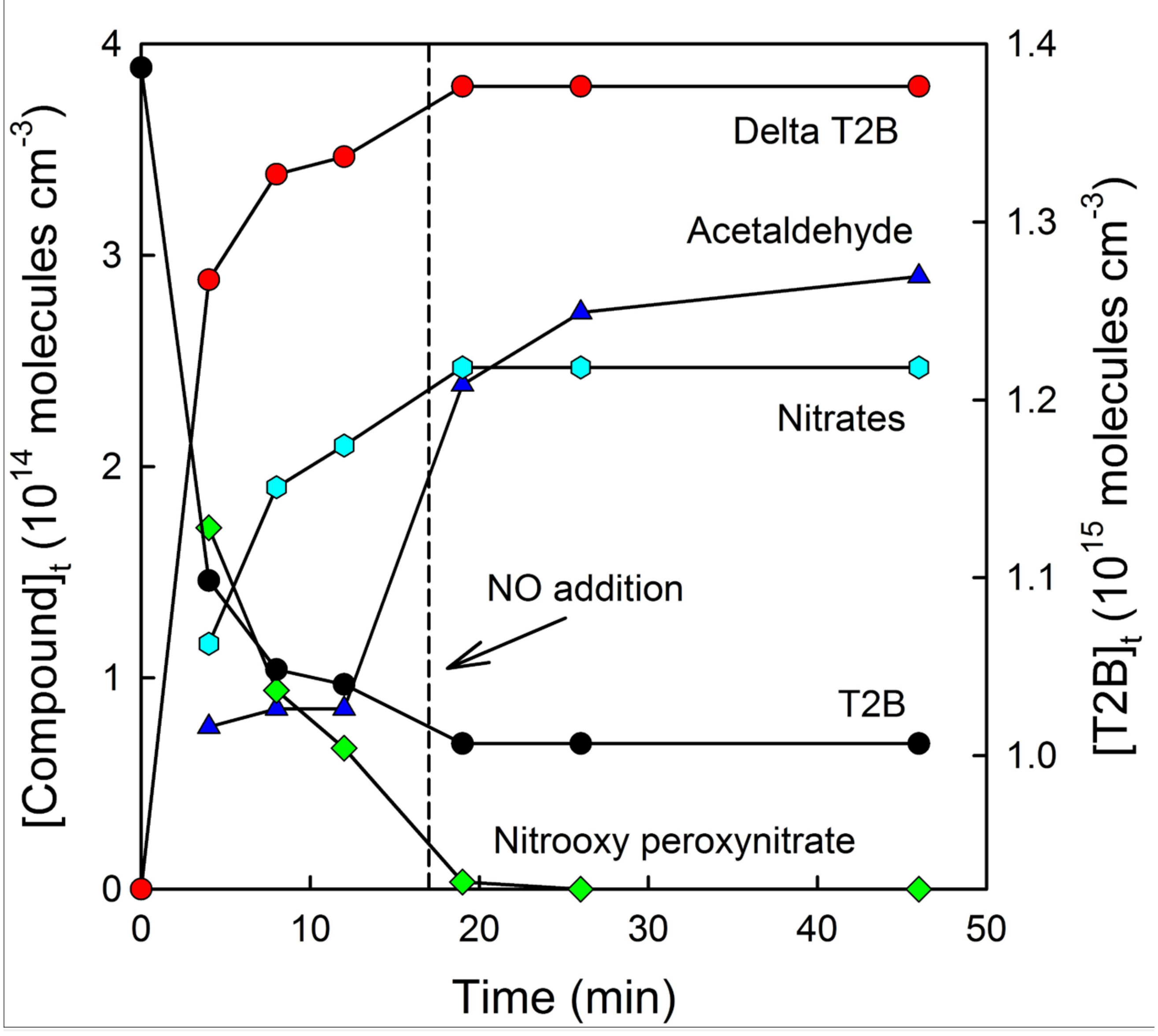

Figure 1. The loss of T2B (black circles, right y-axis), the change in T2B concentration (Delta T2B, red circles, left y-axis), and the concentrations of products formed in the reaction of T2B + NO3: acetaldehyde (blue triangles, left y-axis), nitrooxy peroxynitrate (green diamonds, left y-axis), and nitrates (light blue hexagons, left y-axis). NO was added to the reaction mixture at 19 minutes (indicated by the dashed line) to scavenge peroxy radicals. The solid lines are drawn through the data to aid visual inspection.

Experiments have been performed to study the mechanisms of reactions of the NO_3 radical with a series of linear and branched alkenes in collaboration with Freja Osterstrom (Copenhagen Center for Atmospheric Research, University of Copenhagen, Denmark). These were selected as representative molecules to test our understanding of alkoxy radical behavior, and as a stepping stone to predicting the oxidation products of larger molecules such as terpenes. As an example, some results are shown for trans-2-butene (T2B) in the figure. N_2O_5 was produced in the ACOM environmental simulation chamber, then the T2B was added. Loss of reactants and formation of products was followed by in-situ FTIR spectroscopy. After 19 minutes, NO was added to the system to scavenge any remaining peroxy radicals. On addition of NO, there is a large increase in the concentration of acetaldehyde, formed from the decomposition of 3-nitrooxy-2-butoxy radicals, accompanied by a smaller increase in the formation of nitrate, from the O_2 reaction of the alkoxy radical. The decomposition path is accompanied by release of NO_2 from the radical.

$CH_3CH(ONO_2)\text{-}CH(O)CH_3 \rightarrow CH_3CH(ONO_2) + CH_3CHO \rightarrow 2\ CH_3CHO + NO_2$

$CH_3CH(ONO_2)\text{-}CH(O)CH_3 + O_2 \rightarrow CH_3CH(ONO_2)\text{-}C(=O)CH_3 + HO_2$

Comparison of the products from a number of alkenes with predictions from two currently used chemical mechanisms show that the mechanisms generally capture the behavior observed, but the rate constants differ by an order of magnitude. After a full analysis of the data is complete, improvements to the structure-activity relationships underlying the chemical mechanisms will be possible.

‹ 1.1 The O2/N2 Ratio and CO2 Airborne Southern Ocean (ORCAS) Study | up | 1.3 Lifecycle of semi-volatile organic carbon in the CESM model ›

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1.3 LIFECYCLE OF SEMI-VOLATILE ORGANIC CARBON IN THE CESM MODEL

One of the fundamental challenges for current chemistry-climate models is the representation of the complex lifecycle of semi-volatile organic compounds, which are emitted from the biosphere and anthropogenic activities, and are constantly evolving due to their oxidative chemistry, conversion into secondary organic aerosols (SOA) and interactions with clouds (removal). This is especially the case now that the production of sulfate aerosols has been substantially decreasing, and semi-volatile organic aerosols are becoming the dominant aerosol component for climate forcing. The recent intercomparison study by Tsigaridis et al. (2014) of more than 30 state-of-the-art global chemistry-climate models including CESM1 showed that estimates of the SOA annual production rate are highly uncertain and vary among models by an order of magnitude, which is an issue that needs to be urgently addressed.

In the past year, ACOM scientists have worked intensively on integrating insights from the process- and regional-model studies into the CESM model and estimating the effects on organic aerosol global budgets and lifetime. Typically global models include highly simplified (and often ad hoc and incomplete) approaches to model organic aerosol lifecycle. The ACOM scientists have developed new constraints on both the formation and removal processes of semi-volatile organic gases and aerosols including: (i) updated MOZART gas-phase mechanism to include additional precursors species for organic chemistry, (ii) new production rates corrected for chamber wall losses based on process modeling with GECKO-A (at NCAR) and the Statistical Oxidation Model (SOM, UC Davis), (iii) the production of organics from the emissions of long-chain semi-volatile and intermediate volatility organic compounds from additional anthropogenic sources that were missing in the current emission inventories, (iv) the effect of water-solubility of condensable organic gases and their wet and dry removal, and (v) removal of organics by photo-fragmentation reactions.

The updated CESM simulations have been performed for the 1960-2005 time period, and the results compared against an extensive dataset of ground, aircraft and satellite measurements of organic aerosols to assess the extent to which these improved representations of organic aerosol formation and removal processes are consistent with observed characteristics of their distribution. The updated model presents a more dynamic picture of the lifecycle of atmospheric SOA, with higher production rates and faster sinks than in the traditional model, resulting in a very different vertical distribution of organic aerosols. This work has allowed reconciling for the first time the observed vertical profiles of OA with the predicted ones allowing for a much higher OA concentrations near the surface without creating large overpredictions in the upper troposphere.

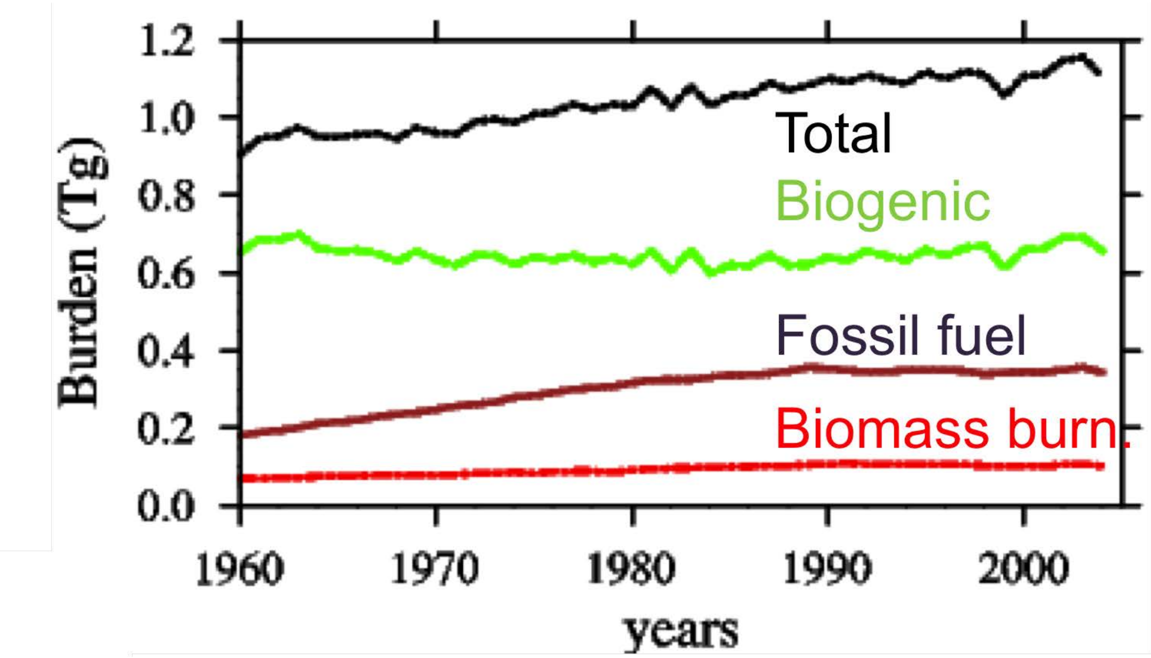

Figure 1: Evolution of the SOA burden from biogenic, fossil fuel and biomass burning sources as predicted by the updated CESM model.

‹ 1.2 Reactions of NO3 Radicals with Some Alkenes up 1.4 Non-linear partitioning and organic volatility distributions of urban aerosols ›

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1.4 NON-LINEAR PARTITIONING AND ORGANIC VOLATILITY DISTRIBUTIONS OF URBAN AEROSOLS

S. Madronich, A. J. Conley, J. Lee-Taylor, A. Hodzic (NCAR/ACOM)
L. I. Kleinman (Brookhaven National Lab)
B. Aumont (U. Paris)

Urban air typically contains large amounts of organic aerosols (OA) composed of emitted hydrocarbons and their atmospheric oxidation products – thousands of different multifunctional organic molecules (aldehydes, ketones, alcohols, and organic nitrates and peroxides) – that can condense to generate particles in a size range (0.1-1.0 μm) critical to both human health and radiative budgets. We used NCAR's detailed chemical model (Generator of Explicit Chemistry and Kinetics of Organics in the atmosphere, GECKO-A) to quantify for the first time the scaling relationships between urban emissions and consequent OA particle mass.

Particle formation and growth is controlled by (i) the saturation vapor pressures of the molecules and (ii) the existing mass of particles into which the gases can dissolve. For pure compounds, the latter condition can induce highly non-linear growth of the particle phase as a function of the total (particle + gas) burden, e.g. supersaturation of water in fogs/clouds. For complex urban OA mixtures, the extent of such non-linearity is less clear because it depends on the vapor pressures of the many different molecules involved, and such data are generally not available from either measurements or models. The question arises whether such non-linearities could be exacerbating already high pollution levels in megacities like Mexico City or Beijing.

We used GECKO-A to simulate the chemical evolution of gases and particles in urban air parcels. Because GECKO-A retains the chemical identity of all molecules produced during hydrocarbon oxidation, it allows explicit computation of thermodynamic properties such as saturation vapor pressure, for every molecule and for the entire system. Figure 1 shows the resulting distribution of organic vapor pressures in Mexico City and its outflow plume, over the course of several days: The initial aerosol (day 1) is dominated by highly volatile material, with relatively small amounts in the particle phase. As oxidation proceeds (days 2-5) the abundance of low volatility molecules increases sharply, leading to condensational growth of particle mass. A sensitivity study using this volatility distribution showed that for a 1.0% increase in the total OA burden (e.g., a 1 % increase in the emission of precursor hydrocarbons), the particle mass will increase by 1.1-1.3%, only slightly more than the 1.0% expected from simple linear growth. Such near-linearity implies that there are no disproportionate benefits of emission reductions. Rather, megacity particulate pollution is not an inevitable convergence of non-linear effects, but can be addressed (much like in smaller urban areas) by rational and proportionate reductions in emissions.

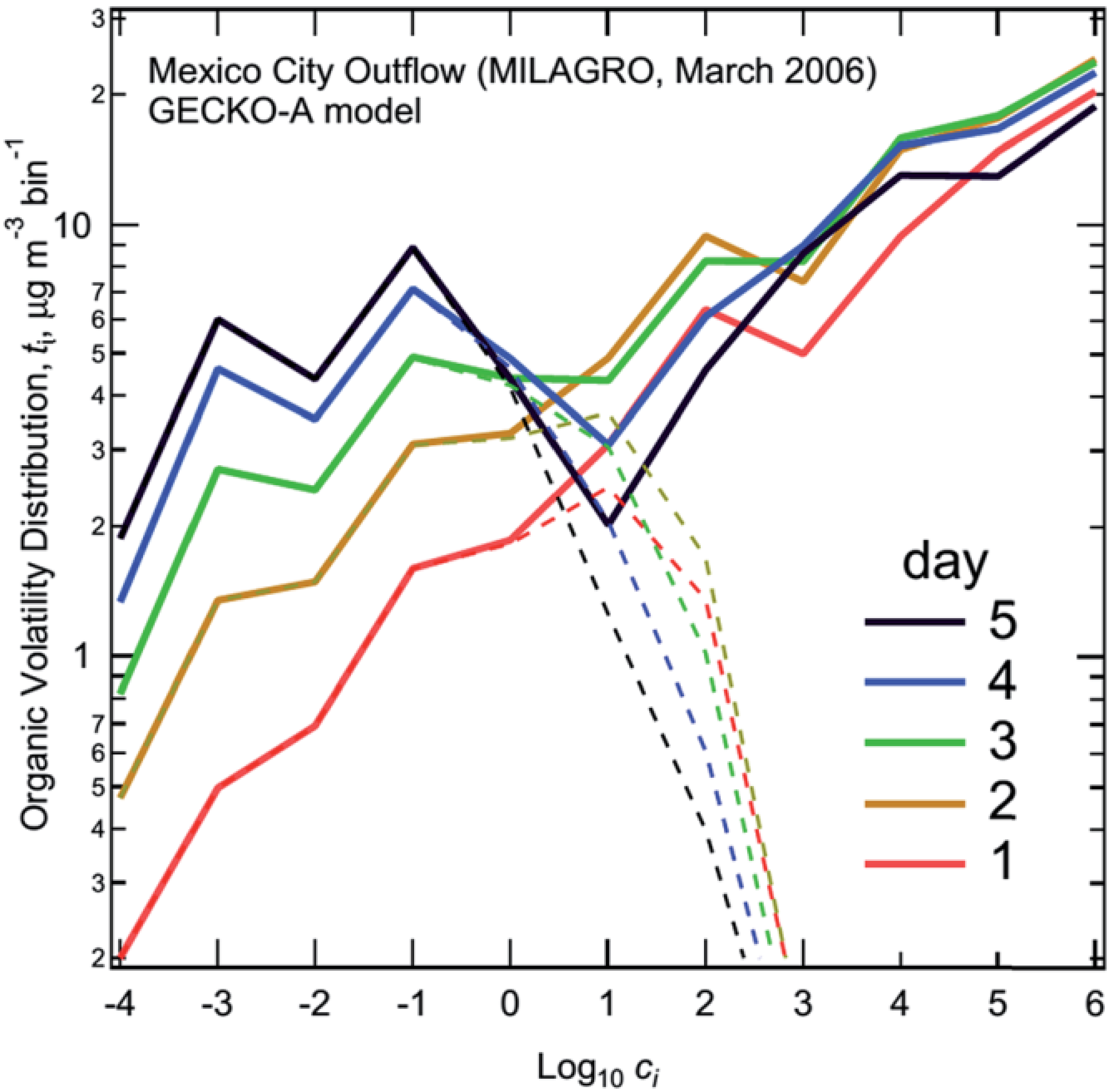

Figure 1: Volatility distribution of organic aerosols in Mexico City outflow, shown as the total amount available t_i (particle + gas, µg/m^3) in each saturation vapor pressure range c_i (µg/m^3). The distribution is shown for five days, the first of which represents the urban environment while the later ones represent multiday outflow. Dashed curves show particle phase.

Madronich, S., A. Conley, J. Lee-Taylor, L. Kleinman, A. Hodzic and B. Aumont, Non-linear partitioning and organic volatility distributions in urban environments, *Royal Soc. Chem. Faraday Discussions*, **189**, 515-528, doi:10.1039/C5FD00209E, 2016.

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1.5 TRANSPORT OF SOLUBLE TRACE GASES IN THUNDERSTORMS

Mary Barth (ACOM/MMM), Megan Bela (U. Colorado), Alan Fried (U. Colorado)

Convective transport is a major pathway for rapidly moving chemical constituents and water from the boundary layer to the upper troposphere and in some cases to the lower stratosphere. These plumes of convective outflow in the upper troposphere are often rich in ozone precursors. Nitrogen oxides are formed from lightning, while volatile organic compounds, peroxides, and formaldehyde are transported from the boundary layer. However, the key precursors, hydrogen peroxide, methyl hydrogen peroxide, and formaldehyde, are soluble and can be partially removed from the atmosphere via dissolution into cloud drops that grow into precipitation. ACOM and university scientists estimated the fraction of these peroxides and formaldehyde removed by thunderstorms that were observed during the Deep Convective Clouds and Chemistry (DC3) field campaign, which took place over the central U.S. in May and June 2012.

The DC3 aircraft sampled the composition of the air in both the low-level inflow region and the upper-level outflow region (where the visible anvil is). Vertical profiles by the aircraft measured trace gas concentrations in clear sky outside the storms. Using these data, investigators determined the entrainment rate of clear air into the storm with trace gases that are not soluble or chemically changing over a several hour period. The scavenging efficiency of peroxides and formaldehyde could be determined by comparing the measured outflow concentrations to the estimated concentrations if the soluble trace gas were only transported, using the entrainment rate model. Fried et al. (2016) found formaldehyde scavenging efficiencies were 41-58% for storms sampled in Oklahoma, Colorado, and Arkansas. Barth et al. (2016) estimated that the more soluble hydrogen peroxide scavenging efficiencies were > 77% while the less soluble methyl hydrogen peroxide scavenging efficiencies were 12-84%. The high scavenging efficiencies found for methyl hydrogen peroxide are surprising and may be caused by entrainment of low concentrations of the species into the storm and/or cloud physical processes. Simulations performed by WRF-Chem reveal that methyl hydrogen peroxide scavenging efficiencies vary depending on the fraction of the trace gas retained in frozen cloud particles as cloud drops freeze (Bela et al., 2016). The low concentrations of methyl hydrogen peroxide in upper-level, convective outflow regions is crucial to understand, as previous studies have suggested that methyl hydrogen peroxide is the primary precursor producing ozone in these regions.

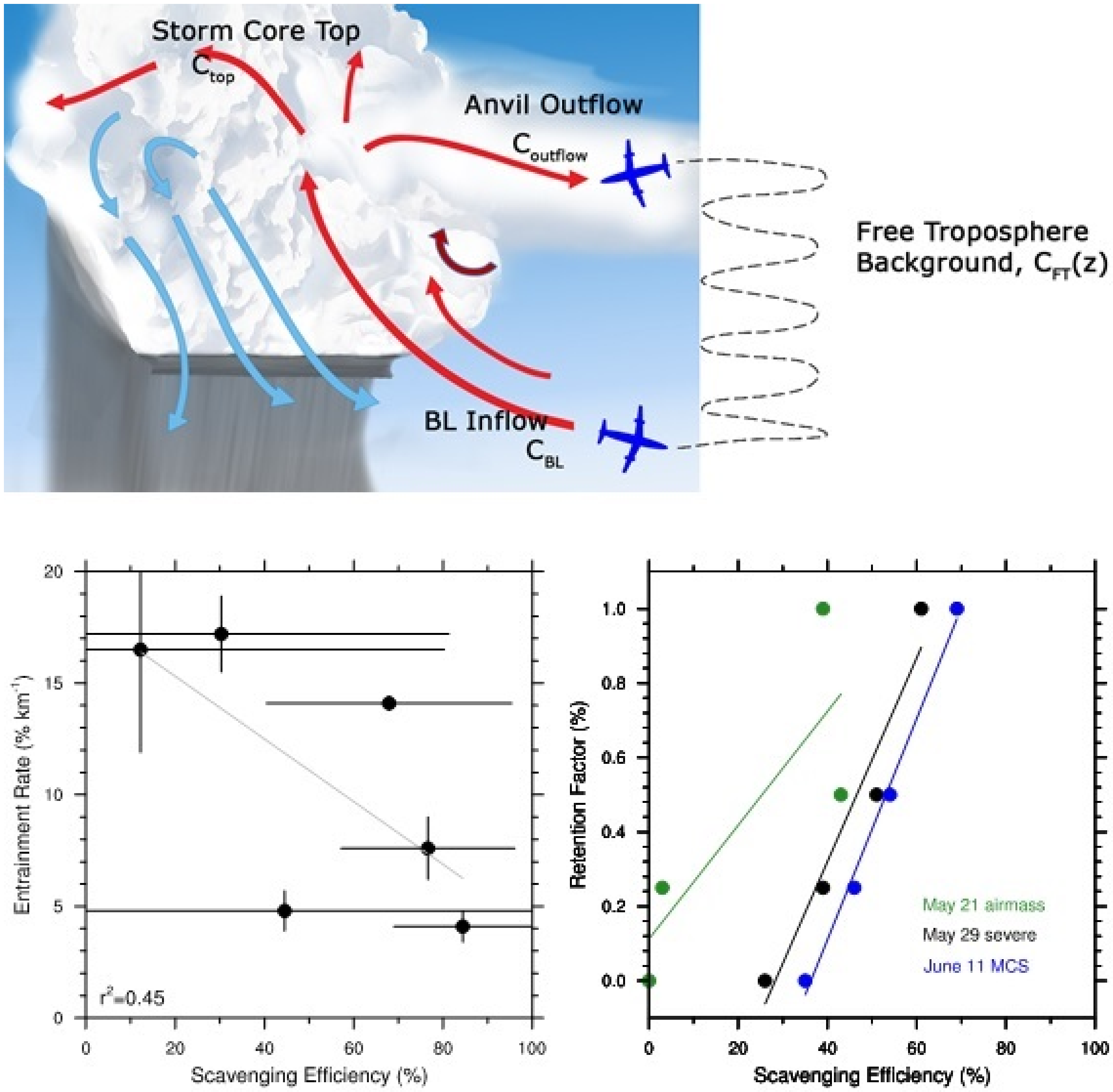

Figure 1. a) Air motions associated with deep convection in an environment with high vertical wind shear. The schematic is annotated with locations of the measured trace gas mixing ratios in the boundary layer inflow, free troposphere background, anvil outflow, and storm core top. b) Correspondence of the scavenging efficiency of methyl hydrogen peroxide and entrainment for 6 DC3 storms. Values are derived from observations. c) Correspondence between methyl hydrogen peroxide scavenging efficiency and the retention factor of methyl hydrogen peroxide in drops that are freezing. Values are from WRF-Chem simulations of three different thunderstorms.

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1.6 EVALUATING STRATOSPHERIC TEMPERATURE TRENDS IN WACCM

The temperature of the stratosphere has decreased over the last several decades because of the combined effects of increases in well-mixed greenhouse gases (GHGs) and changes in stratospheric ozone. How well is this behavior simulated in current generation chemistry-climate models? Recent work in ACOM has aimed at deriving updated estimates of stratospheric temperature changes from satellite measurements (beginning in 1979), and making detailed comparisons with simulations from WACCM.

The observational record of satellite temperature changes in the middle and upper stratosphere has recently been updated (1979-2015) based on combining measurements from SSU, MLS and SABER satellite instruments (Randel et al., 2016), and these data are available to the wider community (https://acomstaff.acom.ucar.edu/randel/SSU%20data.html). Time series of global average temperature anomalies from these data are shown in Fig. 1, compared to WACCM results (this version of WACCM includes specified SSTs, observed changes in greenhouse gases and ozone depleting substances, along with volcanic and QBO effects). Overall the model shows excellent agreement to satellite observations for the global averages, including long-term stratospheric cooling, solar cycle and volcanic effects. Current work is aimed at understanding detailed behavior of the long-term temperature changes and difference among separate WACCM realizations.

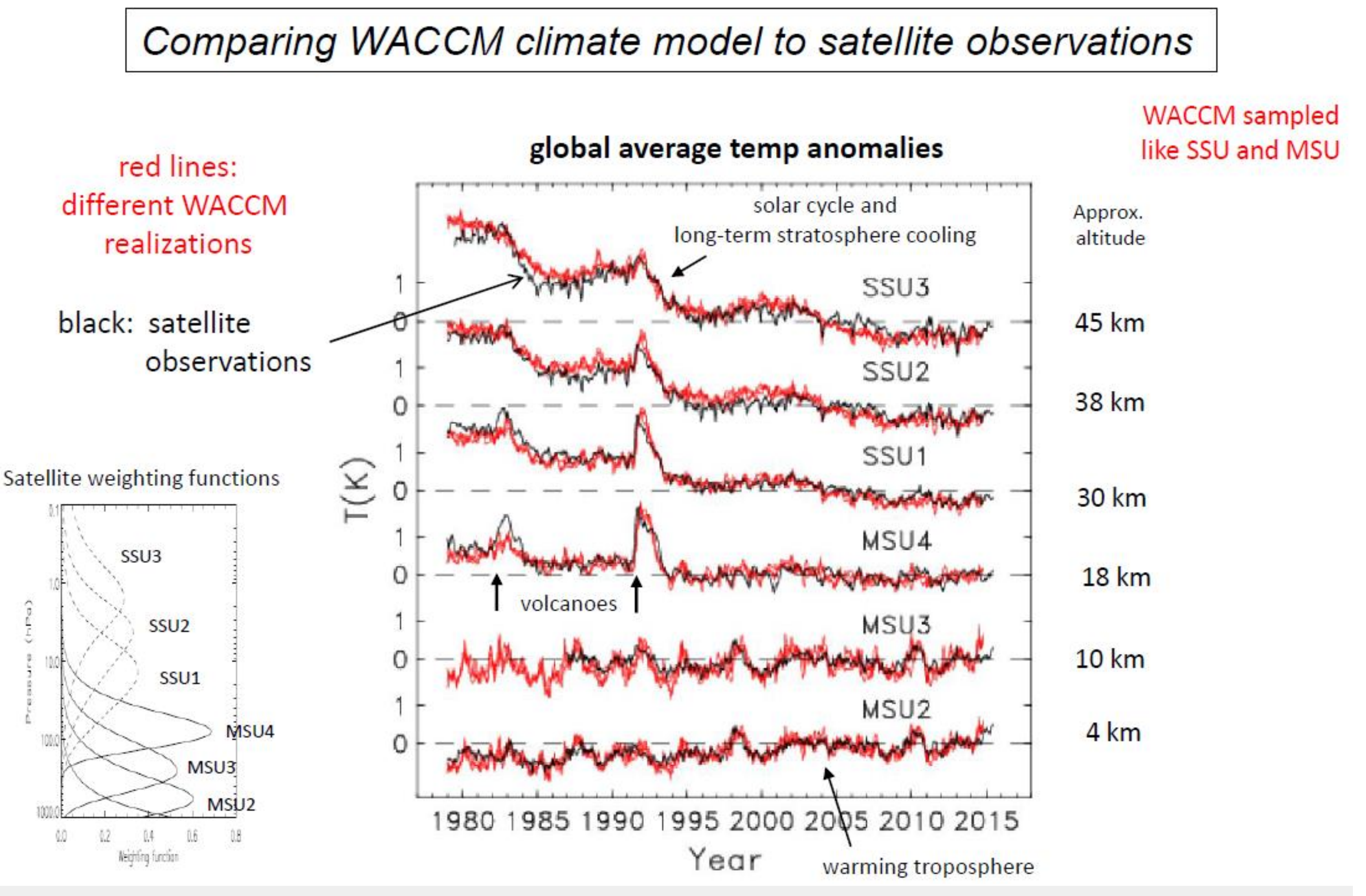

Figure 1. Time series of global average temperature anomalies for 1979-2015 derived from satellite measurements (black lines) for different satellite channels (with weighting functions shown at left, covering altitudes from the lower troposphere to the upper stratosphere). Red lines show the corresponding results from three separate WACCM realizations.

Randel, W.J., A.K. Smith, F. Wu, C.-Z. Zou and H. Qian, 2016: Stratospheric temperature trends over 1979-2015 derived from combined SSU, MLS and SABER satellite observations. J. Climate, 29, 4843-4859, doi:10.1175/JCLI-D-15-0629.1

‹ 1.5 Transport of Soluble Trace Gases in Thunderstorms | up | 1.7 Dry, ozone-rich layers in the tropical troposphere as a fingerprint of UTLS transport ›

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1.7 DRY, OZONE-RICH LAYERS IN THE TROPICAL TROPOSPHERE AS A FINGERPRINT OF UTLS TRANSPORT

The Convective Transport of Active Species in the Tropics (CONTRAST) experiment was an aircraft-based field campaign conducted from Guam (14^o N, 145^o E) during January-February 2014. Aircraft measurements included over 80 vertical profiles from the boundary layer to the upper troposphere (~15 km), and a large fraction of these profiles revealed layered structures with very low water vapor (relative humidity < 20%) and enhanced ozone, primarily in the lower-middle troposphere (~3-9 km). Comparing CONTRAST water vapor measurements with co-located profiles from NCEP Global Forecast System (GFS) analyses showed overall good agreement for dry layers, including profile-by-profile comparisons and statistical behavior. The GFS data provide a global perspective to the campaign measurements, and allow analysis of the climatological spatial structure and frequency of subtropical dry air. GFS data show that dry layers occur ~50-80% of the time in the subtropical troposphere, maximizing on the equatorward side of the subtropical jets in the winter hemisphere (see Fig. 1). Subtropical dry layers occur most frequently over isentropic levels ~320-340 K, which extend into the extratropical upper troposphere-lower stratosphere (UTLS). Similar statistical behavior of dry, ozone-rich layers is found in long-term balloon measurements from Reunion Island (21^o S, 56^o E). The climatologically frequent occurrence of dry, ozone-rich layers, plus their vertical and spatial structure linked to the subtropical jets, all suggest that dry layers are linked to quasi-isentropic transport from the extratropical UTLS. These results demonstrate a ubiquitous UTLS influence on the subtropical troposphere.

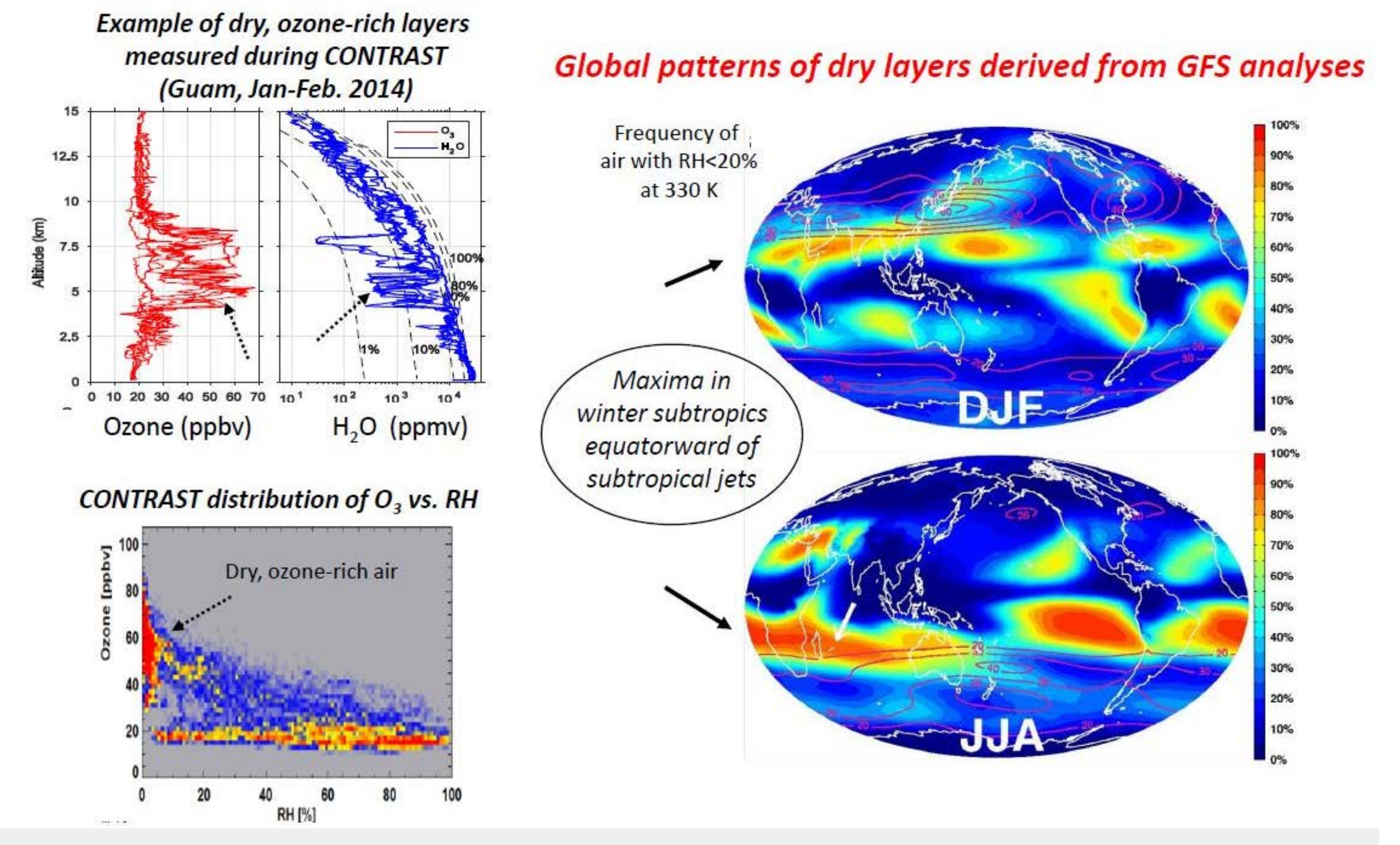

Figure 1. Upper left: Example of CONTRAST aircraft measurements showing dry, high ozone layers in the tropical Pacific. Lower left: Two-dimensional distribution of ozone vs. relative humidity (RH) for all of the CONTRAST vertical profiles. Right: Global climatology of

dry layers derived from GFS meteorological analyses (frequency of air with RH < 20%), during DJF and JJA. These results are for the 330 K isentrope, which is near 5 km in the tropics.

Randel, W.J., L. Rivoire, L. Pan and S. Honomichl, 2016: Dry layers in the tropical troposphere observed during CONTRAST and global behavior from GFS analyses. *J. Geophys. Res.*, in press.

‹ 1.6 Evaluating stratospheric temperature trends in WACCM | up | 1.8 Emergence of healing in the Antarctic ozone layer ›

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1.8 EMERGENCE OF HEALING IN THE ANTARCTIC OZONE LAYER

Antarctic ozone depletion has been a focus of attention for scientists, policy-makers, and the public for over three decades. The fundamentals of polar ozone depletion are well known and driven by chlorine and bromine chemistry linked to industrial halocarbon emissions. Ozone-depleting halocarbons have been phased out under the Montreal Protocol and subsequent amendments starting in the 1990s. In response to this historic agreement, a chemically driven increase in polar ozone is expected. Ozone recovery involves multiple stages, starting with (i) a reduced rate of decline followed by (ii) a leveling off of the depletion and (iii) an identifiable ozone increase that can be linked halocarbon reduction. This third stage of recovery can be referred to as “healing”. In **Figure 1**, this healing is shown for the post-2000 period for both observations (i.e., Solar Backscatter Ultra-Violet satellite (SBUV); ground-based South Pole station) and model calculations. The model calculations were carried out with the Community Earth System Model 1 (CESM1) Whole Atmosphere Community Climate Model (WACCM), which is a fully coupled state-of-the-art interactive chemistry climate model. We used the specified dynamics option, SD-WACCM, in which meteorological fields, including temperature and winds, are derived from observations. The analysis fields allow the time-varying temperature-dependent chemistry that is important for polar ozone depletion to be simulated in detail. This work included four WACCM-SD simulations for the post-2000 period: 1) all chemical, dynamical processes with volcanic eruptions (Chem-Dyn-Vol); 2) same as 1), but without volcanic eruptions (Vol-Clean); 3) repeating year 1999 meteorology showing only the impact of halogen recovery chemistry (Chem-Only); and 4) one simulation for pre-2000 period based on the Chemistry Climate Model Initiative (CCMI). This simulation includes volcanic eruptions.

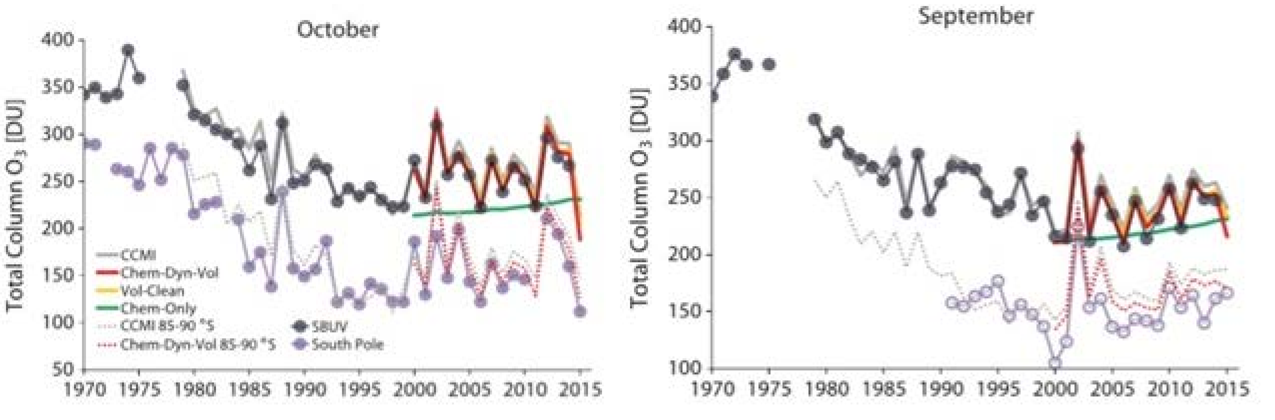

Figure 1. Monthly averaged Antarctic total ozone column for October and September, from SBUV and South Pole station observations and a series of model calculations. Total ozone data measured at the geographic South Pole are from Dobson observations (filled circles) for October (left) and balloon sondes (open circles) for September (right), when there is not sufficient sunlight for the Dobson. SBUV data for each month are compared with model runs averaged over the polar cap latitude band that is accessible by the instrument; South Pole station data are compared with simulations for 85°S to 90°S.

This work shows for the first time that chemical recovery is occurring. Observations and model calculations together indicate that healing of the Antarctic ozone layer has now begun to occur during the month of September (**Figure 2**). This is not yet true for October where dynamical variability is too large relative to chemical recovery. Fingerprints of September healing since 2000 include (i) increases in ozone column amounts, (ii) changes in the vertical profile of ozone

concentration, and (iii) decreases in the areal extent of the ozone hole. Along with chemistry, dynamical and temperature changes have contributed to the healing but could also represent feedbacks to chemistry. Volcanic eruptions have episodically interfered with healing, particularly during 2015, when a record October ozone hole occurred after the Calbuco eruption. Our results underscore the combined value of balloon and satellite ozone data, volcanic aerosol measurements, and a chemistry-climate model in documenting progress in the recovery of the ozone layer since the Montreal Protocol.

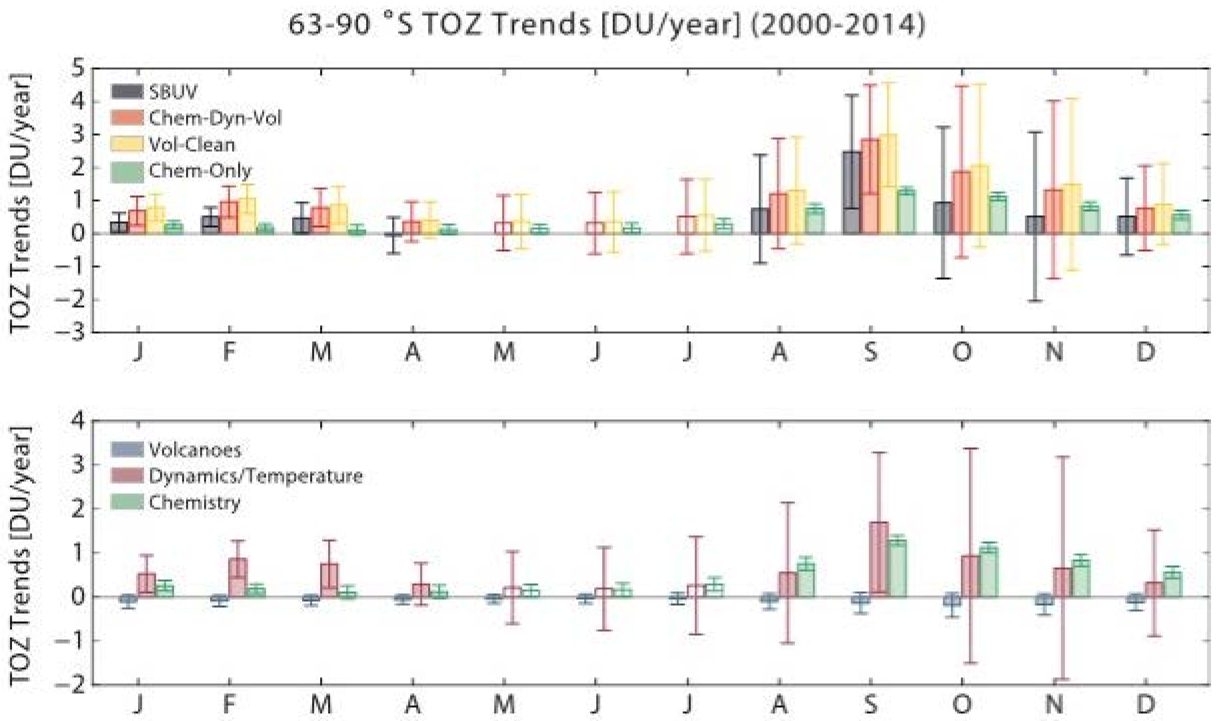

Figure 2. Model trends in total ozone abundance (TOZ) by month from 2000 to 2014. Error bars denote 90% statistical confidence intervals. Contribution to the simulated monthly trends in TOZ driven by dynamics and temperature, chemistry only, and volcanoes.

PUBLICATION:

Solomon, S., D. J. Ivy, D. E. Kinnison, M. J. Mills, R. R. Neely III, and A. Schmidt, Emergence of healing in the Antarctic ozone layer, *Science,* 353, 269-274, 2016.

‹ 1.7 Dry, ozone-rich layers in the tropical troposphere as a fingerprint of UTLS transport | up | NCAR Imperative 2: Develop, maintain and deploy advanced observational facilities and services. ›

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2.1 UPDATE ON ACTIVITIES OF ACCORD (ATMOSPHERIC CHEMISTRY CENTER FOR OBSERVATIONAL RESEARCH AND DATA)

The ACCORD is a relatively new partnership between NCAR's Atmospheric Chemistry Observations and Modeling (ACOM) Laboratory, 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.

ACCORD is governed by a Science Committee (consisting of 6 University and 3 NCAR scientists, and an NSF representative, https://www2.acom.ucar.edu/accord/science-committee) that was formed in spring 2014. A major initial effort was a community workshop (held in Boulder, Spring 2015) that was designed to obtain a bottom-up consensus on major science questions facing our field and the facilities needed to answer these questions. Activities resulting from discussions at the 2015 workshop are now being undertaken, and science ideas developed at the workshop are coming to fruition. Among the activities carried out in 2016, or being planned for the near future, under the ACCORD umbrella include the following:

1) A community workshop on Atmospheric Radiation science, see the summary elsewhere in this Annual Review.

2) A community workshop on Cloud Water chemistry, see the summary elsewhere in this Lab Annual Review.

3) The initiation of an ACCORD Seminar Series hosted by ACOM. Five speakers presented seminars in 2016, and a similar number is planned for 2017. The seminars were given by a diverse group of scientists, ranging from tenured professors to newly-appointed faculty.

4) Planning for a ‘virtual campaign’ on science topics related to biomass burning. One of the ideas put forward at the ACCORD workshop (and echoed by the recent NAS report on the future of atmospheric chemistry) is that there is often insufficient time and funds available to properly analyze and derive scientific conclusions from field campaign data. Thus, ACCORD, ACOM and the International Global Atmospheric Chemistry (IGAC) program are partnering to host a workshop aimed at initiating and promoting the coordinated re-analysis of field campaign data associated with biomass burning. The workshop will be held in Summer 2017 in Boulder.

5) An ACCORD aircraft inlet subcommittee was formed to report on the state of the science regarding aircraft inlets. The committee report is available at the ACCORD website, https://www2.acom.ucar.edu/sites/default/files/accord/InletCommiteeRepor.... A proposal addressing was recently funded by NSF Atmospheric Chemistry, and work is underway (involving collaboration between NCAR ACOM and EOL, Clarkson University, and Denver University) to develop four new inlets:

a) a new turbulent inlet for the measurement of ‘sticky’ compounds, such as nitric acid, organic acids and ammonia.
b) an inlet for use in the GV large wing-pods, for the measurement of reactive gases and/or radicals.
c) a low turbulence inlet for the sampling of large particles, and possibly for highly reactive gases.
d) a side-facing particle-rejection inlet for accurate sampling of gas-phase compounds.

‹ NCAR Imperative 2: Develop, maintain and deploy advanced observational facilities and services.   up   2.2 NASA Atmospheric Tomography mission (ATom) ›

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2.2 NASA ATMOSPHERIC TOMOGRAPHY MISSION (ATOM)

The goal of the NASA Atmospheric Tomography mission (ATom), led by Steve Wofsy (Harvard) and conducted using the NASA DC-8 aircraft, is to identify and quantify human impacts on the chemistry of the remote atmosphere. ACOM scientists provided key data: 1) spectrally resolved down- and up-welling in situ ultraviolet and visible actinic flux measurements from approximately 280-650 nm (Hall and Ullman, CAFS instrument) and 2) speciated measurements of a wide range of

VOCs (Apel, Hornbrook, and Hills) using the Trace Organic Gas Analyzer (TOGA). The ATom-1 campaign consisted of eleven research flights covering a wide longitudinal and latitudinal range (Figure 1) and investigated the vertical chemical structure from 0-11 km in both the Atlantic and Pacific.

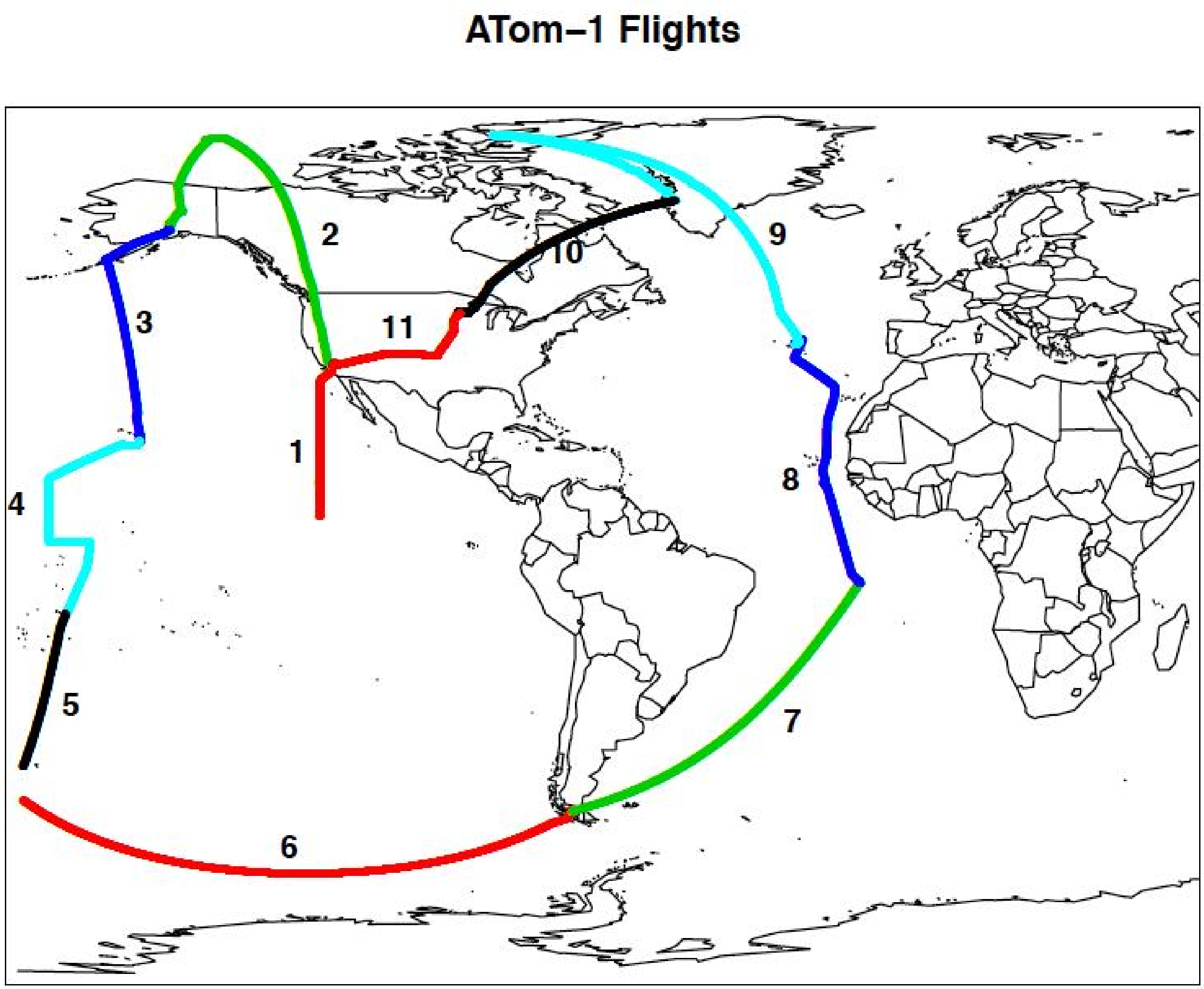

Figure 1. DC-8 flight tracks for the 11 ATom-1 research flights.

Among the VOCs measured by TOGA was acetonitrile (CH_3CN), a biomass burning (BB) tracer. Figure 2b displays measurements of CH_3CN in both the Pacific and the Atlantic clearly showing air that was impacted by Siberian fires in the Pacific and African fires over the equatorial Atlantic. Figure 2a shows O_3 measurements over the same regime with strong indications that the fires were responsible for the large enhancements of tropospheric ozone in these regions.

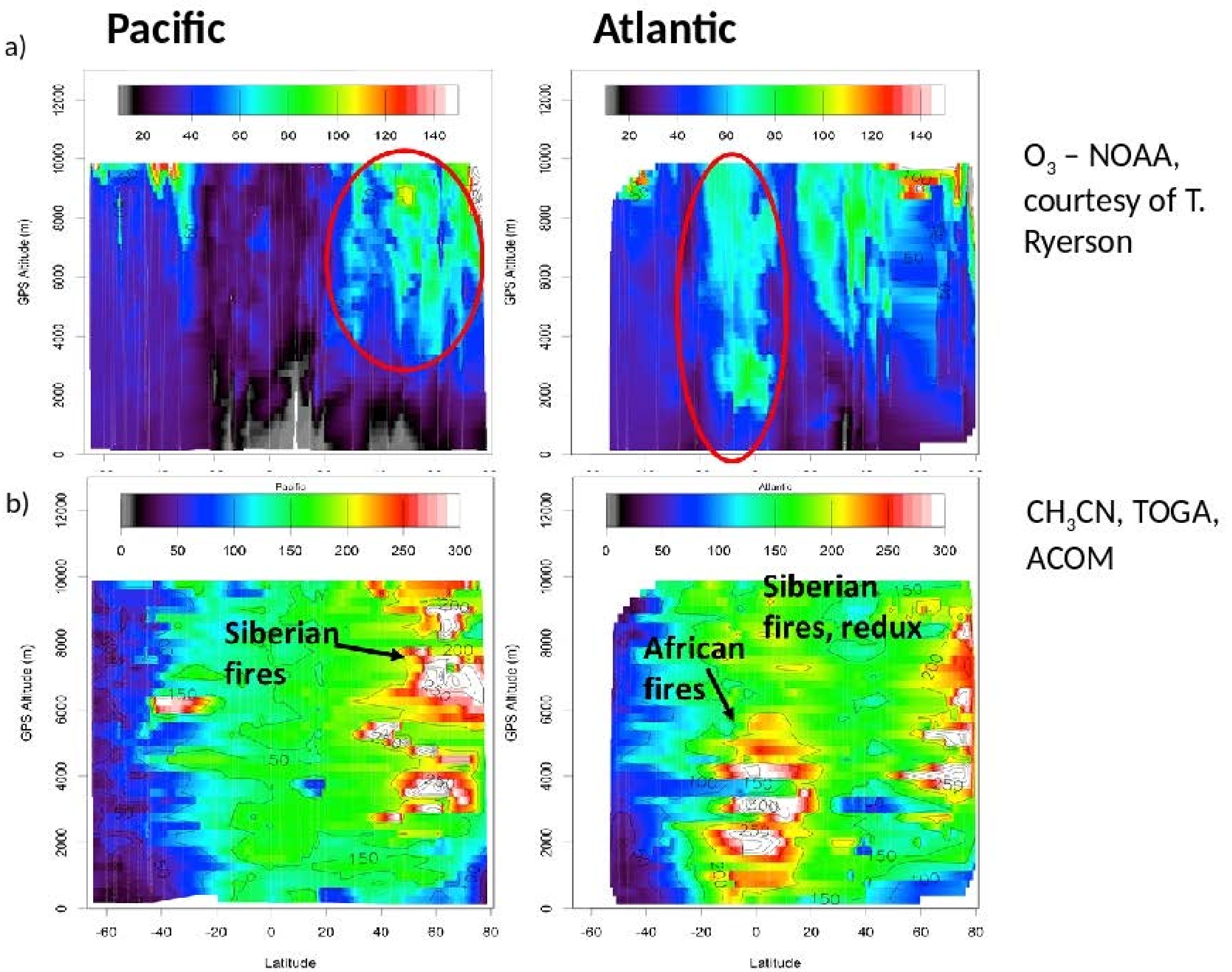

Figure 2. Interpolated curtain plots obtained during ATom-1 for a) ozone (O3) and b) acetonitrile CH3CN)

‹ 2.1 Update on Activities of ACCORD (Atmospheric Chemistry Center for Observational Research and Data) up 2.3 Chemical Measurements at the PROPHET Field Station in Michigan ›

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2.3 CHEMICAL MEASUREMENTS AT THE PROPHET FIELD STATION IN MICHIGAN

ACOM Scientists participated through the month of July 2016 in a field campaign in a forested area of Northern Michigan. The PROPHET-AMOS campaign – Program for Research on Oxidants; Photochemistry, Emissions and Transport - Atmospheric Measurements of Oxidants in Summer – took place at the PROPHET

PROPHET Tower at the University of Michigan.

Lab and Tower at the University of Michigan Biological Station near Pellston, MI (shown in photo). The goal of the project was to study the cycling of chemicals between the biosphere and the atmosphere, and to understand the roles of various oxidants in the system. The project involved a comprehensive suite of measurements of ambient concentrations of biogenic organic compounds, their oxidation products, and various oxidants (O_3, OH, HO_2 and peroxy radicals RO_2). Approximately 20 research groups participated; ACOM's team (Geoff Tyndall, John Ortega, Deedee Montzka, and Andy Weinheimer) measured concentrations of NO and NO2 from a manifold running from the top of the 100-ft tall tower down to the lab. Other instruments either sampled from the manifold or, in the case of measurements of highly reactive (or low-volatility) compounds, were positioned directly on the tower to avoid delays between sampling and measurement. Rates of emission of a number of compounds were also measured by eddy correlation and gradient techniques, as well as by direct measurements employing enclosures placed over branches and over the soil.

The forest consists of a mixture of broad leaf and coniferous trees, most of a similar age and height. The chemistry was dominated by isoprene emissions, and up to 90% of the OH reactivity was due to isoprene. The ambient NOx concentrations were found to be very low, and were probably usually dominated by local soil emissions. A typical pattern showed NO2 building up during the night, then dropping after daybreak, as the boundary layer rose. NO, which was typically zero at night, was produced in the early morning from photolysis of NO2, but also decreased by late morning as the NO2 was vented. Two full days of NO_2 and NO data are shown in the Figure.

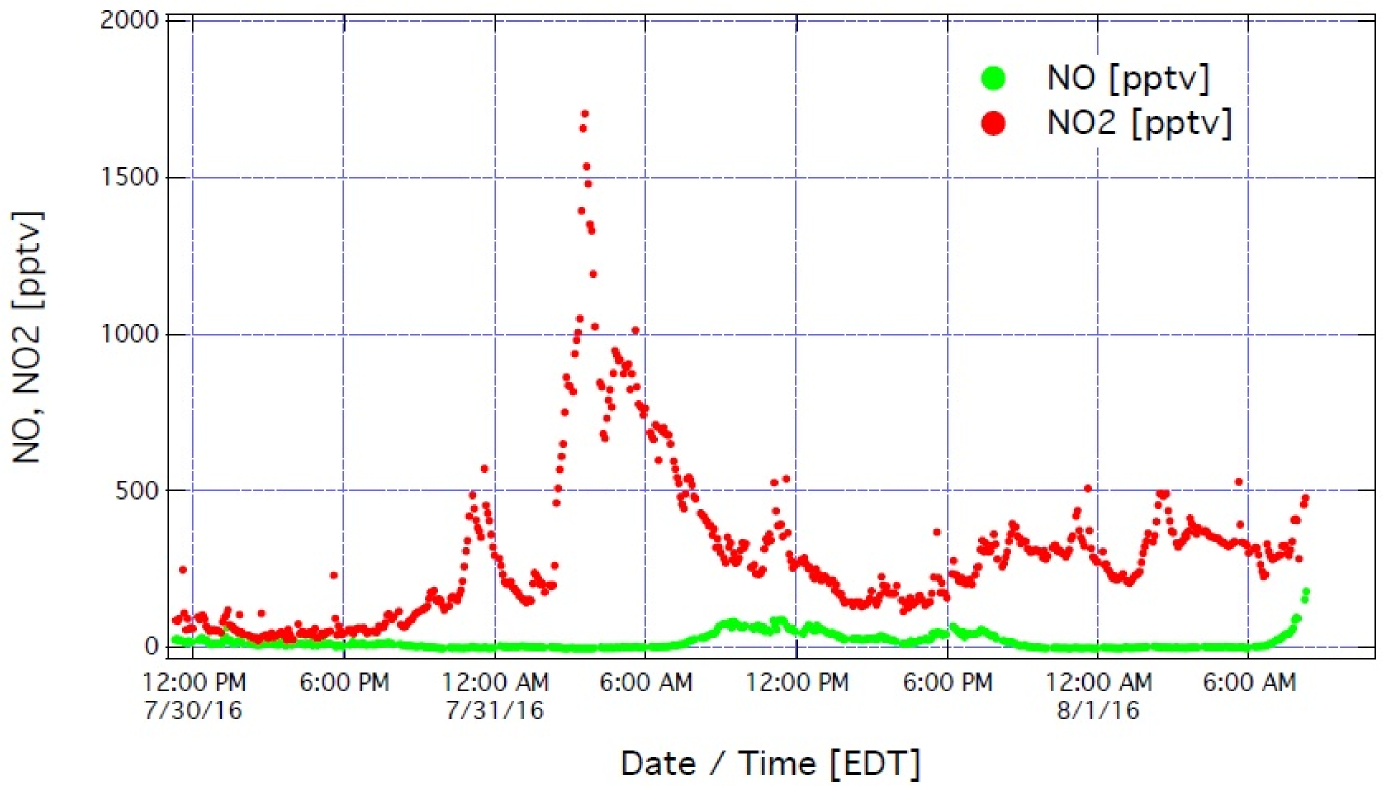

Figure 1. NO_2 and NO data from PROPHET field campaign.

A number of the measurements were made more challenging by the low concentrations. One of the project organizers, Steve Bertman (Western Michigan University) noted that since such campaigns began in 1998, the levels of anthropogenic pollutants at the site have dropped noticeably. Under the low concentrations of NO encountered, peroxy radicals react at similar rates with NO and HO_2, making for a rich suite of product molecules including nitrates and peroxides. As anthropogenic NOx levels continue to decline as a result of tighter emissions controls, more and more of the continental US will be in such a transition region between NOx-dominated and NOx-limited chemistry. The results from the PROPHET study will provide interesting insights into the fascinating and vigorous chemistry occurring in this setting.

‹ 2.2 NASA Atmospheric Tomography mission (ATom) | up | 2.4 Coronal Spectral measurements in the mid-IR during the Solar Eclipse of 2017 ›

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2.4 CORONAL SPECTRAL MEASUREMENTS IN THE MID-IR DURING THE SOLAR ECLIPSE OF 2017

As part of the larger ground and airborne project we plan to measure, for the first time, the infrared spectrum of the solar corona from 2 to 12 μ. No such IR spectral survey of the corona has ever been performed, yet some of the most magnetically sensitive spectral lines are theoretically predicted in this region. All of the infrared coronal lines are forbidden

lines of magnetic dipole character. We do not know how infrared emission line intensities are distributed in the corona, nor do we know wavelengths accurately enough to determine detrimental effects of telluric absorption on these particular lines. The project is led by NCAR/HAO, the G-V is operated by NCAR/EOL, the primary airborne instrument is from SAO (Smithsonian Astronomical Observatory) and the ground-based IR survey is by NCAR/ACOM.

The experiments are planned to fly on the Gulfstream V (GV) aircraft to accompany a spectral survey from the ground, producing images of the corona and polarization measurements during the extended eclipse afforded by the aircraft platform. The main science goals are (1) to identify spectral lines ideally suited to measure coronal magnetic fields, (2) to find the range of temperatures spanned by the lines (ions from 6 to 14 times ionized), (3) to identify the typical range of features sampled by the lines (active regions, source regions of fast and slow solar wind) and (4) to find precisely where coronal lines lie relative to telluric absorption features.

Our proposed experiments will collectively provide the information needed to build the next generation of instruments probing the magnetic structure of the solar corona, and thus put the origins of space weather events on a quantitative footing. The National Science Foundation's (NSF's) huge investment in the Daniel K. Inouye Solar Telescope (DKIST) and future investment in the COronal Solar Magnetism Observatory (COSMO) will especially benefit from these new experiments. We anticipate publications identifying optimal spectral lines for future work, the origins and nature of noise in coronagraphic polarimetric data by comparison with eclipse data, and analysis of the magnetic and dynamical state of the corona using infrared (IR), X-ray and Extreme Ultraviolet Variability Experiment (EUV) data from operating spacecraft.

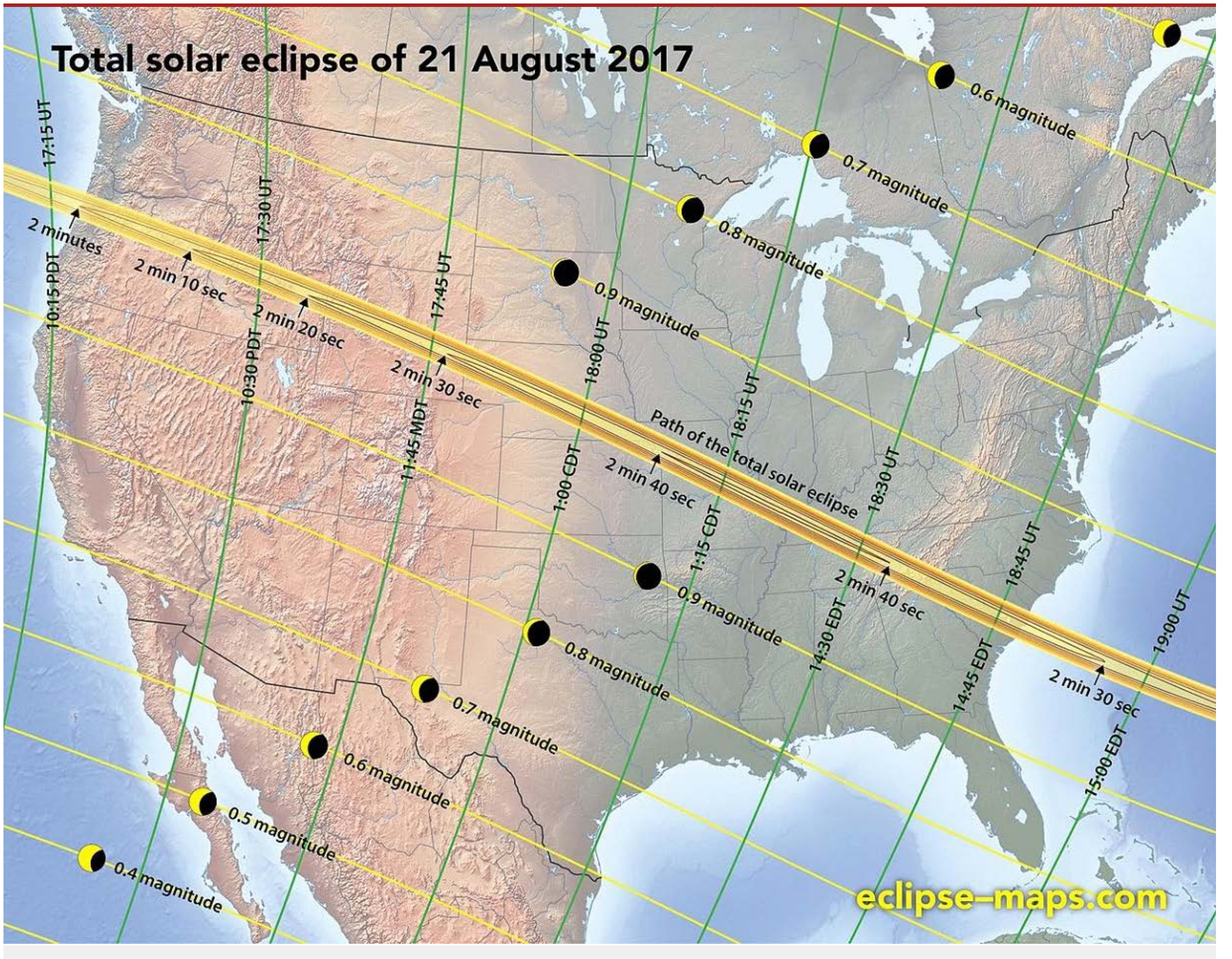

Figure 1. Path of total solar eclipse 21 August 2017.

The eclipse will occur on 21 August 2017 near mid-day. Figure 1 shows the path of totality across the continental US. The ACOM instrument will be stationed on a mountain top at approximately 2900masl near Casper Wyoming and less then 2km off the path of totality. The instrument originally designed as a replacement for the long time airborne FTIR program at ACOM will be fitted into a trailer along with solar tracking capability for this experiment. The instrument shown in Figure 2, is a compact multi-pass Michaelson interferometer designed to operate at variable optical paths to 250cm and acquire spectra from 1.5 to 14 µm using cryogenically cooled detectors.

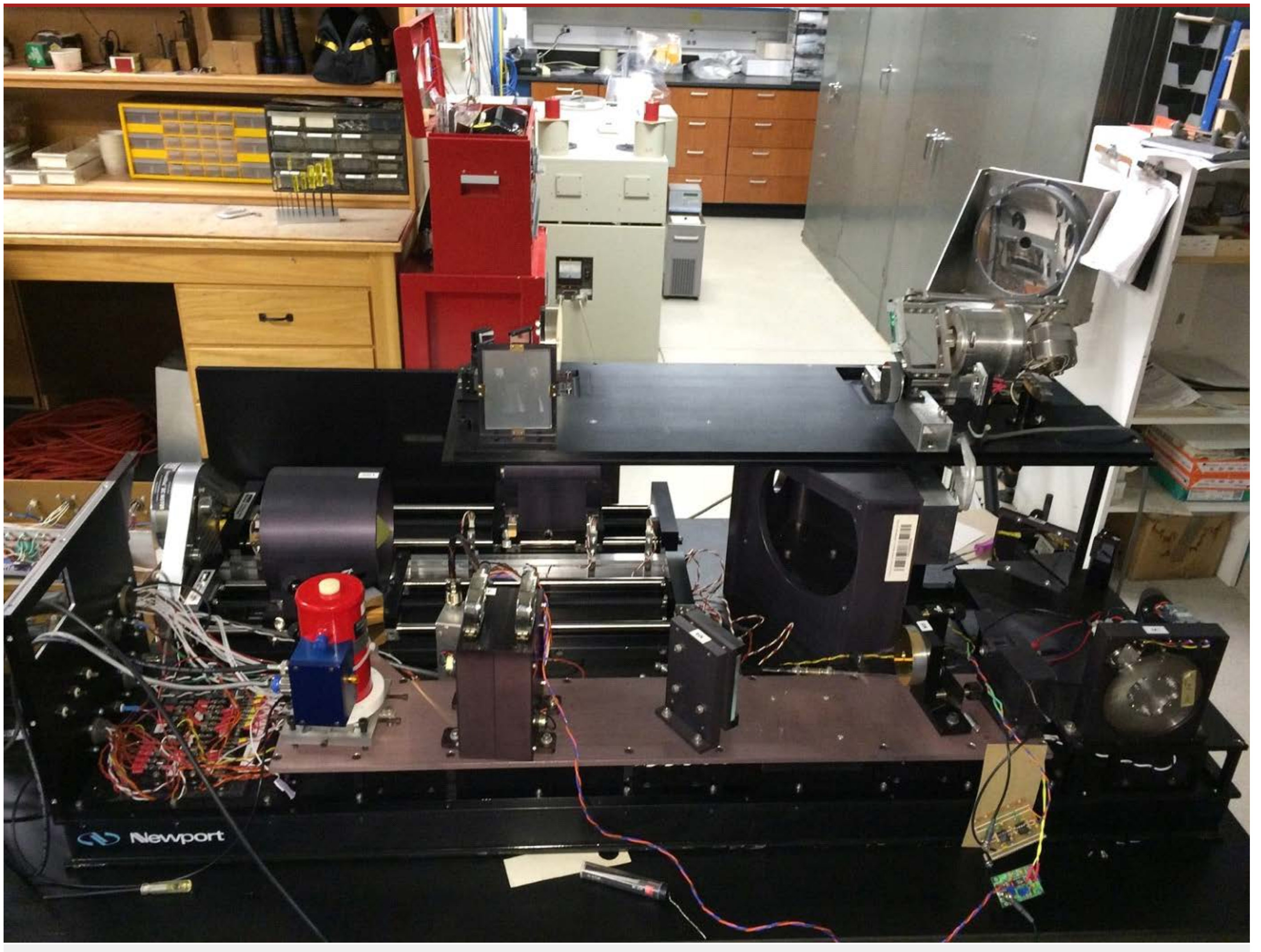

Figure 2. Compact multi-pass Michaelson interferometer.

‹ 2.3 Chemical Measurements at the PROPHET Field Station in Michigan up NCAR Imperative 3: Develop, deliver and support a suite of advanced community models. ›

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‹ 2.4 Coronal Spectral measurements in the mid-IR during the Solar Eclipse of 2017 | up | 3.1 Release of Tropospheric Ultraviolet-Visible (TUV) model version 5.3 ›

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3.1 RELEASE OF TROPOSPHERIC ULTRAVIOLET-VISIBLE (TUV) MODEL VERSION 5.3

The Tropospheric Ultraviolet-Visible (TUV) model continues to be used widely by the scientific community for applications including atmospheric photochemistry, solar radiometry, and environmental photobiology. The model calculates spectral radiance, irradiance, and actinic flux over 120-750 nm at an underlying resolution of 0.01 nm, as well as weighted spectral integrals including wavelength bands (visible, UVA, UVB, UVC), photolysis coefficients (112 reactions), and biologically active irradiances (UV index, DNA damage, vitamin D production, etc.). Atmospheric inputs include vertical profiles of N2, O2, O3, NO2, SO2, clouds, and aerosols. The propagation of radiation through multiple atmospheric layers (concentric spherical shells for direct solar beam, plane-parallel for diffuse radiation) is computed using a fast 2-stream approximation or a multi-stream discrete ordinates scheme. Version 5.3 provides updated spectroscopic data for a number of photolysis reactions.

The propagation of radiation in surface waters (rivers, lakes, oceans) can now be calculated with TUV. The model uses simple refraction and absorption optics, including Snell's law at the air-water interface, Fresnel reflection, and Beer-Lambert attenuation under-water for direct and diffuse light (but no underwater scattering). Biologically significant UV exposures, e.g. DNA-damaging radiation, can be calculated as a function of depth, and used to estimate the effectiveness of solar disinfection within surface waters. This is illustrated in Figure 1 for Lake Giles (Pennsylvania) based on water absorbance measured recently compared to over 20 years ago. This lake has experienced a marked increase in turbidity due to increased agricultural runoff, and illustrates the extent of change that might be expected in lake environments, in the face of climate change.

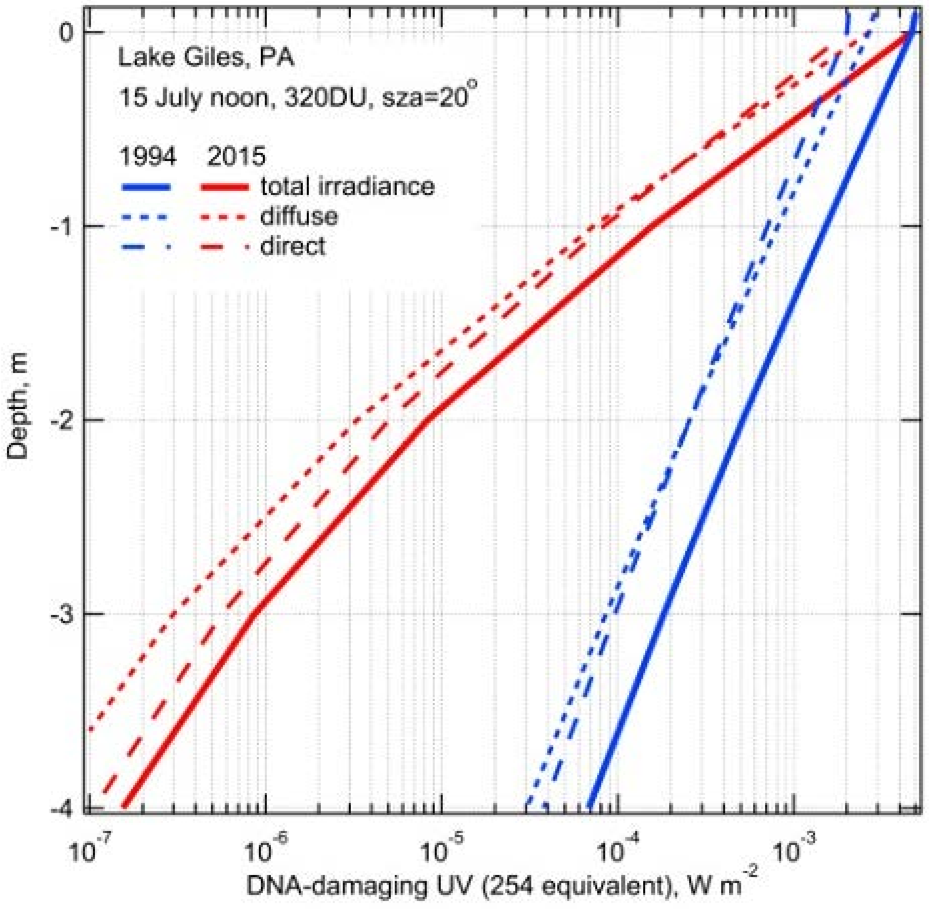

Figure 1: Penetration of DNA-damaging radiation into the waters of Lake Giles (Pennsylvania), calculated with the TUV (v.5.3) model, based on spectral absorbance of water sampled in 1994 (blue) and 2015 (red). Deviations from Beer-Lambert behavior are due to integration over

multiple wavelengths.

‹ NCAR Imperative 3: Develop, deliver and support a suite of advanced community models. up 3.2 WRF-Chem Model Development ›

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3.2 WRF-CHEM MODEL DEVELOPMENT

Mary Barth (ACOM/MMM), Alma Hodzic (ACOM), Young-Hee Ryu (ACOM), Gabriele Pfister (ACOM) and Stacy Walters (ACOM)

ACOM scientists have continued to add improvements to the WRF-Chem model. Two recent developments are an upgrade to the photolysis rate calculations and the addition of trajectories. The photolysis rate calculations now include the data and algorithms used in the most recent Troposphere Ultraviolet-Visible radiation model (TUV v5.3) that was released in summer 2016. The upgraded module includes cloud and aerosol feedbacks on the photolysis rates as well as the most recent data for quantum yields and cross-sections. The new TUV code in WRF-Chem predicts photolysis rates that are similar to observations (Figure 1) and are generally improved compared with predictions by other methods.

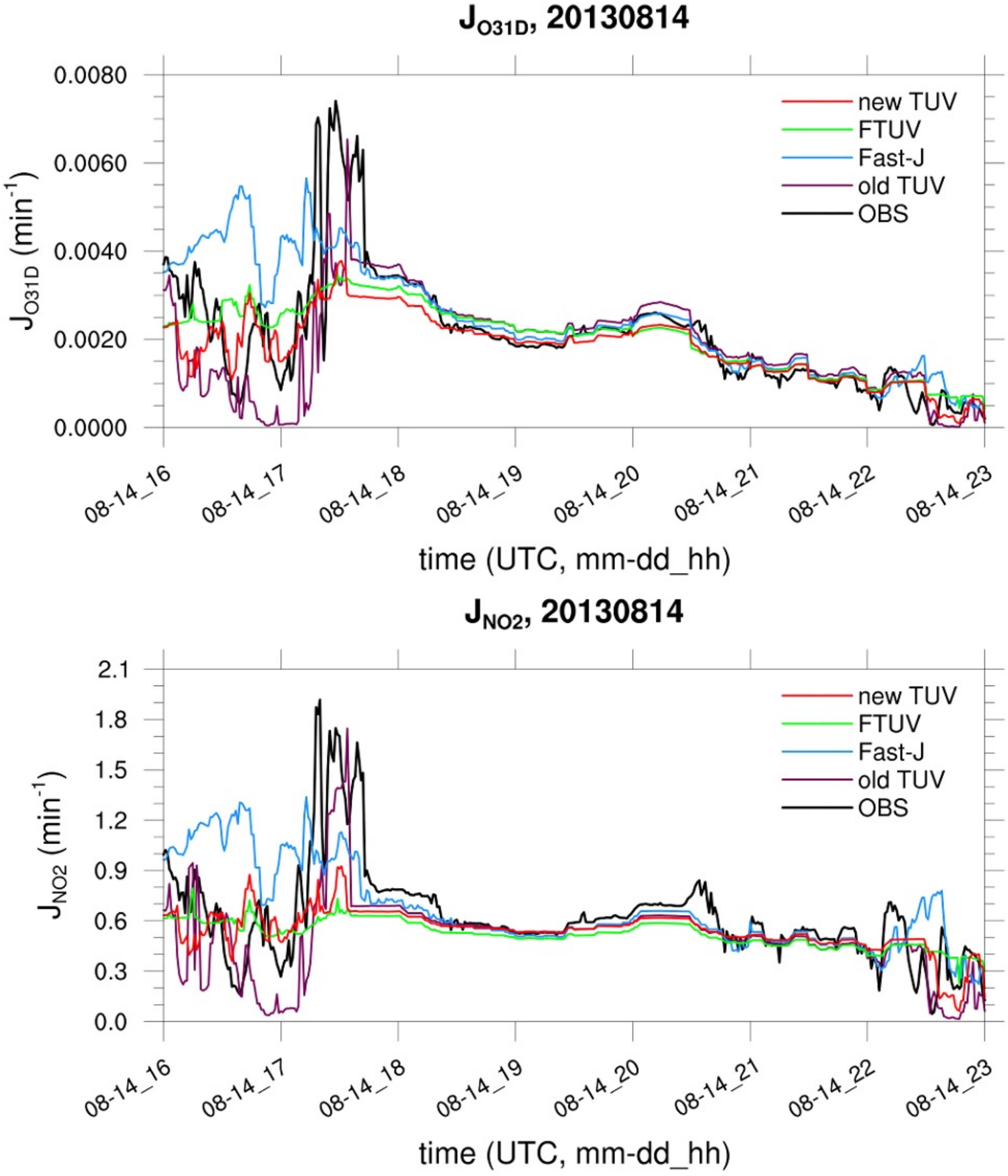

Figure 1. Comparison of photolysis rates as observed during the SEAC^{4}RS field campaign on 14 August 2013 (black line), and predicted

by the WRF-Chem model using different parameterizations to predict the photolysis rates. Purple line is the previous version of TUV used in WRF-Chem, blue line is the Fast-J parameterization (Wild et al., 2000), green line is fast TUV (Tie et al., 2003), and red line is the new TUV version just implemented. The two photolysis rates are O_3 dissociating to $O^1D + O_2$ (top panel) and NO_2 dissociating to NO + O (bottom panel).

Trajectories have been added to WRF-Chem to monitor meteorological and chemical parameters characterizing an air parcel as it follows the resolved-scale air motions predicted by WRF. With the output of the air parcel characteristics, WRF-Chem researchers can do additional analysis of air parcels as they are transported from urban centers or through thunderstorms. An example is shown below for air parcels that are ingested into a thunderstorm. For this case, 864 trajectories were tracked. The initial locations of these trajectories were place in the inflow region of the storm (panel a of Figure 2) at altitudes ranging from 0.5 to 3.0 km and over a 4-minute period. Analysis of the trajectory output found 251 trajectories were ingested into the updraft and lofted above 7 km altitude. These trajectories that reached the upper troposphere were then analyzed to produce a histogram of the time the air parcel was in contact with cloud water (panel b), showing that most air parcels spend 5-15 minutes in contact with cloud water.

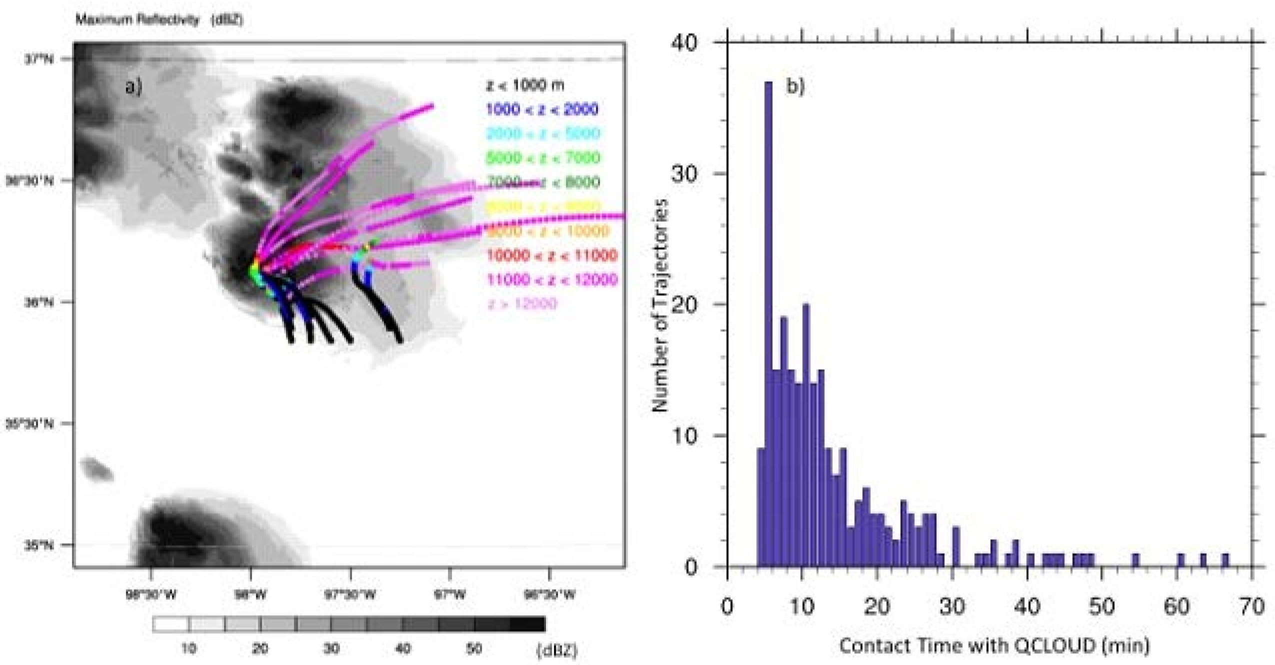

Figure 2. a) WRF-Chem simulated maximum radar reflectivity (gray shading, dBZ) and 10 trajectories that reach altitudes > 7 km. The trajectories are colored by altitude ranging from < 1 km (black) to over 12 km (pink). b) Frequency distribution of time in contact with cloud water for 251 trajectories that reached altitudes > 7 km.

NCAR/ACOM WRF-Chem activities are found at https://www2.acom.ucar.edu/wrf-chem.

‹ 3.1 Release of Tropospheric Ultraviolet-Visible (TUV) model version 5.3 | up | 3.3 WACCM & IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) ›

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3.3 WACCM & IGAC/SPARC CHEMISTRY-CLIMATE MODEL INITIATIVE (CCMI)

Simulations using the Community Earth System Model version 1 - Whole Atmosphere Community Climate Model (**CESM1-WACCM**) were conducted in support of the International Global Atmospheric Chemistry / Stratosphere-troposphere Processes And their role in Climate (**IGAC/SPARC**) Chemistry Climate Model Initiative (**CCMI**). The CESM1-WACCM simulations performed under various chemical composition scenarios performed for CCMI are designed to support upcoming international assessments. The WACCM group completed seven different hindcast and projection scenarios that spanned the period between years 1850 and 2100 – a total of over 2600 simulations years. The results have been made available on the NCAR Earth System Grid.

Improvements in CESM1-WACCM for CCMI included an improved orographic gravity wave forcing that reduced the cold bias in Antarctic polar temperatures [Garcia et al., 2016]. These improvements, coupled with an enhanced representation of both tropospheric and stratospheric chemistry greatly improved comparisons with ground-based, aircraft, and satellite observations. An example of these results are shown in **Figure 1**. Here, the southern hemisphere total column ozone (TOZ) polar cap average is shown for October. The WACCM ozone hole chemistry as described in Wegner et al., [2013] and Solomon et al., [2015] accurately represents the observed ozone depletion. The WACCM model results suggest that the polar TOZ will recover to 1980 conditions around year 2060.

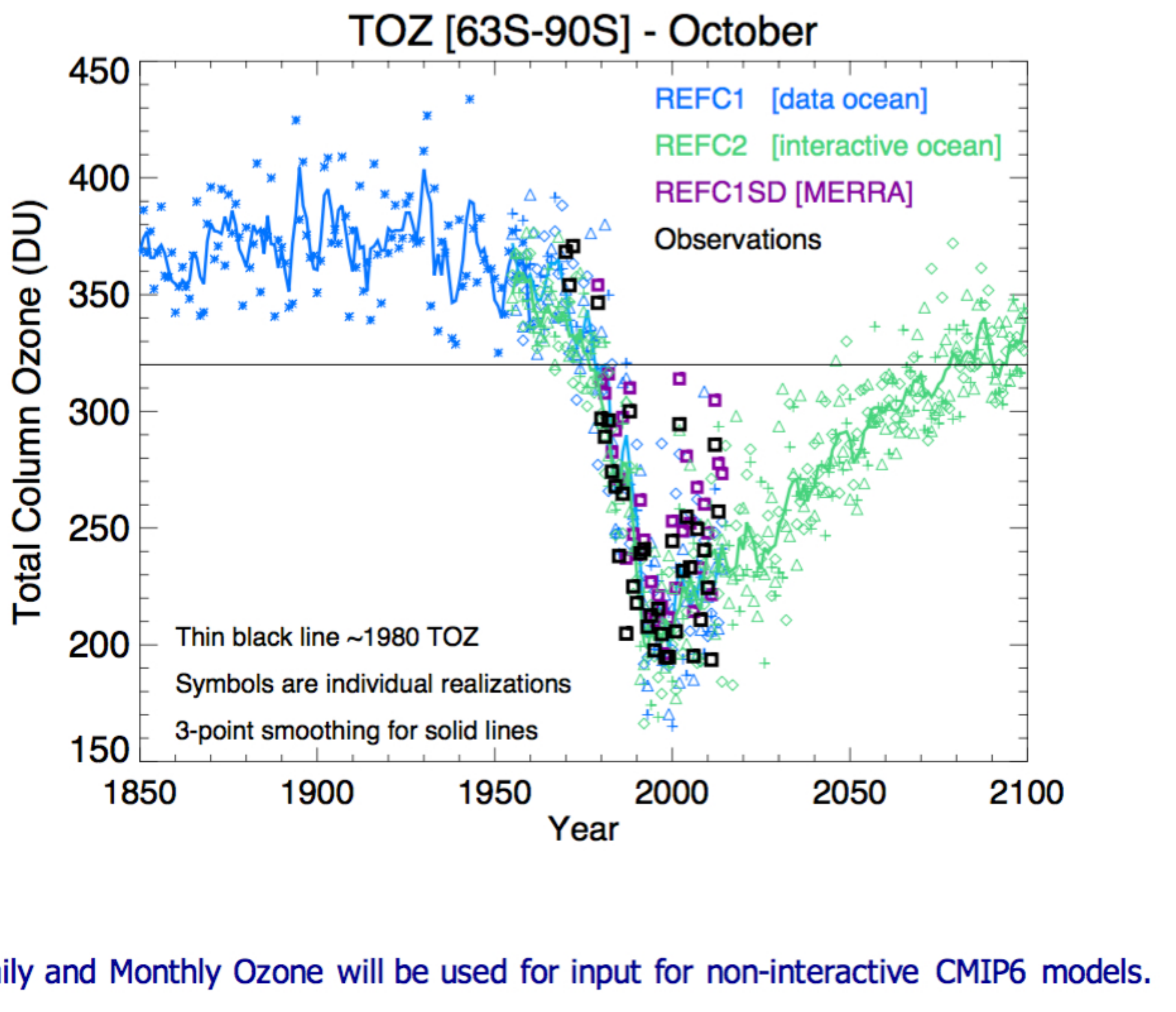

Figure 1. Polar cap total column ozone for October. Black squares represent observations based on satellite observations. Purple squares

are results from the WACCM model run in specified dynamics model. The input meteorological fields are taken from NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis. Blue and Green symbols represent two versions of WACCM forced with a data ocean and interactive ocean respectively.

PUBLICATIONS:

Eyring et al., Overview of IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) Community simulations in Support of Upcoming Ozone and Climate Assessments, SPARC newsletter, n40 –January 2013.

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Wegner, T, D. E. Kinnison, R. R. Garcia, S. Madronich, and S. Solomon, Polar Stratospheric Clouds in SD-WACCM4, *J. Geophys. Res.*, VOL. 118, 1-12, doi:10.1002/jgrd.50415, 2013.

‹ 3.2 WRF-Chem Model Development | up | 3.4 CESM-CAM4chem participation in the Chemistry-Climate Model Initiative (CCMI) ›

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3.4 CESM-CAM4CHEM PARTICIPATION IN THE CHEMISTRY-CLIMATE MODEL INITIATIVE (CCMI)

Simone Tilmes, Jean-Francois Lamarque, Louisa Emmons, CAMchem and WACCM team

The IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) was established to coordinate SPARC chemistry-climate model evaluation and associated modeling activities. A set of reference and sensitivity simulations have been defined to address emerging science questions, improve process understanding and support of upcoming ozone and climate assessments (Eyring et al., 2014). The Community Earth System Model, CESM1 CAM4-chem has been used to perform the Chemistry Climate Model Initiative (CCMI) reference and sensitivity simulations, as described in Tilmes et al. (2016). Important improvements of CESM1 CAM4-chem in recent years resulted in a very good representation of tropospheric ozone mixing ratios and trends, and a good representation of aerosols in comparison to observations (Figure 1).

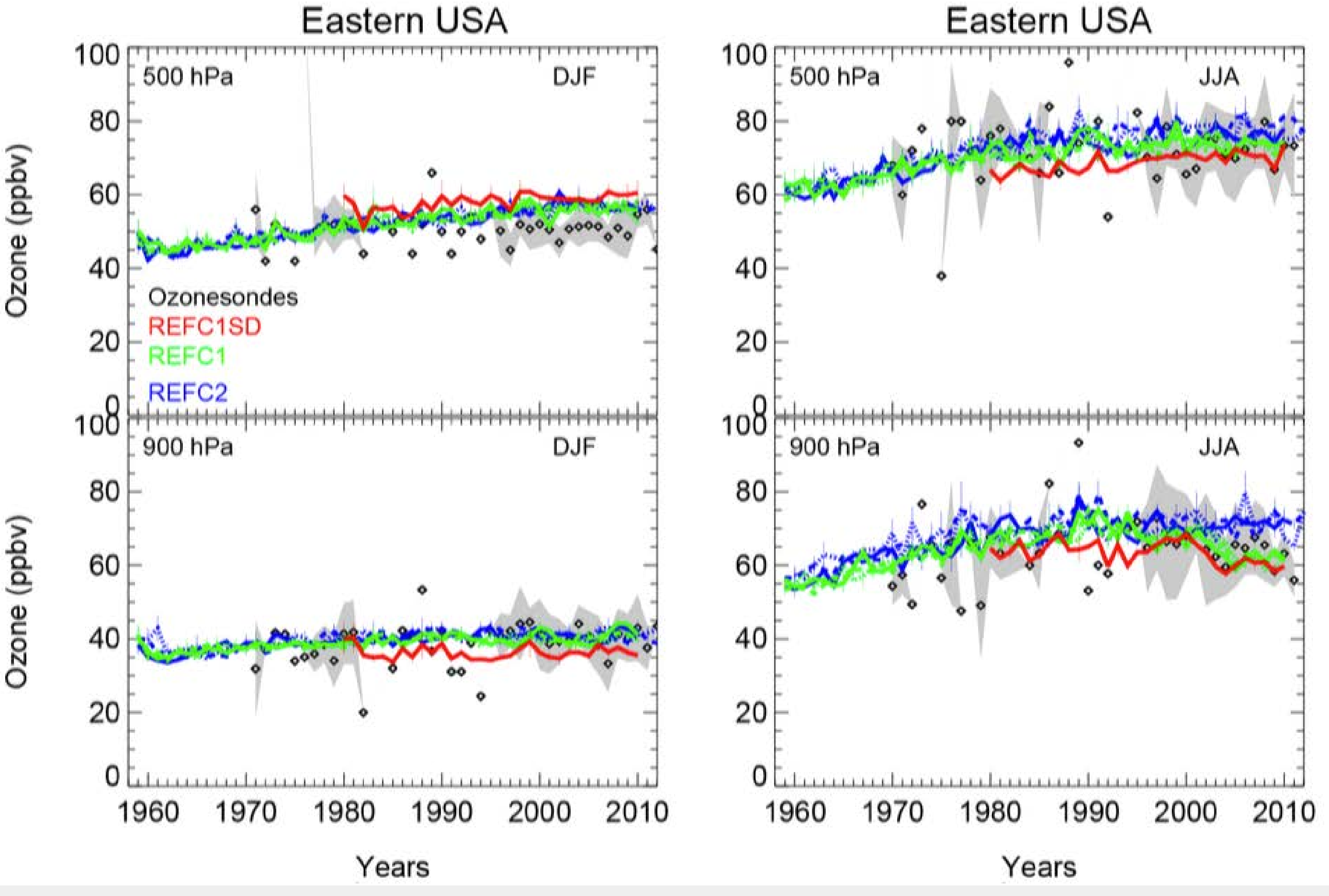

Figure 1: Time evolution of seasonal averaged and regionally aggregated ozone mixing ratios derived from ozone soundings (black diamonds) and model results (colored lines) at two different pressure levels, two different seasons (DJF: left, JJA: right). (Tilmes et al., 2016).

For the troposphere, near-surface ozone mixing ratios and trends are very well reproduced and within 25% of the values from ozonesonde and satellite observations throughout the troposphere. Some biases in the model have not been resolved compared to earlier versions of the model. CO is still biased low in all model experiments in the NH, especially in spring. Some differences between the experiments may be attributed to differences in biogenic emissions. Correspondingly, methane lifetime is low compared to observational estimates, which is likely related not only to shortcomings in emissions, but also to too large an oxidation capacity of the atmosphere. Significant shortcomings of hydrocarbons (shown for ethane)

are identified in particular in the NH. The hemispheric gradient of BC in the model is reproduced well in most seasons, while the fall and winter values in mid-latitudes are often overestimated in mid-latitudes. BC in the tropics is largely overestimated for most seasons. This points to potential shortcomings in emissions, but also loss processes in the model. Ongoing work is focusing on reducing existing biases in the model in the troposphere, for example through improvements in the chemical mechanisms, aerosol descriptions, understanding and improvement of biases in emission data sets.

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‹ 3.3 WACCM & IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) up 3.5 Process and regional modeling of cloudy-sky actinic flux using satellite cloud retrievals ›

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3.5 PROCESS AND REGIONAL MODELING OF CLOUDY-SKY ACTINIC FLUX USING SATELLITE CLOUD RETRIEVALS

By Alma Hodzic, Young-Hee Ryu, Samuel Hall, Sasha Madronich, Kirk Ullmann

The large uncertainties in the modeling of cloud fields and their optical properties often prevent chemistry-climate models from predicting accurately the radiation (actinic flux) available for photochemistry, which can result in large biases in the predicted production of secondary pollutants such as ozone or organic aerosols. To improve the accuracy in photochemical modeling in presence of clouds, we have developed a methodology for calculating the vertical distribution of tropospheric ultraviolet actinic fluxes based on satellite cloud retrievals and the NCAR TUV radiative transfer model. The satellite products employed include cloud optical depth, cloud height and cloud fraction, and are available at $4x4km^2$ spatial resolution routinely over the U.S.

We have applied and evaluated this approach with the NCAR actinic flux measurements collected within the 2013 Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC4RS) campaign. We showed that satellite constrained actinic fluxes can accurately reproduce airborne-measured actinic fluxes (see Fig.1), and that our product can be used quite efficiently when actinic flux measurements are not available. Our results also showed that actinic flux is reduced below optically moderate-thick clouds inversely with cloud optical depth, and can be enhanced by more than a factor 2 above clouds. Inside clouds, the actinic flux can be enhanced by 2–3 times in the upper part of clouds or reduced by 90% in the lower parts of clouds. This work has been submitted for publication to GRL (Ryu et al., 2016). Currently we are using the satellite-derived actinic fluxes as input to chemistry-transport models to estimate by how much we can improve the accuracy of photochemistry calculations in WRF-Chem.

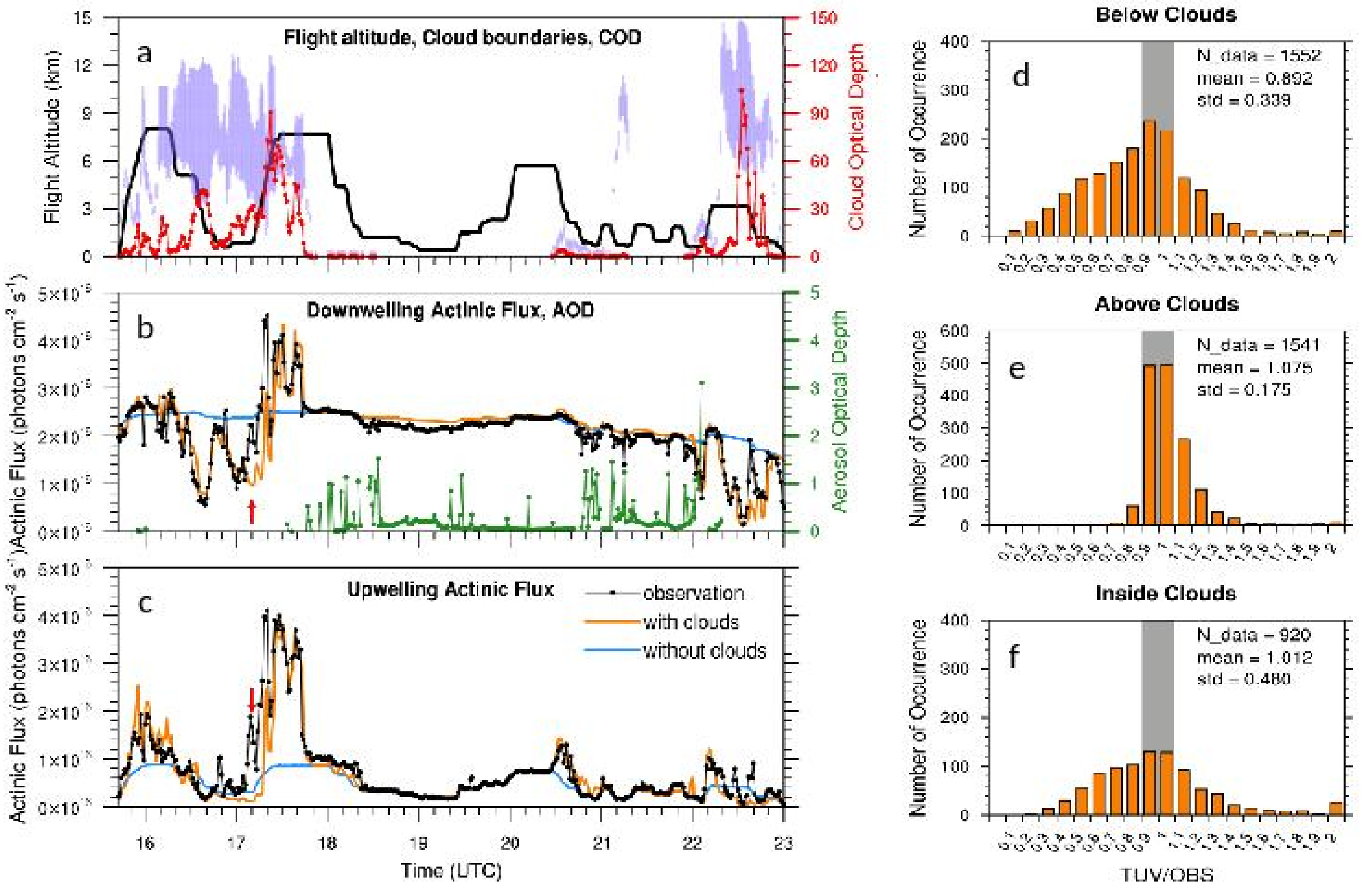

Figure 1: (a,b,c.) Comparison of down- and up-welling actinic flux from observations and the TUV model simulations with clouds (orange

line) and without clouds (light-blue line) on 14 August 2013. Flight altitude and cloud boundaries with cloud bottom and top heights from satellite retrievals (violet shading) are also shown. (d,e,f.) Histograms of ratio of TUV modeled total actinic flux with clouds to observed total actinic flux for below-cloud, above-cloud, and inside-cloud conditions for all 19 SEAC4RS flights. Adapted from Ryu et al., 2016 submitted to GRL.

‹ 3.4 CESM-CAM4chem participation in the Chemistry-Climate Model Initiative (CCMI) | up | 3.6 Simulation of the Quasi-biennial Oscillation (QBO) ›

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3.6 SIMULATION OF THE QUASI-BIENNIAL OSCILLATION (QBO)

The Quasi Biennial Oscillation (QBO) of the tropical zonal mean wind is a prominent feature of the tropical stratosphere, and the main source of interannual variability in the Tropics between the tropopause and 40 km. The QBO has been observed for over 50 years, and its influence on stratospheric dynamics has been well documented; however, very few General Circulation Models (GCMs) can model this phenomenon.

Giorgetta et al. (2002) and Richter et al. (2014) have shown that high vertical resolution is needed in order to simulate the QBO in a GCM. To address this problem, a high-resolution version of WACCM has been developed by J. Richter (CGD) and R. Garcia (ACOM). This version is based upon the standard version of WACCM, but with a vertical grid of 110 levels (110L) that provides very high vertical resolution (500 m) between the boundary layer and the middle stratosphere. The 110L model is now being used to simulate the QBO for present-day climate and for high-CO_2 conditions. **Figure 1** shows a comparison of the simulated QBO winds at the Equator with ERA-Interim reanalysis data and with a standard WACCM run (70 vertical levels; 70L). The structure, period and amplitude of the QBO in the 110L model compares very well with the reanalysis. By contrast, the 70L model produces a much weaker QBO that fails to propagate below 50 hPa. The difference is directly attributable to the ability to represent short-vertical wavelength equatorially trapped waves (Kelvin, Rossby-gravity). These waves, whose vertical wavelength is as small as 4-6 km are properly represented in the 110L, but not in the 70L model, whose vertical resolution in the critical upper troposphere and lower stratosphere region is no better than 1.25 km.

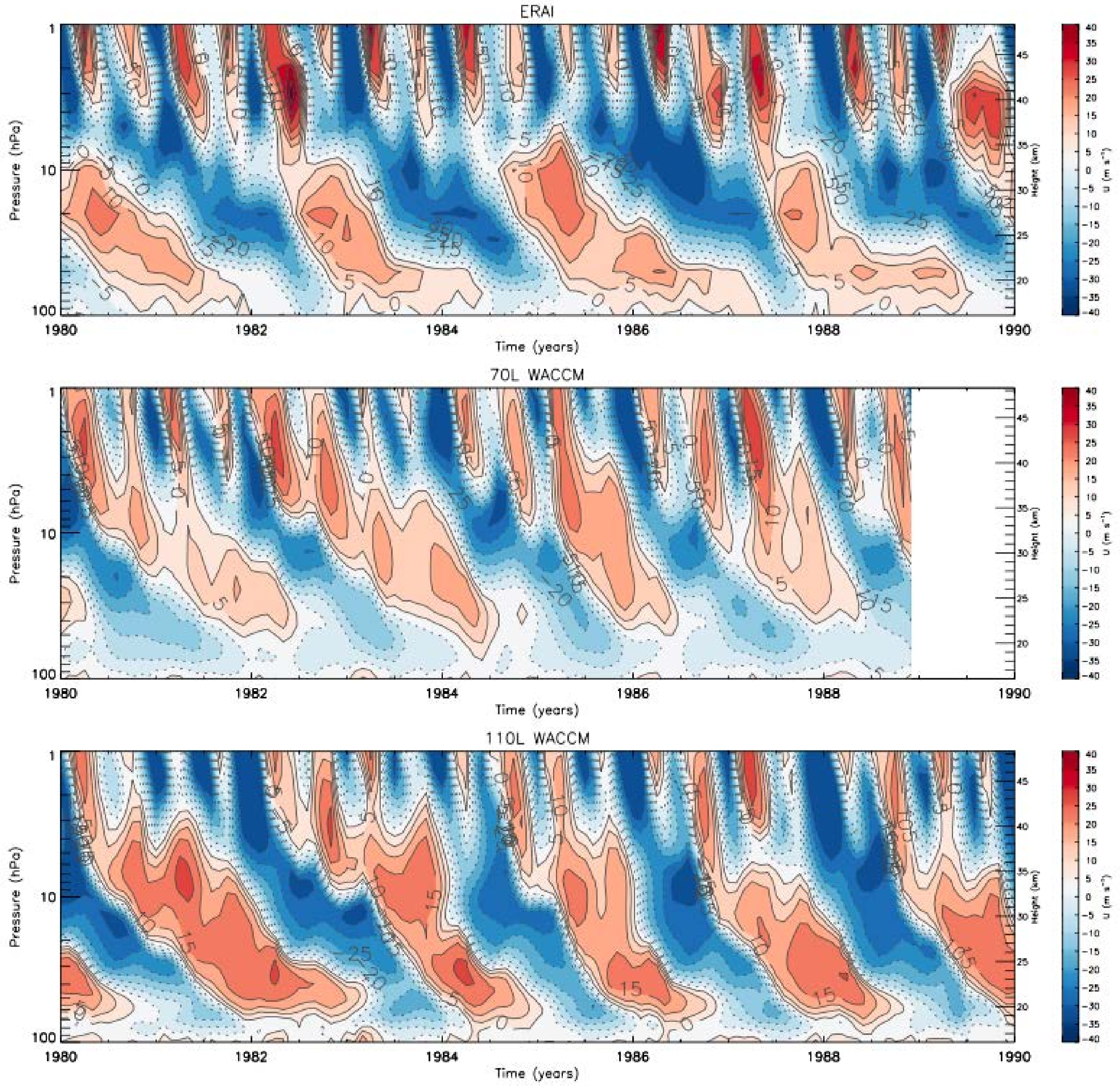

Figure 1: Tropical (2°S to 2°N average) zonal-mean zonal wind from ERA-Interim (top panel), 70L WACCM (middle panel) and 110L WACCM (bottom panel).

Simulations from the 110L model are part of the NCAR contribution to the QBO Inter-comparisonproject (QBOi; http://www.sparc-climate.org/activities/quasi-biennial-oscillation/)

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Richter, J. H., A. Solomon, and J. T. Bacmeister, 2014: On the simulation of the quasi-biennial oscillation in the Community Atmosphere Model, version 5, *J. Geophys. Res. Atmos.*, **119**, 3045–3062, doi:10.1002/2013JD021122.

‹ 3.5 Process and regional modeling of cloudy-sky actinic flux using satellite cloud retrievals up NCAR Imperative 5: Develop and transfer science to meet societal needs. ›

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‹ 3.6 Simulation of the Quasi-biennial Oscillation (QBO) up 5.1 MOPITT data used to study pollution effects of 2015 El Niño fires in Indonesia ›

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5.1 MOPITT DATA USED TO STUDY POLLUTION EFFECTS OF 2015 EL NIÑO FIRES IN INDONESIA

During September and October 2015, agricultural burning in Indonesia caused an air quality disaster. Burning during this time of year is not uncommon, but the large 2015 El Niño resulted in extremely low precipitation in both Sumatra and Kalimantan (Borneo). As reported in Field et al., (2016), measurements of pollution from satellite observations, including carbon monoxide (CO) from MOPITT, all show large increases when precipitation is lower than 4 mm/day. Since fires in Indonesia are mostly set for clearing land or fertilization, this study recommends limiting agricultural burning for low precipitation forecasts. In addition, many of the fires in Indonesia are used to clear peat swamp forests that are drained for farming, which have much higher stored carbon than other forests. This carbon is released to the atmosphere when the peat is burned. Using MOPITT data, Jiang et al., (2016) estimated that the Indonesian fires in October, 2015 emitted 92 Tg

of CO, which is about 3 times higher than the 2006 El Niño driven fires.

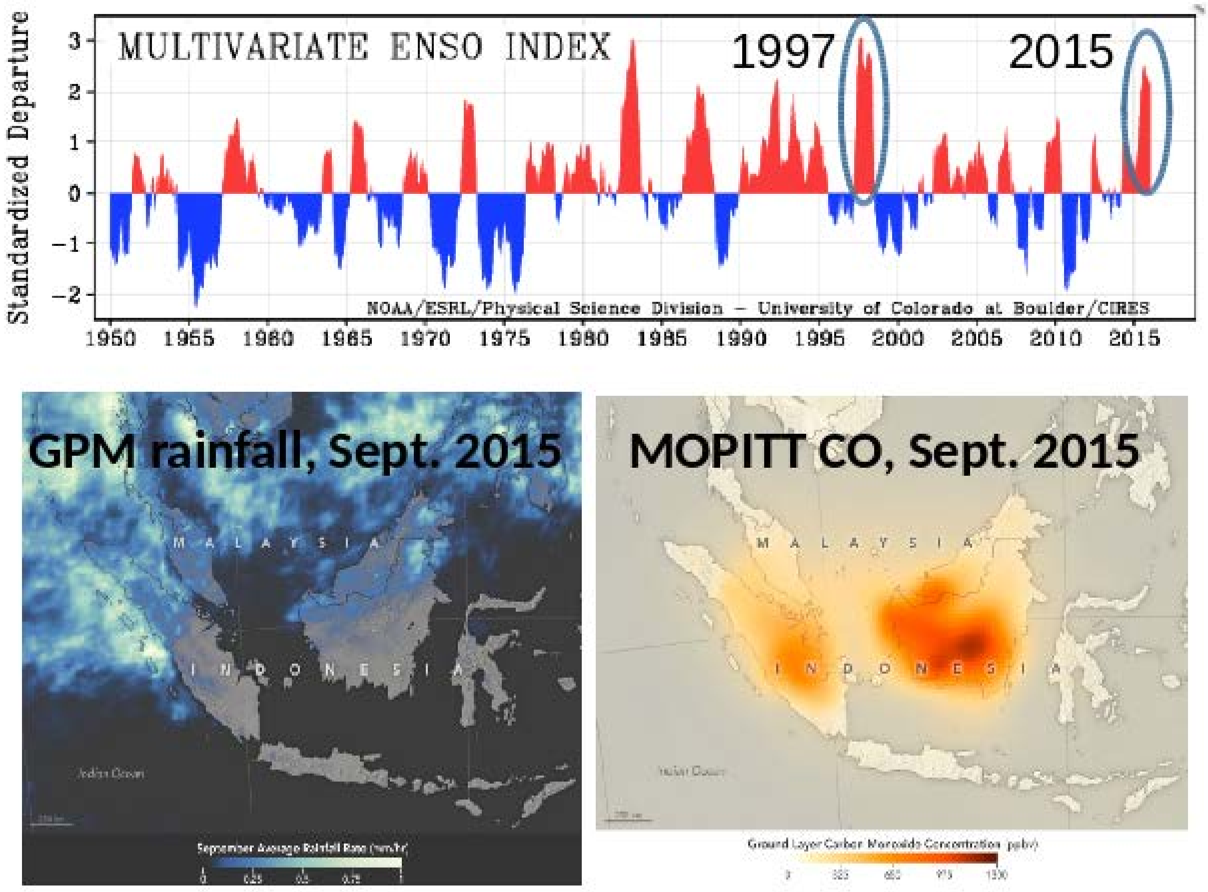

Figure 1. Top panel shows the time series of multivariate ENSO (El Niño/Southern Oscillation) index from NOAA, with the largest recent El Niño events in 1997 and 2015 highlighted. Bottom left panel shows the average rainfall for September 2015 over Indonesia from the NASA Global Precipitation Measurement (GPM). Bottom right panel shows MOPITT CO near the surface averaged for September 2015, where non-polluted levels are typically around 100 ppbv. (Rainfall and CO images from earthobservatory.nasa.gov)

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‹ NCAR Imperative 5: Develop and transfer science to meet societal needs. up 5.2 KORUS-AQ ›

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5.2 KORUS-AQ

ACOM scientists participated in an aircraft campaign in South Korea, led jointly by NASA and the National Institute of Environmental Research of Korea, in May-June 2016. The NASA DC-8 was instrumented to measure numerous gas-phase compounds and particle properties to quantify the air quality over South Korea and to understand its driving sources. ACOM scientists Weinheimer and Montzka measured NO, NO_2, NO_y and O3, and Hall and Ullmann measured actinic flux, from which photolysis rates are derived. The full suite of measurements will improve the capability of satellite remote sensing of air quality, for both the Korean geostationary satellite GEMS, as well as future geostationary satellites over North America. Models for air quality forecasting and analysis will be evaluated and improved with these observations.

ACOM scientists (Emmons, Pfister, Barre, Gaubert, Mizzi, Buchholz) also supported KORUS-AQ by providing regional and

global forecasts. WRF was run at 4 km horizontal resolution over Korea with tracers of NOx emissions, which were a key product for flight planning. WRF-Chem forecasts, with a detailed representation of aerosols, also were run. Global simulations with the assimilation of MOPITT CO were run with CAM-chem/DART and provided a larger-scale context for flight planning.

The left panel of the figure shows the twenty flights that were completed with the NASA DC-8, with coincident overflights with remote sensing measurements of NO_2 on the NASA King Air. Another King Air was operated by the Korean researchers and provided complementary measurements focused on sources and local scales. The middle panel shows an example of the WRF point NO_2 tracer forecast. The right panel shows an example of the measured ozone on a DC-8 flight circling a chemical plant showing the high values downwind of the source to the north.

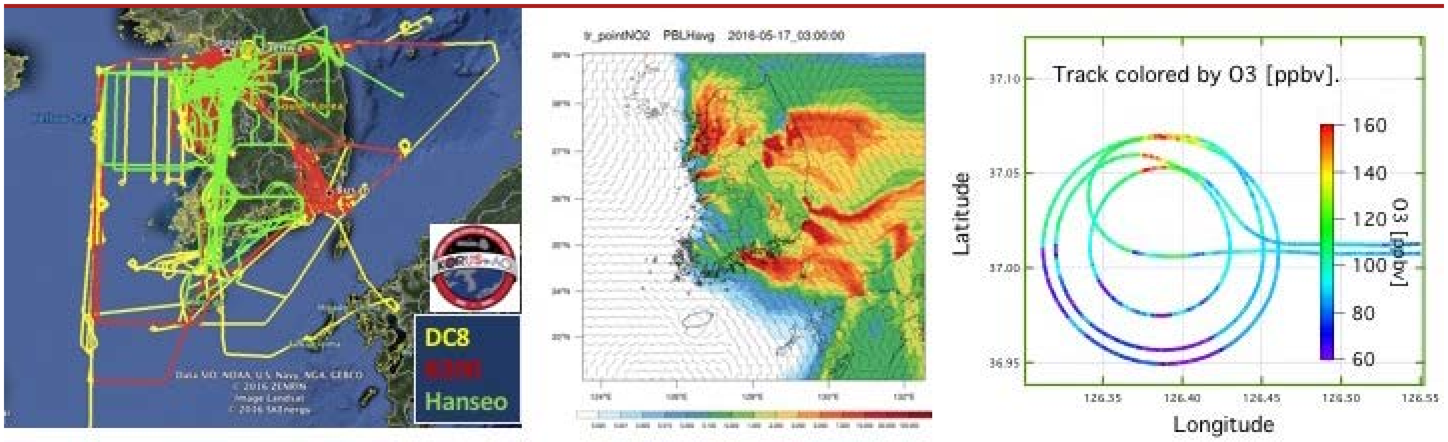

Figure 1. KORUS-AQ flights, tracers, and measured ozone.

After the return of the DC-8 to the NASA Armstrong Flight Research Center in Palmdale, CA, ACOM scientists participated in the Student Airborne Research Program (SARP). This was a unique educational opportunity for advanced undergraduates in which the KORUS science team trained the students in airborne instrument operation during two research flights to measure air quality, one in the Central Valley and one in the LA basin.

‹ 5.1 MOPITT data used to study pollution effects of 2015 El Niño fires in Indonesia | up | 5.3 Regional-scale chemistry-climate simulations over South Asia show air pollution will continue to be a risk ›

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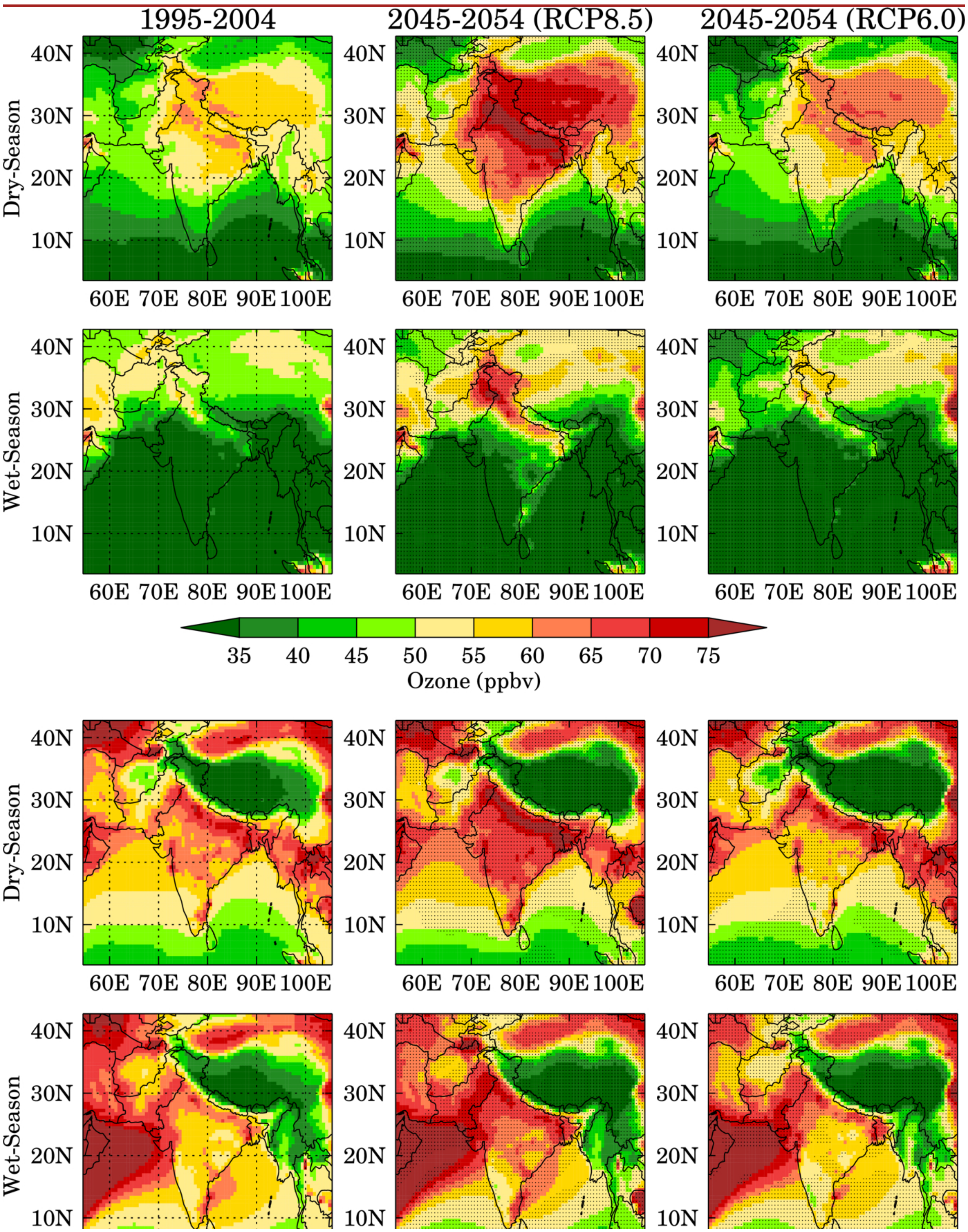
5.3 REGIONAL-SCALE CHEMISTRY-CLIMATE SIMULATIONS OVER SOUTH ASIA SHOW AIR POLLUTION WILL CONTINUE TO BE A RISK

Rajesh Kumar (ACOM/RAL) and Mary Barth (ACOM/MMM)

High-resolution air quality simulations with the nested regional climate model coupled with chemistry (NRCM-Chem) have been conducted to quantify future changes in air quality over South Asia, which is a region where elevated air pollution levels are already adversely affecting human health and food security. By performing regional-scale simulations, several atmospheric processes (e.g. urban emissions, topographic effects and convection) relevant to air quality can be better represented than global chemistry-climate simulations. Thus, these simulations give much better information as to where air quality exceedances may occur. Three 10-year simulations, one present day conditions and two future scenarios

bounding estimates of future emissions, have been performed for two domains. The outer domain covers a broad region of South Asia (see accompanying Figure) at 60-km grid spacing, and the inner domain covers the Gangetic Plain (where over 500 million people live) at 12-km grid spacing.



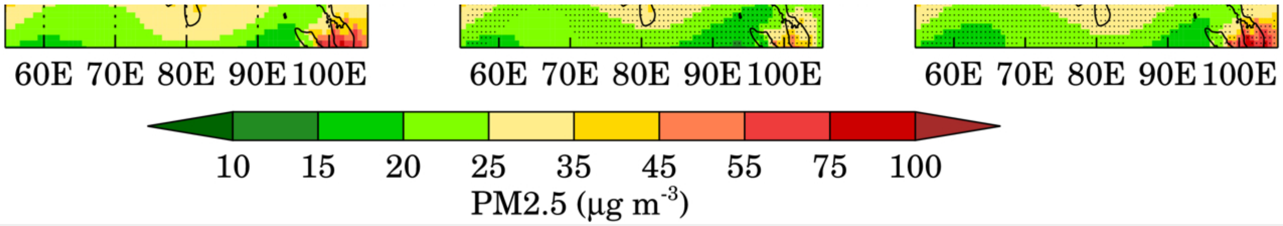


Figure. 1: Dry- and wet-season daily 8-hour average (MDA8) ozone and 24-h average (DA24) $PM_{2.5}$ over the parent model domain for present day and future (RCP8.5 and RCP6.0) scenarios. Green colors show areas where MDA8 ozone and DA24 $PM_{2.5}$ are below the WHO limits of 50 ppbv and 25 μgm^{-3}, respectively, while yellow-red colors depict the areas of exceedance. Black dots in future scenarios indicate that changes are robust (statistically significant at 99% confidence level) relative to present-day conditions.

Based on NRCM-Chem projections, we find that ozone pollution occurs primarily during dry season, while $PM_{2.5}$ pollution persists throughout the year in South Asia (see Figure). Despite projections of improved air quality elsewhere, our model projections show that air quality in South Asia will either worsen by mid-century (RCP8.5) or remain similar to the present-day conditions (RCP6.0). For present-day conditions, ozone and $PM_{2.5}$ levels exceed their corresponding World Health Organization (WHO) limits for up to ~ 6 and ~ 10 months respectively. Such exceedances are projected to increase by 70-120 days and 20-40 days in most parts of South Asia by 2050 under RCP8.5. The Indian states located in the Indo-Gangetic Plain and Bangladesh experience the largest number of exceedance days. We estimate that the number of South Asian people living in exceedance areas will increase from ~1.2 billion in 2000 to ~1.9-2.5 billion by mid-century.

These simulations have been supported by the NCAR Strategic Capability Project granted by NCAR/CISL.

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NCAR IMPERATIVE 6: EDUCATE AND ENTRAIN A TALENTED AND DIVERSE GROUP OF STUDENTS AND EARLY CAREER PROFESSIONALS.

‹ 5.3 Regional-scale chemistry-climate simulations over South Asia show air pollution will continue to be a risk

up

6.1 Whiteface Mountain Cloud Chemistry Workshop ›

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6.1 WHITEFACE MOUNTAIN CLOUD CHEMISTRY WORKSHOP

Mary Barth (ACOM/MMM), Annmarie Carlton (University California – Irvine), Sara Lance (Atmospheric Sciences Research Center, University at Albany, SUNY)

The Whiteface Mountain Cloud Chemistry Workshop was held at the Marble Mountain Lodge near Wilmington, New York, 16-17 September 2016 to design a coordinated investigation of the effect of clouds on tropospheric composition. Approximately 40 people attended with expertise ranging from cloud chemistry modeling to measurements of clouds, aerosols, and trace gases.

Clouds cover 60% of the Earth's surface at a given time and are the primary means by which constituents from the polluted boundary layer are lofted to the free troposphere. Clouds also are aqueous-phase chemical reactors, scavenging soluble gas-phase precursors and supporting oxidation reactions that contribute to increased aerosol mass when the cloud drops evaporate. However, atmospheric chemistry observations (field campaigns and satellite retrievals) typically avoid clouds resulting in a lack of knowledge of cloud chemistry impacts on tropospheric composition.

The workshop reviewed past mountaintop cloud chemistry studies, including historical and current Whiteface Mountain activities, the Great Dun Fell experiments in northern England, and the FEBUKO and HCCT-2010 experiments in Germany, to learn about successful operations and needed improvements with these types of studies. In anticipation of a future field campaign at the Whiteface Mountain Observatory, results from regional and 0-dimensional box model studies were discussed to learn what might be expected in terms of atmospheric composition and cloud chemistry effects on that composition.

Workshop participants agreed on the importance of the following science objectives for future field campaigns.

1. Quantify the clear-sky bias in chemical characterization of the troposphere.
2. Identify key oxidants driving aqueous phase chemistry, especially pertaining to organic compounds.
3. Quantify how aerosol characteristics and gas-phase composition change as a result of cloud processing.
4. Identify chemical tracers for cloud processing.
5. Quantify entrainment and transport of chemical constituents into the free troposphere.
6. Determine the importance of aqueous-phase biological processes on aqueous chemistry.

With these science objectives in mind, workshop participants discussed the capabilities at Whiteface Mountain for conducting a cloud chemistry experiment and how such an experiment would be designed. Whiteface Mountain Summit Observatory routinely collects and analyzes cloud water samples during summertime, while the Marble Mountain Lodge site hosts NADP and CASTNet monitors. Based on hourly data, the summit of Whiteface Mountain experiences cloud 20-60% of the time during summer (June—September), making Whiteface Mountain an excellent location to investigate aqueous organic chemistry in warm, low-level clouds.

Figure 1. Whiteface Mountain Summit Observatory near Wilmington, New York.

The workshop concluded with the decision to begin with small measurement and modeling studies. Workshop participants are currently analyzing cloud water samples from recent cloud events for more in-depth and coordinated analysis of cloud water composition information. Researchers are mining the literature and devising measurement strategies to more fully characterize typical cloud properties and airflow patterns in the region. Model intercomparisons are being pursued for both regional-scale and chemistry box models. A small-scale pilot study is being planned to examine cloud processing of trace gases and aerosols at Whiteface Mountain Observatory, with a focus on water-soluble organic carbon. Based on these efforts, future field intensive operations will be designed.

More information on the workshop can be found at https://www2.acom.ucar.edu/cloud-chemistry. The workshop was sponsored by the U.S. National Science Foundation.

Figure 2. Project logo.

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6.2 ATMOSPHERIC RADIATION SCIENCE WORKSHOP

The Atmospheric Radiation Science Workshop (ASRW) was held at the NCAR Mesa Laboratory in Boulder, Colorado from 8-11 March, 2016. Participants included over 80 scientists and engineers from universities, national laboratories, NOAA, NASA and industry. The 4-day meeting facilitated discussion of current and future scientific directions for shortwave science, observational needs and priorities and assessment of current and emerging technology, platforms, and experimental approaches. Special emphasis was given to optimizing airborne observations as part of the ground- and satellite-based observational system to best meet modeling needs. Many of the topics draw from lessons learned from recent and planned experiments (e.g. DC3, SEAC4RS, CSET, ARISE, ORACLES).

The workshop intentionally encompassed the broad range of expertise covering *in situ* observations of radiance, irradiance and actinic flux density, satellite remote sensing and retrievals, radiative transfer and chemistry models and instrumentation engineers to examine cross-cutting technologies and scientific priorities and generate new collaborations and approaches. Funding agency representatives provided insight into research opportunities while student participants gained a broad overview of radiation science and engineering aspects of the field.

University (USA)	University (Int'l)	NASA	NOAA	DOE	NRL	NSF/ NCAR	Industry
33	3	11	11	5	1	16	4

Figure 1. ASRW attendee institutions.

The workshop was organized as a series of plenary talks and two plenary discussions

- Emerging science, technology, and platforms
- Future experiments and flight planning strategies

and seven breakout sessions

- Radiometry (calibration, components, performance parameters)
- Radiation and microphysics in observations and modeling
- High-latitude observations and radiation budget
- Atmospheric complexity in cloud-aerosol observations and radiative transfer modeling
- Airborne vehicle coordination and air traffic regulation
- Photochemistry
- Satellite validation

The unprecedented community-building effort laid the foundation for future activities and collaborations. A sampling of outcomes include assessments of radiative science priorities (e.g. spectral and global constraints on aerosol impacts, cloud-aerosol interactions and heating rate profiles and changing arctic budgets), observational needs (e.g. ultraviolet aerosol single scattering albedo, instrument miniaturization and statistical satellite validation techniques) and greater community interactions (e.g. optimal sampling strategies from the surface to space, 3-D model development and future sub-topic workshops and campaigns). A comprehensive summary of outcomes is in preparation for publication and more information is available at the ASR Workshop website.

The ASRW was jointly hosted by the ACOM Laboratory and the University of Colorado under the sponsorship of the Atmospheric Chemistry Center for Observational Research and Data (ACCORD) and the NASA Radiation Science Program.

‹ 6.1 Whiteface Mountain Cloud Chemistry Workshop | up | 6.3 NCAR/ASP 2016 Summer Colloquium: Recent Advances in Air Quality Analysis and Prediction – Science and Policy ›

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6.3 NCAR/ASP 2016 SUMMER COLLOQUIUM: RECENT ADVANCES IN AIR QUALITY ANALYSIS AND PREDICTION – SCIENCE AND POLICY

ORGANIZERS: DR. ARTHUR P. MIZZI, NCAR/ACOM AND PROF. AVELINO F. ARELLANO, UNIV. OF ARIZONA – DEPT. OF HYDROLOGY AND ATMOSPHERIC SCIENCE

Figure 1. NCAR/ACP 2016 Summer Colloquium: July 25 – August 5, 2016.

During the summer of 2016, ACOM organized the NCAR/ASP Summer Colloquium titled “Recent Advances in Air Quality Analysis and Prediction – The Interaction of Science and Policy. This was the 50th anniversary of that event. The Colloquium lasted two weeks – July 25 to August 5, 2016. ACOM hosted approximately 40 lecturers and 30 students. The participants were as international as the subject with multiple representatives from the United States, Canada, South America, Europe, and Asia.

Air quality is an atmospheric science topic of great domestic and international importance. It directly impacts human health and welfare across multiple temporal and spatial scales. Its research is taking place in a rapidly evolving regulatory and technological environment. Those changes are creating two challenges: (i) air quality scientists and researchers find it difficult to keep up with the regulatory/policy changes that motivate the funding for much or their research, and (ii) air quality regulators/policymakers find it difficult to keep up with the technological advances that underlie the air quality issues/remedies their regulations/policies are meant to address. The Colloquium addressed those challenges by bringing together graduate students, early career scientists, and lecturing experts from around the world to explore/discuss the following subject areas: (i) The Air Quality Problem (international/domestic), (ii) Air Quality Regulation and Policy (international/domestic), (iii) Air Quality Observations (regulatory/research/*in situ*/remote), (iv) Air Quality Modeling (regulatory/research/operational), (v) Assimilation of Atmospheric Composition Observations, and (vi) Emission Inventories and Estimation Methods.

Figure 2. Colloquium attendees participating the break-out group discussions on emission inventories.

The Colloquium students were selected from over 60 applicants who are pursuing careers in air quality science or policy. The applicants came from graduate/post-graduate programs in the United States, Canada, Germany, France, Holland, Greece, Chile, China, Japan, and Korea. During the Colloquium, the students participated in lectures, panel discussions, field trips, tutorials, and presentations. The break-out group discussions/exercises and computer-based tutorial covered the following: (i) adding a new criteria pollutant to the United States' National Ambient Air Quality Standard (NAAQS) list, (ii) regulating carbon dioxide as an air pollutant under the United States' Clean Air Act, (iii) working with and comparing satellite retrievals with *in situ* observations of atmospheric composition, (iv) using WRF-Chem to simulate the advection/evolution of atmospheric dust, (v) future directions in operational air quality forecasting (United States, Canada, Europe, and China/Asia), (vi) meteorological and chemical data assimilation, and (vii) using inverse methods for "top-down" emissions estimation. The participants also took field trips to visit: (i) a Colorado Air Care – Rapid Screen mobile emissions monitoring site, and (ii) a CASNET and IMPROVE monitoring site in the Rocky Mountain National Park Wilderness Area.

Figure 3. Colloquium attendees on field trip to CASNET and IMPROVE monitoring sites in the Rocky Mountain National Park Wilderness Area.

‹ 6.2 Atmospheric Radiation Science Workshop up

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DIRECTORS MESSAGE

The Advanced Study Program at the National Center for Atmospheric Research (NCAR) manages opportunities for educational and professional development for graduate students, postdocs and early career scientists and engineers, and research sabbaticals for faculty. ASP provides early career researchers and engineers access to NCAR's world-class research, engineering and computing facilities with the goal of promoting the advancement of science and innovation, especially in emerging areas of the geosciences. 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 other 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 10 new postdoctoral fellowships in Spring 2016 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 137 months of long-term visits to NCAR in FY16. Most of the GVP awards also include an advisor visit.

As a new activity the ASP, in partnership with the SOARS program and JOSS, ran a three–day career development program for postdoctoral fellows who are funded by the NSF.

In addition, the ASP also supported other workshops, such as the Software Engineering Assembly (SEA) conference on scientific computing and software development that included 120 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.

FY2017 PLANS

ASP will continue to engage and develop the scientific workforce of the future through its core visitor and fellowship programs. In addition, we are strengthening the community building and career development elements of the ASP that will be accessible to all graduate students and postdoctoral fellows at NCAR. Annual retreats and bi-monthly career

development seminars, bi-weekly Teas, training opportunities in leadership, time management and supervisory skills, and ongoing mentoring services support our graduate students and postdocs to take leadership roles in the community upon leaving ASP.

The next ASP Colloquium will focus on “The Interaction of Precipitation with Orography” and will be led by a team of NCAR scientists and university faculty. The two-week colloquium will be held at the NCAR in June 2017 and in addition to receiving excellent scientific training, participants will have the opportunity to explore NCAR and will receive guidance on career planning and professional development. ASP will continue to provide organizational and mentoring support for the activities of the Early Career Scientists Assembly. Additional details along with other ASP plans are included in this report.

Rebecca Haacker
ASP Director

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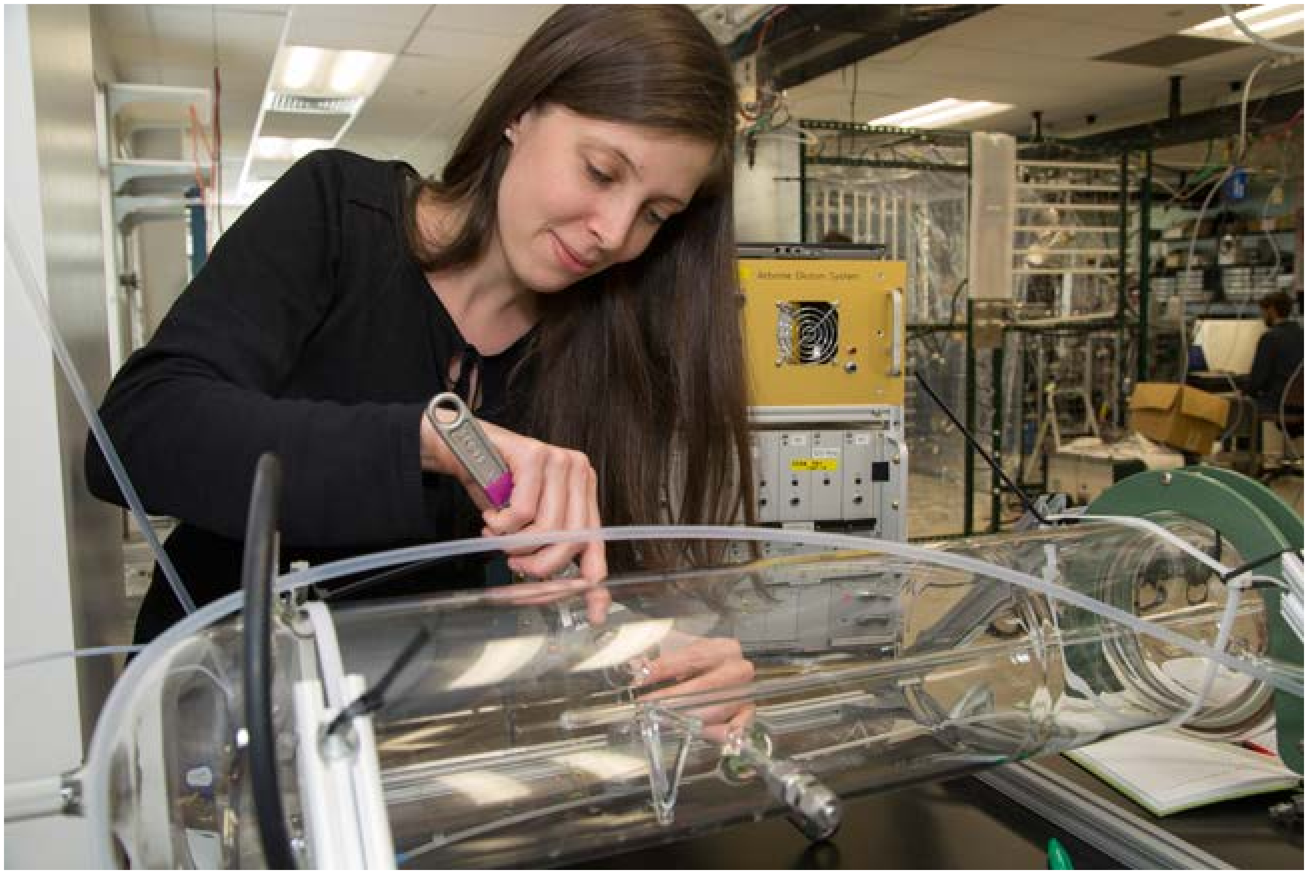
POSTDOCTORAL FELLOWSHIPS

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.

ASP postdoc Sara Paull, student assistant Savannah Ciardelli-Mullis, and NCAR scientist Mary Hayden

In FY16, the ASP appointed 10 new fellows (from over 120 applications) in a diversity of disciplines spanning the NCAR activities. Also in FY2016, the ASP was involved in the NSF-sponsored A Career Development Workshop for NSF Geosciences Postdoctoral Researchers in March. The event was open to the NSF AGS postdocs in addition to all postdocs at NCAR and included:

- Proposal writing
- Writing papers and publishing
- Teaching excellence
- Mentoring and managing students
- Insights into the hiring process



ASP postdoc Lisa Kaser

In FY16, five ASP fellows became faculty members at the University of Oklahoma, Boston University, The University of Alabama, Huntsville, Colorado State University, and Texas A & M.

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 FY2017, ASP plans to continue the core elements of the program, including monthly seminars, regular research reviews, regular career development activities, monthly teas and the Thompson Lecture Series along with the annual research planning sessions and on-going mentoring that all ASP postdocs receive.

Group photo with Dr. Richard Seager of Columbia University, 2016 Spring Thompson Lecturer

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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 3-12 months at NCAR. 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 2016 and 31 May 2018. ASP received 10 viable applications. Five applicants were extended offers for visits as a result. Included with the faculty visits were five visits made by students. **We supported 48 months of faculty/scientist and student visits through this program in FY16.**

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.

In 2016, The ASP also supported a six-month outgoing visit by an NCAR Scientist to Boston University.

FACULTY FELLOWSHIP PROGRAM TESTIMONIALS

Bas van Ruijven, NCAR Project Scientist

My experience during this stay at Boston University has been overwhelmingly positive. At Boston University my projects have contributed to stronger connections between the Pardee Center and the department of Earth and Environment and helped shape a research agenda on the interactions between climate change and development.

The period at BU has allowed me personally to become highly focused on several very interesting research projects. So far, the results of those projects are promising and hopefully will be accepted for publication in high-level journals. It has enabled me to participate in academic life around the Boston area, especially by regularly joining the Friday lunch meetings at the MIT Joint Program. I have greatly expanded my network of research colleagues in the Boston area which will be very helpful for future research proposals and collaborations.

Kathryn Steinmann, Student, San Jose State University

Being part of the ASP fellowship program has helped me in many ways. It allowed me to work on my research that will be used for Master's Thesis. I had the ability to get up close to the aircraft that was used for the flight campaigns that I am using data from. I also had the opportunity to meet many scientists from a wide range of research areas, including atmospheric chemistry and aircraft instrumentation. I was able to present some of my work to the atmospheric chemistry department, where scientists gave me feed back on my research. Being a part of this program was an amazing opportunity that helped me work on my research and meet scientists in the fields that I am interested in working in.

Howard Bluestein, Faculty Visitor, University of Oklahoma

I appreciated very much the support the NCAR Faculty Fellowship provided me.

During my residence at NCAR, I collaborated with Morris Weisman at MMM on simulating, using WRF, the effect of surface drying from dissipating convective systems late at night and early in the morning. The local drying can affect the behavior of subsequent convective activity during the following day. Based on our results (with assistance from Kevin Manning at MMM), and more simulations, we will draft a manuscript for publication in which we will make the community aware of the importance of properly simulating the drying so that forecasts of convection can be improved.

I approached Rich Rotunno with a problem concerning flow on heated, sloping topography, and how it could lead to enhanced low-level vertical shear, which is important for supercell behavior; I sought his advice because I had made little headway on the problem by myself. It turned out, unknown to me, that he had published recently on this problem. Consequently, he, Glen Romine (MMM), one of my current and one of my former graduate students, and I, are collaborating on our specific problem, using WRF simulations. I will be giving a seminar at the fall AGU meeting on this topic and eventually will draft a manuscript for publication. We will be trying to explain why the surface wind tends to turn in a counterclockwise manner with time (based on our analyses of surface mesonet data), rather than in a clockwise manner, as suggest by other, idealized studies.

Finally, Andy Heymsfield (MMM) and I collaborated on a pilot project to collect in situ hail data using disdrometers while our mobile, polarimeteric, Doppler radar scans the hailstorm. Andy will be drafting a proposal to NSF to continue our studies and also to draft a manuscript based on our field results last spring, for publication.

In summary, this fellowship allowed me to interact with scientists at NCAR, resulting in collaborative projects that would probably not have otherwise been instigated.

Minghui Diao, Faculty Visitor, San Jose State

I received the ASP Faculty Fellowship to visit NCAR for three months in May – August 2016. The ASP Faculty Fellowship provided tremendous help to me as a junior faculty to conduct research at NCAR, develop my research career, and also provided opportunities for my two graduate students, John D'Alessandro and Kathryn Steinmann to conduct their research with me at NCAR this summer.

During the three month period, we had conducted research at NCAR hosted by the Earth Observing Laboratory. I conducted laboratory calibration on the VCSEL hygrometer onboard the NSF/NCAR Gulfstream-V aircraft. As a former ASP postdoc fellow, coming back to NCAR in the summer helped me to access laboratory support for experimental work, which is harder to conduct at my university at San Jose State. In addition, as a result of my laboratory work, I provided a new calibration code for the VCSEL hygrometer, which will be applied to the QC/QA water vapor data in the NSF ORCAS campaign.

My student, John, conducted research on WRF simulations, in collaboration with several researchers at EOL and MMM. After we got back from NCAR, we submitted a manuscript to JGR in this October. This work would not have been done so efficiently without the support from ASP, especially for the hours allowed on the NCAR Yellowstone supercomputer.

My second graduate student, Kathryn, was able to finish some preliminary analysis on WRF-chem, as well as on the NSF CONTRAST campaign. She submitted an abstract to the upcoming AMS annual meeting and received an oral presentation.

Overall, I don't think there could have been any better place, or better way, for me and my students to develop our research in the past summer. As an assistant professor, being connected with the researchers and resources at NCAR really helped me and my groups in many ways. I myself would not have been able to afford my group's visit if we did not receive the support from the ASP Faculty Fellowship. Last but not the least, ASP program often organizes fun activities such as the hike at the Mesa lab. So my visit to NCAR was both a fruitful trip for my research, and a wonderful experience personally.

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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 eleventh 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 -3-12-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.

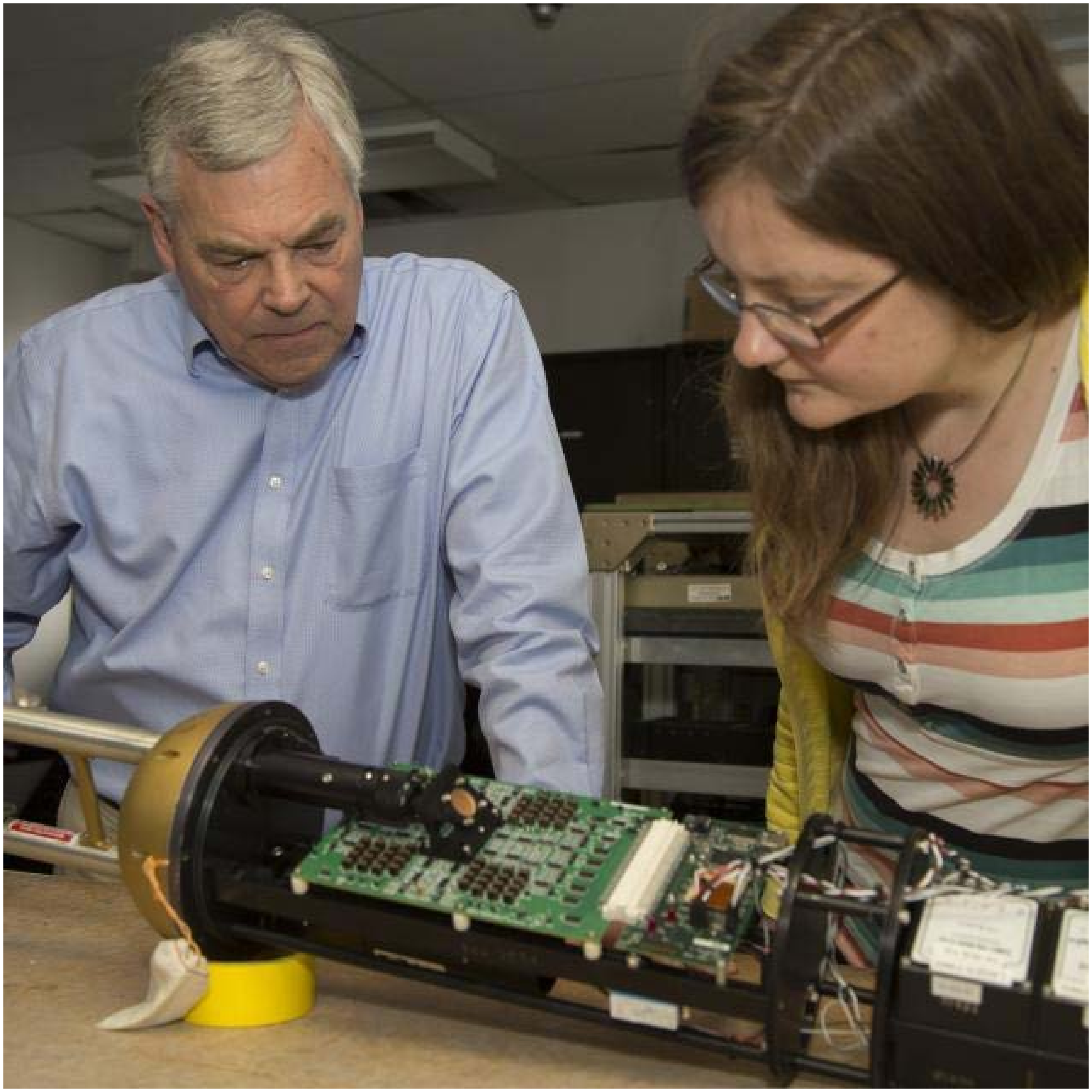

Photo courtesy of Carlye Calvin - NCAR

The ASP made 15 awards in the GVP program as a result of our FY2016 GVP competition. ASP supported 79 months of GVP visits and 11 advisor visits in 2016.

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.

TESTIMONIALS FROM GRADUATE VISITORS

Anna Merrifield, University of California, San Diego

The program helped my research by exposing me to the cutting edge of climate research. It's really rare for a young scientist to be in close proximity to so many of the leading researchers in his or her field. Someone once described it to me as "switching from a last name to a first name basis with the scientists you are citing"; I was incredibly star struck when I first arrived and by the end, I felt comfortable bouncing ideas of researchers I idolize. I got a lot of valuable feedback on every aspect of my project: from statistical methods to try, to pros and cons of climate dataset, to tips on writing and presenting my ideas; even just casual chats over lunch about someone's experiences were incredibly helpful. NCAR is a unique place and getting to be on the "inside" for a few months will do more for my career than years of reading papers, going to conferences and trying to get my foot in the publishing door from my home institution. I still tune in remotely for seminars and really got a lot out of research reports: seeing research in prep rather than just as a finished paper helped publishing feel less impossible.

Annareli Morales, University of Michigan

Participating in the ASP Graduate Visitor Program allowed me to have a prolonged stay at NCAR, where I had the opportunity to collaborate with scientists and learn from post-doctoral fellows. I was able to make progress on my research and receive a lot of valuable feedback from NCAR scientists. In addition to ASP I was awarded the WISE internship, which gave me the opportunity to meet and have individual conversations with all the RAL directors. I received great career advice and words of encouragement from the directors. I learned more about applied research and the options available to me after graduation, which was one of my goals for the summer. Another goal of mine that was made possible through ASP/WISE was mentoring a young scientist. I gained experience designing a summer project for a high school student and guiding her through the research process. Overall, my summer at NCAR gave me opportunities that I could not have received at my home institution. I gained valuable skills and connections that will be helpful throughout my career.

Samuel Li, University of Oregon

I like the ASP graduate visitor program because it brings me to work closely with the scientists at NCAR. It helped to advance my research by active discussion and experiments with the scientists. We were able to progress faster because we're working together. Our work together resulted in a publication, and I'm actually now an NCAR employee. All I wish for the graduate visitor program is to provide more funding to grad students, so the program becomes more competitive.

Aishwarya Raman, University of Arizona

1. It was a truly educational experience where I was working on my paper 3 for my PH.D with Luca, and his team in RAL lab.
2. It was a highly interdisciplinary team and I loved the willingness of everyone to help me throughout my project.
3. We developed a new framework for real time air quality forecasting.
4. The ASP program also helped me to interact closely with folks in ACOM team which otherwise would have not been possible.

Marysa Laguë, University of Washington

Participating in ASP was a very rewarding experience, and I'm so happy to have had the opportunity to visit NCAR as a

graduate student. I have been developing an idealized land surface model that couples in to CESM; physically being at NCAR was instrumental to the progress of my research, and to the development of this model. Being able to frequently discuss my work with the knowledgeable NCAR scientists and software engineers - regarding both the science aspect of my work, and the many coding hurdles I encountered - resulted in me gaining a much better understanding of Fortran, land modeling, and the CESM infrastructure. Additionally, being at NCAR let me build professional relationships with many scientists in my field with whom I would otherwise have had little chance to interact with. Being included in weekly CLM meetings gave me a much deeper understanding of the inner workings of the Community Land Model, and an appreciation for the process of model development that I don't think I would have received had I remained only in my university's environment.

The graduate visitor program has helped further my career as it has allowed me to become confident in my abilities developing, writing, and debugging models. ASP gave me the time and resources necessary to build the tool that will form the basis of my PhD work, and allowed me to meet and network with many scientists within the NCAR community. I particularly like that the graduate visitor program provides funds to cover housing while visiting Boulder, as I was still paying rent at my regular house. Lastly, ASP gave me the chance to spend a significant amount of time experiencing life in sunny and snowy Boulder (which is a very fun place!), and gave me a glimpse at possible careers staying in science but not necessarily affiliated with a university.

Huancui Hu, University of Arizona

What I like most about the graduate visitor program is to be able to work closely with NCAR scientists. It helped my research a lot because I can have my problems solved so efficiently, both in the sense of scientific and technical problems. I can just knock my office neighbor’s door who could be the developer of the tool/model that I am using. It could take more than one semester to accomplish the work I’ve done in two months at NCAR.

Another thing I liked very much is the opportunity to meet other graduate students, who might study a different field but have the same confusion as I had. The friendship I developed through this program could last my whole life, and I think it could benefit my long-term career. There were also interesting discussions with post-docs and senior scientists, which initiated connection and potential collaborations.

Susanne Glienke, Johannes Gutenberg Universitat

It was a really great opportunity for me to be a part of the ASP program, since it helped my research significantly. The fruitful discussions with several colleagues (both from NCAR and also visiting) not only during my stay at NCAR, but also since have helped to shape my research and deepened our collaborations further. I learned how to better interpret and analyze my data for my PhD project through the many discussions with my mentor at NCAR. The stay of my advisor at NCAR was also very helpful and sparked many more discussions. I also felt generally welcome in the ASP program, and always knew that there was someone I could talk to if necessary. Luckily, this need did not arise during my stay in Boulder since my mentor was really great.

Jacob Fugal (adviser), Johannes Gutenberg Universitat

The visitor program was a chance to be with our doctoral student to plan future research given the results of the CSET field campaign. It was also the chance to be there for the CSET data meeting which showed the other researchers our developing work and inspire ideas for paper writing. It advances the work of CSET field campaign which sponsored by NSF and student support also funded by NSF.

I see the ASP Graduate Visitor Program and the funded advisor visits as a wise investment to enhance and advance projects and student research NSF fund through other channels.

Rosimar Rios-Berrios, University at Albany

The ASP graduate visitor program offered me unique opportunities I would not have elsewhere. The last component of my PhD thesis was challenging, but being at NCAR helped a lot because I had access to model developers, experts on my topic, and really many people willing to help. Being able to knock their doors and ask for advice helped tremendously to move forward and complete my research. At the same time, I enjoyed the opportunity of chatting with scientists about research topics of mutual interests for them and me. These interactions sparked new collaborations and new ideas for future research. Being at NCAR also gave me the access to a supportive group of graduate students and post docs, from whom I have learned about career planning and job search.

Yue Li, University of New South Wales

Firstly, I have two wonderful thesis advisors from Regional Climate sector in MMM. We meet every week to discuss my research project. Thanks for their encouraging advice, my project is going so well. Apart from my advisors, people in the group are always ready to help me. During my four-month stay in NCAR, I learnt how to be an independent researcher. ASP provides a good opportunity for me to communicate with people with diversity of experiences, viewpoints and background. In particular, I had a chance to talk to a group of early-career researcher who shared their experience and advice to help me on my career path.

Alicia Klees, Pennsylvania State University

My visit to NCAR honestly pretty much saved my PhD, and I'd be happy to elaborate further on the below. I am so grateful for the program!

Participating in the Graduate Visitor Program was incredibly valuable to my research. Through my visit, I made a lot of progress that had proven to be very challenging to achieve at my home university. My NCAR mentor taught me how to run DART, which involves many complicated scripts/moving parts. I can now independently run basic WRF-DART simulations - a huge and key step forward in my project. Thanks to my visit, I also now have a much better understanding of storm-scale modeling and data assimilation, as well as a lot more interest in pursuing a career in this field (perhaps a postdoc at NCAR, to begin!)

Avelino Arellano, (adviser) University of Arizona

My PhD student, Aish Raman, visited Luca Del Monache last summer to learn more about an analog ensemble approach to improving aerosol prediction. Her summer work with Luca and his team brought important progress, not only in her PhD dissertation, but more importantly, in terms of her professional development. It provided a unique opportunity for her to work in a research environment (outside of University). Her visit paved the way for a new direction to the final section of her PhD dissertation.

It was certainly an enriching experience and a great complement to her PhD program.

Yvette Richardson, (adviser) Penn State University

The ASP Visitor program was very beneficial for my graduate student. She was able to meet with experts in data assimilation and make significant progress in her research. The ability to meet regularly with scientists having this

technical expertise was invaluable. The visit also offered opportunities for professional development, as she gave a seminar at NCAR and broadened her professional network.

‹ Building Partnerships with University Faculty up ASP Summer Colloquium ›

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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 2016, the summer colloquium was titled *Recent Advances in Air Quality Analysis and Prediction – The Interaction of Science and Policy* and was held July 25 – August 5, 2016. The organizers were Dr. Arthur P. Mizzi, NCAR/ACOM and Prof. Avelino F. Arellano, Univ. of Arizona – Dept. of Hydrology and Atmospheric Science.

ASP hosted approximately 40 lecturers and 30 students. The participants were as international as the subject with multiple representatives from the United States, Canada, South America, Europe, and Asia.

Group photo of colloquium participants in front of the NCAR Mesa Lab

Air quality is an atmospheric science topic of great domestic and international importance. It directly impacts human health and welfare across multiple temporal and spatial scales. Its research is taking place in a rapidly evolving regulatory and technological environment. Those changes are creating two challenges: (i) air quality scientists and researchers find it difficult to keep up with the regulatory/policy changes that motivate the funding for much or their research, and (ii) air quality regulators/policymakers find it difficult to keep up with the technological advances that underlie the air quality issues/remedies their regulations/policies are meant to address. The Colloquium addressed those challenges by bringing together graduate students, early career scientists, and lecturing experts from around the world to explore/discuss the following subject areas: (i) The Air Quality Problem (international/domestic), (ii) Air Quality Regulation and Policy (international/domestic), (iii) Air Quality Observations (regulatory/research/*in situ*/remote), (iv) Air Quality Modeling (regulatory/research/operational), (v) Assimilation of Atmospheric Composition Observations, and (vi) Emission Inventories and Estimation Methods.

The Colloquium students were selected from over 60 applicants who are pursuing careers in air quality science or policy. The applicants came from graduate/post-graduate programs in the United States, Canada, Germany, France, Holland, Greece, Chile, China, Japan, and Korea. During the Colloquium, the students participated in lectures, panel discussions, field trips, tutorials, and presentations. The break-out group discussions/exercises and computer-based tutorial covered the following: (i) adding a new criteria pollutant to the United States' National Ambient Air Quality Standard (NAAQS) list, (ii) regulating carbon dioxide as an air pollutant under the United States' Clean Air Act, (iii) working with and comparing satellite retrievals with *in situ* observations of atmospheric composition, (iv) using WRF-Chem to simulate the advection/evolution of atmospheric dust, (v) future directions in operational air quality forecasting (United States, Canada, Europe, and China/Asia), (vi) meteorological and chemical data assimilation, and (vii) using inverse methods for “top-down” emissions estimation. The participants also took field trips to visit: (i) a Colorado Air Care – Rapid Screen mobile emissions monitoring site, and (ii) a CASNET and IMPROVE monitoring site in the Rocky Mountain National Park Wilderness Area.

Group hike to air quality monitoring station in Rocky Mountain National Park

Generally, reviews of the Colloquium were very positive. The participants found the juxtaposition of science and policy interesting and educational. Several participants requested that future workshops include broader coverage of the air quality regulatory structure from Europe, Asia, and Australia. The participants also found the panel discussions, break-out sessions, and tutorial exercises very helpful and suggested the future workshops provide more time for such exercises. Clearly one challenge in organizing such workshop is finding the proper balance between such diverse subjects as science and policy and lectures and tutorials.

Perhaps the best measure of the Colloquium's success is found in the participant small group presentations. At the beginning of the Colloquium, the participants were broken into three small groups of between ten and fifteen persons to facilitate collegiality and more in-depth discussions. The small group were also told that at the end of the Colloquium they would need to make fifteen minute presentations about what they had learned during the Colloquium considering the comparative roles of policy and science in resolving domestic/international air quality issues. The final presentations displayed creativity, understanding, and enthusiasm – suggesting the the Colloquium had successfully engaged the participants and conveyed an understanding of the current state and future direction of air quality science and policy.

‹ Providing University Students Access to the Resources of NCAR up

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0.0 CGD DIRECTOR'S MESSAGE

CGD Director Bill Large.

The 2016 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. Over the coming year, CGD will focus on producing its contributions to the Coupled Model Intercomparison Project (CMIP-6).

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://www.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.

The report of the CGD Advisory Panel (CAP) was perhaps the first of a series of events that have aligned and led to NSF support for an NCAR/CGD request for supplemental funding to implement many of the Panel recommendations concerning CESM component model development, and university involvement. NCAR/CGD now has the funding for three years starting in January 2017. In addition to the Panel report, other stars to align include: consistent remarks in the letter from the CESM Advisory Board (CAB), based on Sumant's presentation of your CAP report; NSF oceanography's response in the form of organizing a town hall on ocean modeling at Ocean Sciences 2016; a detailed assessment last November of the impact of diminishing DOE support for the CESM component models from LANL, especially the ocean, sea-ice and land-components; these components happen to be of interest to divisions of NSF/GEO beyond AGS; and very importantly the interest of NSF program managers from across GEO in advancing these CESM components.

The supplemental will enable replacing the POP ocean component, co-developing the sea-ice model CICE to be consistent with the replacement and state-of-the-art, and configuring the CISM land-ice model for Antarctica in addition to Greenland. The plan is to have these all three of these components working together as coupled CESM components within three years, so that as CMIP-6 winds down, they are part of foundation from which to develop CESM-3 over the following 2 to 3 years. There are 3-year work plans for each component that will be implemented in association with the three relevant working groups, namely; Ocean Modeling, Polar Climate and Land-Ice. Key to this work will be the hiring of both an ocean modeler and a land-ice modeler supported by the supplemental for the first three years, then by NSF base funding to NCAR.

The supplemental will also support a full complement of 2 full time liaisons for each of the three relevant CESM Working Groups. In keeping with the theme of the CAP meeting, up to one-half the effort of these liaisons will be to engage the university community in the development of the ocean, sea-ice and land-ice models. Ongoing CAP advice on how best to deploy these resources would be very much appreciated over the three years of the supplemental. It should be possible to continue the most successful activities beyond the three years of the supplemental funding.

‹ 2016 CGD Annual Report | up | NCAR Imperative 1 | ORCAS Field Campaign ›

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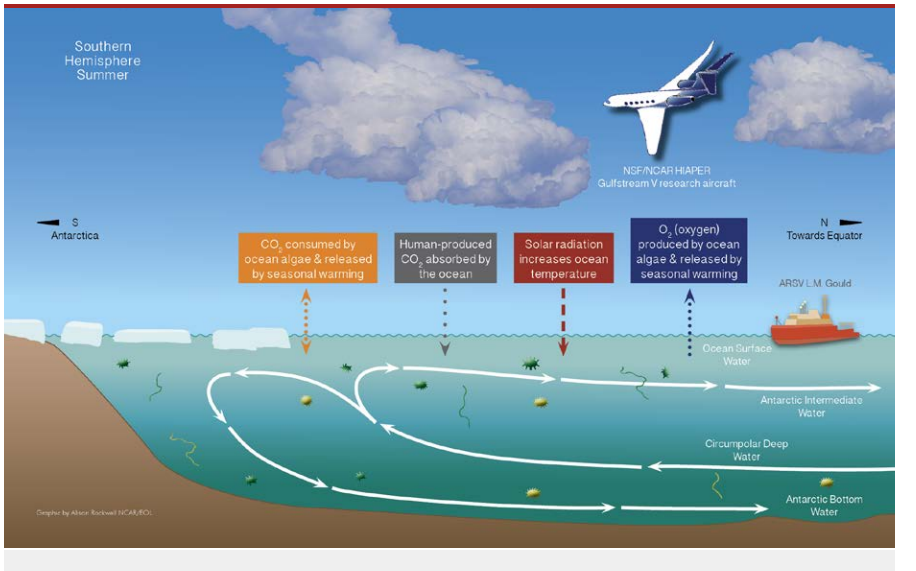
NCAR IMPERATIVE 1 | ORCAS FIELD CAMPAIGN

The ORCAS | O_2/N_2 Ratio and CO_2 Airborne Southern Ocean field (https://www.eol.ucar.edu/field_projects/orcas) campaign provided scientists a rare look at how oxygen and carbon dioxide are exchanged between the air and the seas surrounding Antarctica. The data collected helps to illuminate the role the Southern Ocean plays in soaking up excess carbon dioxide emitted into the atmosphere by humans.



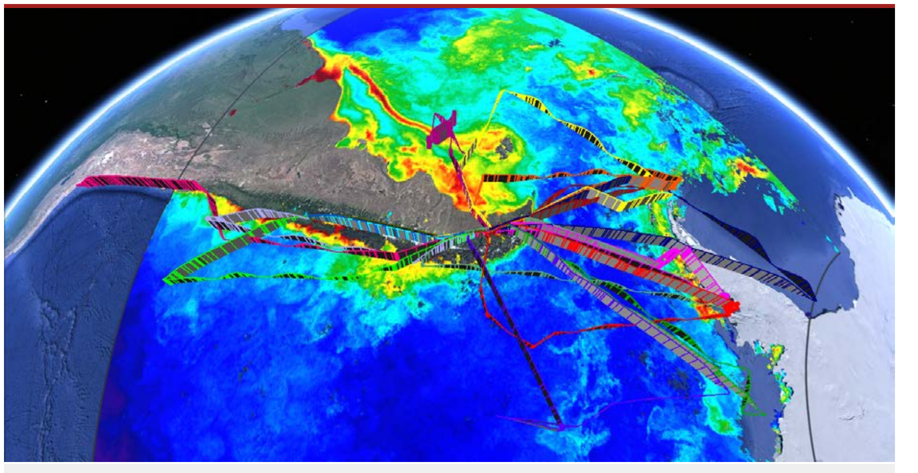
The science campaign was led by NCAR with other principal investigators from the Scripps Institution of Oceanography, University of Michigan, and the Cooperative Institute for Research in Environmental Sciences (a partnership of the National Oceanic and Atmospheric Administration and the University of Colorado Boulder), University of Miami, and NASA's Jet Propulsion Laboratory.

Measuring oxygen alongside carbon dioxide gives scientists a clearer picture of the ocean processes affecting carbon dioxide than they would get from measuring carbon dioxide alone. Carbon dioxide in the ocean is drawn into a chain of chemical

reactions that buffer the impact of biological and physical ocean processes on carbon dioxide in the overlying atmosphere. Oxygen air-sea fluxes, however, are more directly tied to these same biological and physical factors. So if scientists know what's going on with oxygen, they can better understand the processes affecting carbon dioxide as well. Additionally, if scientists know how the concentrations of the two gases change relative to one another with location and time, they can disentangle how biology and physics separately affect the ocean's ability to absorb carbon dioxide.

ORCAS Infographic. High resolution image.

Operating out of Punta Arenas, near the southern tip of Chile, the researchers used the NSF/NCAR HIAPER research aircraft to make 14 flights across parts of the Southern Ocean between Jan. 15 and Feb. 28, 2016. A suite of instruments on the modified Gulfstream V jet measured the distribution of oxygen and carbon dioxide as well as other gases produced by marine microorganisms, plus aerosol and cloud characteristics in the atmosphere.



ORCAS flight tracks colored by flight, including satellite chlorophyll and altitude of track. High resolution image.

Physics and biology affect the ratio of carbon dioxide to oxygen in the air in different ways. In the austral spring the warmth of the returning Sun drives both carbon dioxide and oxygen out of the Southern Ocean surface and into the atmosphere. But the sunlight also triggers the growth of phytoplankton in the water. As the organisms begin to flourish, they take in carbon dioxide and release oxygen, causing the relative amounts of those two gases in the atmosphere to shift in opposite directions. Observations of these shifts can ultimately tell scientists how much carbon is going where and, more importantly, why.

The Southern Ocean is unique among Earth's oceans. Unimpeded by continental landmasses, and driven by a westerly wind, the Southern Ocean is able to form a circular current around Antarctica. This huge flow, the largest current on the planet, connects the adjacent Atlantic, Pacific, and Indian oceans. The complex interactions between this Antarctic Circumpolar Current and currents flowing in from other ocean basins creates an overturning circulation that brings deep water to the surface where it can exchange gases with the atmosphere before it is returned to depth.

Once it dives toward the ocean floor, that surface water—and any carbon dioxide it takes with it—can stay sequestered in the deep ocean for hundreds or even thousands of years. Data collected by the ORCAS flights will help determine how much carbon dioxide goes along for the ride. The data generated during the field campaign will be used by the ORCAS team to improve global computer models so they do a better job representing the complexities of the Southern Ocean. The data set, which is managed by NCAR, will be publicly available. While the measurements made during the ORCAS campaign will help scientists fine-tune what they know so far about the Southern Ocean, it's possible the project will also bring to light entirely new aspects of how the ocean works.

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NCAR IMPERATIVE 1 | BGC RUNS

CGD scientists completed 20th Century Runs of the CESM-BGC version 1.5:

- Coupled climate-carbon experiments have been completed with an updated version of CESM. Compared to previous versions of CESM, the bias in CO2 uptake by the land model was significantly reduced, while the bias in CO2 uptake by the ocean did not change much.
- Within a large set of climate models, Antarctic sea ice and SSTs exhibit a 2-timescale response to SAM variability, with initial cooling and ice increases followed by warming and ice decline.
- Late 20th century Antarctic sea ice trends in CMIP5 simulations are related in part to different modeled responses to SAM variability acting on different time-varying transient SAM conditions.

As new parameterizations of eddy mixing are developed there is a need for quantitative guidance from observations and high-resolution modeling to first validate the parameterization, and second to guide the choice of free parameters. A recently developed technique for computing the global distribution of the eddy diffusivity tensor from passive tracer simulations with high-resolution global ocean models was used to develop estimates of the spatial dependence and degree of anisotropy of mixing by mesoscale eddies. These estimates were used to constrain the range of values used in simulations with prototype versions of CESM that incorporate a new anisotropic form of the Gent-McWilliams parameterization.

‹ NCAR Imperative 1 | ORCAS Field Campaign up NCAR Imperative 1 | Coral Reef Bleaching ›

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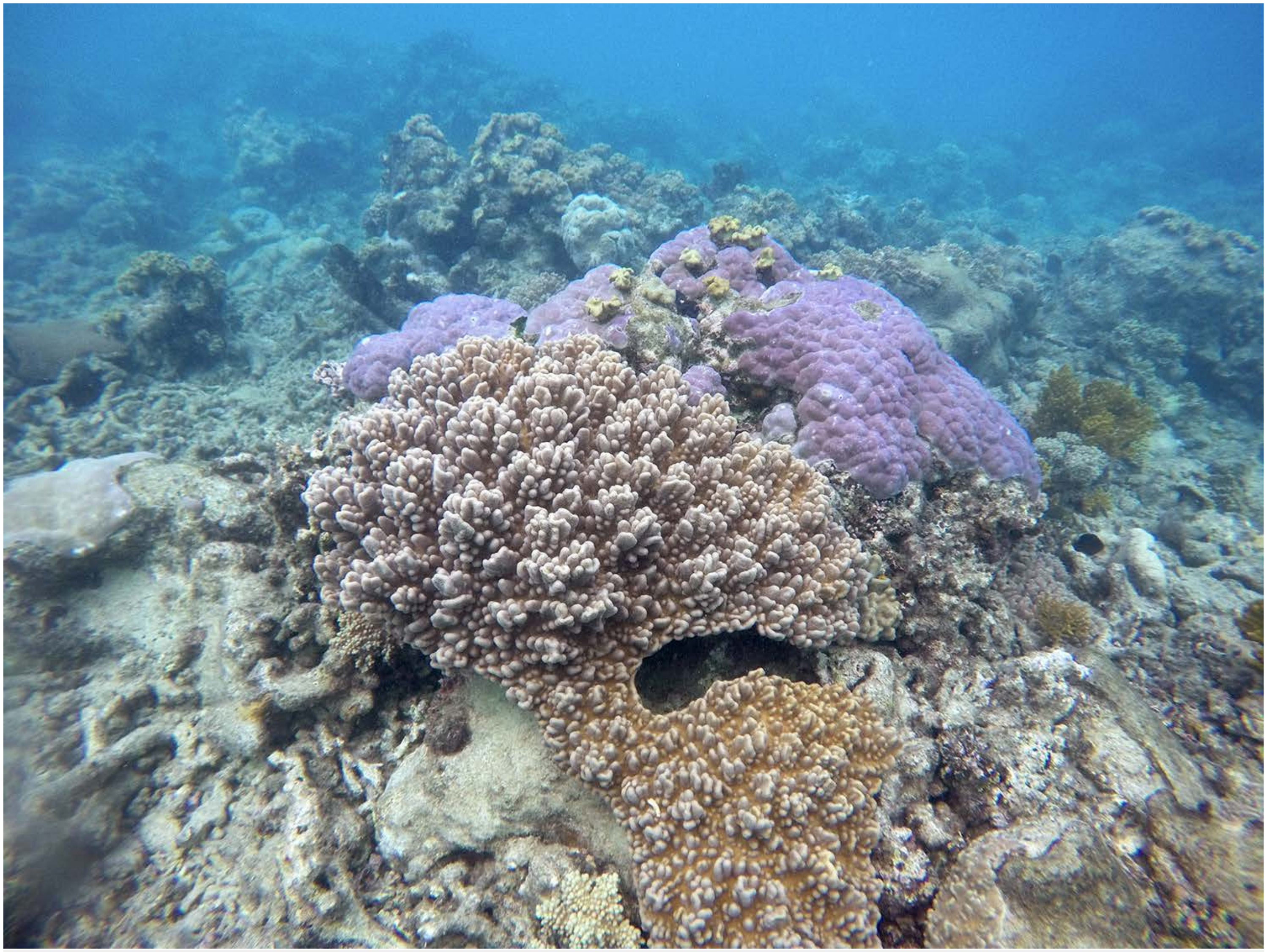
NCAR IMPERATIVE 1 | CORAL REEF BLEACHING

Many corals worldwide are currently being impacted by what has been labeled the third global coral bleaching event. Large-scale bleaching events occur when corals experience thermal stress that arises from a combination of global warming and ENSO conditions. The current global-scale bleaching event began in the summer of 2014, and is predicted to last well into 2017, making it the longest bleaching event on record, and making it likely that some reefs will re-experience bleaching conditions before the corals can recover. In conjunction with colleagues at the Centro de Investigación en Ciencias del Mar y Limnología (CIMAR), CGD's leading expert in coral reef flew to Costa Rica to work on coral reefs in the Golfo Dulce, an embayment on Costa Rica's Pacific coast. Coral reef ecosystems in the Golfo Dulce were decimated in the 1950s by sedimentation resulting from deforestation of the surrounding rainforests. Conditions have improved since then, and the coral ecosystems have been recovering. The CGD project cultured corals in underwater nurseries using different methodologies, and investigated how recovery varies amongst different coral genotypes. Unfortunately, the work is further challenged by the fact that the Golfo Dulce corals are currently experiencing coral bleaching. On the one hand, this can decimate coral populations, but on the other hand, it reveals which corals are better adapted to elevated temperatures, and should thus be selected for propagation.



Bleached and stressed coral on the Great Barrier Reef. Credits: NASA/JPL-Caltech/BIOS

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CGD Strategic Plan

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NCAR IMPERATIVE 3 | ADVANCE COMMUNITY MODELS

We have transitioned much of the CESM infrastructure to the new CIME (Common Infrastructure for Modeling the Earth) paradigm. CIME separates much of the infrastructure of the model such as coupling, IO and support scripting from the science components of the model. By doing so, we have engaged collaborators who are using models similar to CESM to share the burden of infrastructure development code among a bigger user and developer community. With CIME, there is greater developer feedback, and more testing, thus improving robustness of the model.

A critical aspect of CIME was to move 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 is complete and includes many new parameterizations and features including hydrology, snow, vegetation processes, urban, nitrogen processes, and land-use processes including agriculture. CLM5 will be used in upcoming CMIP 6 and CESM2. CGD scientists are Leads or Co-Leads of the Land-use Model Intercomparison Project (LUMIP) and the Land Surface, Soil Moisture and Snow Intercomparison Project (LS3MIP). Protocol papers have been published for both MIPs in GMD. LUMIP and CLM5 have been presented at several national meetings.

Chemical mechanisms were expanded to fully represent tropospheric (including a better representation of secondary-

organic aerosols), stratospheric (including an explicit representation of volcanic aerosols) and mesospheric chemistries. These are all being finalized for inclusion in CESM2 and use in CMIP6 simulations. In addition, it will provide a benchmark against which simplified chemistry mechanisms can be tested. Simulations of atmospheric composition of relevance to society (tropospheric ozone, stratospheric ozone depletion, air quality) will be more accurate and more physically-based as a result of these efforts.

Consolidated list of new parameterizations and features for CLM5.

‹ NCAR Imperative 1 | Coral Reef Bleaching up NCAR Imperative 3 | Community Access: CESM Ensembles ›

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NCAR IMPERATIVE 3 | COMMUNITY ACCESS: CESM ENSEMBLES

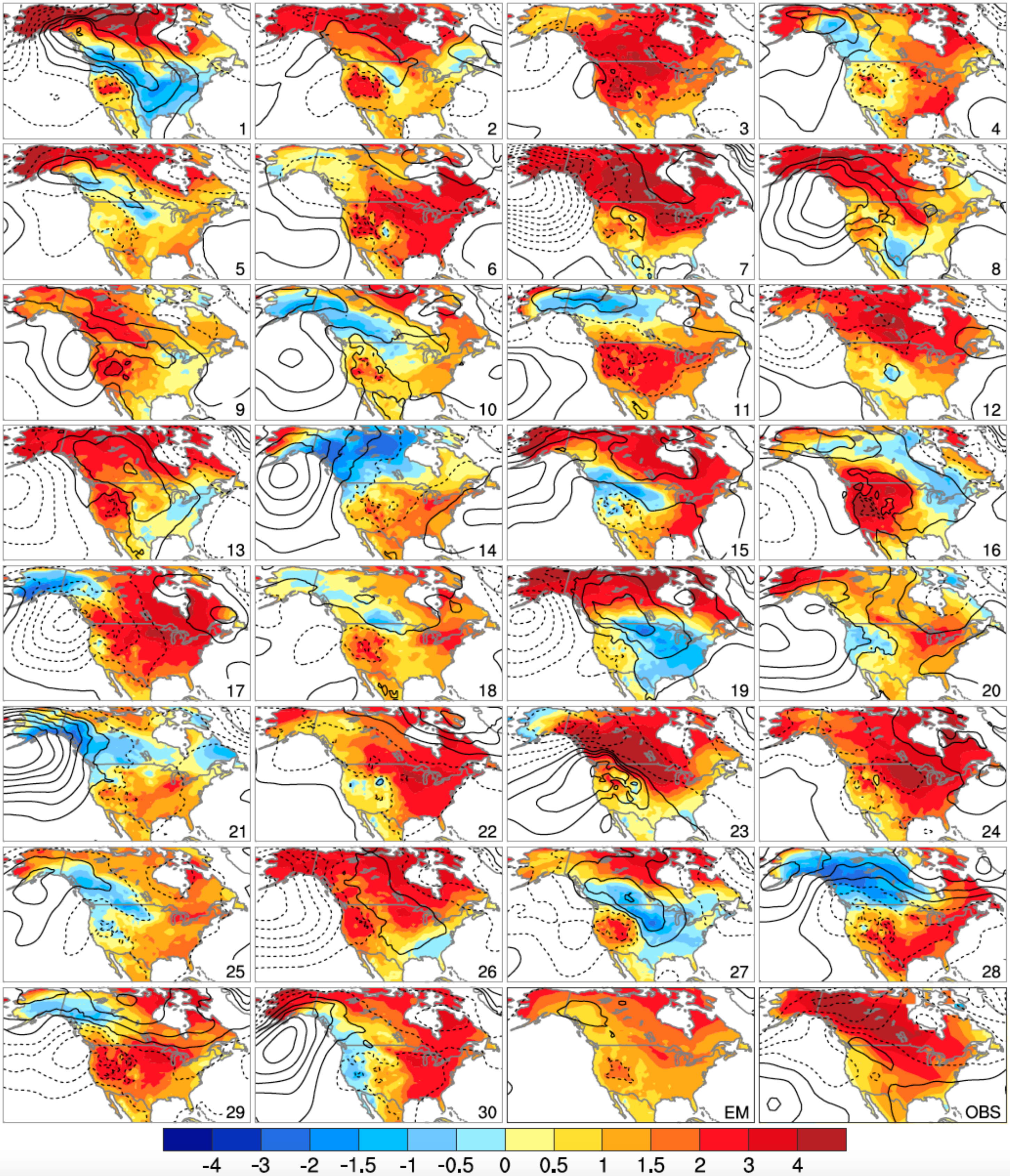
To explore the possible impacts of uncertainties in recent past variations and future projections of natural and anthropogenic forcings in the framework of internal variability of the coupled climate system, NCAR has provided ensembles of CESM simulations (over 100 so far) for community analysis. CGD scientists in collaboration with colleagues at the University of Colorado Boulder led a project to run the NCAR-based Community Earth System Model (CESM) 40 times from 1920 forward to 2100 – producing the CESM Large Ensemble (http://www.cesm.ucar.edu/projects/community-projects/LENS/). With each simulation, the scientists modified the model's starting conditions ever so slightly by adjusting the global atmospheric temperature by less than one-trillionth of one degree, touching off a unique and chaotic chain of climate events, extending to 2100 with the RCP8.5 scenario. Complementing the Large Ensemble, CGD scientists have provided 15-member CESM ensembles for 2006 forward to 2100 using the RCP4.5 scenario forcings (the Medium Ensemble) and using the same forcing as the RCP 8.5 Large Ensemble except that all aerosol emissions and tropospheric oxidants fixed at 2005 levels.

The CESM Large, Medium, and Fixed Aerosol Ensembles are a display of Earth climates that could have been along with a rich look at future climates that could potentially be. The datasets generated during the project, which are freely available, have already proven to be a tremendous resource for researchers across the globe who are interested in how natural climate variability and human-caused climate change interact. In a little over a year, about 100 peer-reviewed scientific journal articles have used data from the CESM Large Ensemble. Scientists have so far relied on the CESM Large Ensemble to study everything from oxygen levels in the ocean to potential geoengineering scenarios to possible changes in the

frequency of moisture-laden atmospheric rivers making landfall. All three ensembles have been utilized by the project on the Benefits of Reduce Anthropogenic Climate changE (BRACE) to assess avoided impacts on climate extremes, health, tropical cyclones, and agriculture and land use by choosing a path forward of reduced emissions.

Complementing these CESM ensembles for the instrumental period and into the future, a 38-member Last Millennium Ensemble (http://www.cesm.ucar.edu/projects/community-projects/LME/) from 850 forward to 2005 has been completed by CGD scientists and is also freely available to the community. The last millennium has a rich archive of annually-dated proxy records – tree rings, ice cores, Arctic lake records, stalagmites, corals – that give a longer perspective on climate variability and change than is available for the instrumental period. The CESM Last Millennium ensemble contains both simulations with all forcings (solar, volcanic, greenhouse gases, orbital, land use, and aerosols) as well as ensembles of simulations with each forcing individually, with the latter providing a longer-term perspective for detection and attribution. Scientists have already used the CESM Last Millennium Ensemble to assess the roles of internal and naturally-forced variability on coastal upwelling to terrestrial aridity to East African hydroclimate.

Running a complex climate model like the CESM many dozens of times takes a vast amount of computing resources, which makes such projects rare and difficult to pull off. With that in mind, NCAR queried scientists from across the community who might make use of the project results — oceanographers, geochemists, atmospheric scientists, biologists, geologists, socioeconomic researchers — about what they really wanted. Scientists have long understood that it makes sense to look at more than one model run. Frequently, however, scientists have done this by comparing simulations from different climate models, collectively called a multi-model ensemble. This method gives a feel for the diversity of possible outcomes, but it doesn't allow researchers to determine why two model simulations might differ: Is it because the models themselves represent the physics of the Earth system differently? Or is it because the models have different representations of the natural variability or different sensitivities to changing natural and anthropogenic forcings? Ensembles with the same model help to resolve this dilemma.



Winter temperature trends (in degrees Celsius) for North America between 1963 and 2012 for each of 30 members of the CESM Large Ensemble. The variations in warming and cooling in the 30 members illustrate the far-reaching effects of natural variability superimposed on human-induced climate change. The ensemble mean (EM; bottom, second image from right) averages out the natural variability, leaving only the warming trend attributed to human-caused climate change. The image at bottom right (OBS) shows actual observations from the same time period. By comparing

the ensemble mean to the observations, the science team was able to parse how much of the warming over North America was due to natural variability and how much was due to human-caused climate change. Read the full study in the American Meteorological Society's Journal of Climate. (© 2016 AMS.)

‹ NCAR Imperative 3 | Advance Community Models up NCAR Imperative 5 Support Decision Making | Population & Fires ›

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NCAR IMPERATIVE 5 SUPPORT DECISION MAKING | POPULATION & FIRES

A new study by a team of scientists, including experts from CGD, found that the future pattern of population growth, not climate change, is likely to be the dominant factor in determining whether the amount of land burned by fires increases or decreases this century. NCAR experts in collaboration with colleagues from Lund University in Sweden and the Karlsruhe Institute of Technology in Germany —found that the anticipated increase in total burned area due to a warmer climate will likely be offset by the carbon dioxide itself, which can act as a fertilizer, affecting plant growth and driving down fire risk globally.

When climate change, carbon dioxide concentration, and population are all considered, the total area burned across the globe could very well decrease over the rest of this century, according to the study, published in the journal Nature Climate Change.

Climate change generally increases global fire risk by drying the fuel — trees, grasses, and other vegetation — that feeds the flames. At the same time, the additional carbon dioxide in the atmosphere tends to decrease global fire risk, largely by encouraging the growth of shrubs in areas that are now grasslands. On average, more than 70 percent of the total area burned each year across the world is on grassland savannah, where fire can spread very quickly. As shrubs encroach, they fragment the grassland and create natural firebreaks. People, on the other hand, have a complex effect on fire risk. In general, humans suppress fires more than they ignite them, leading to an overall downward trend in acres burned when population increase is considered on its own, the study found. This helps explain why global burned area has actually

decreased over the last century, despite a warming climate, Jiang said.

A grass fire burns through an open area. September 1983. Photo credit: CSIRO, Malcolm Paterson

‹ NCAR Imperative 3 | Community Access: CESM Ensembles
up
NCAR Imperative 5 | Support Decision Making | Global Food Supply ›

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NCAR IMPERATIVE 5 | SUPPORT DECISION MAKING | GLOBAL FOOD SUPPLY

Climate change is likely to have far-reaching impacts on food security throughout the world, especially for the poor and those living in tropical regions, according to a new international report that includes three co-authors from NCAR including CGD scientists.

The report (http://www.usda.gov/oce/climate_change/FoodSecurity.htm), issued today at the Paris 2015 United Nations Climate Conference (also known as COP21) warns that warmer temperatures and altered precipitation patterns can threaten food production, disrupt transportation systems, and degrade food safety, among other impacts. As a result, international progress in the past few decades toward improving food security will be difficult to maintain.

The report, Climate Change, Global Food Security, and the U.S. Food System, provides an overview of recent research in climate change and agriculture. Led by the U.S. Department of Agriculture and published under the auspices of the U.S. Global Change Research Program, it includes contributors from 19 federal, academic, nongovernmental, intergovernmental, and private organizations in the United States, Argentina, Britain, and Thailand.

The report focuses on identifying climate change impacts on global food security through 2100. The authors emphasize that food security – the ability of people to obtain and use sufficient amounts of safe and nutritious food – will be affected by several factors in addition to climate change, such as technological advances, increases in population, the distribution of wealth, and changes in eating habits.

Among the report's key findings:

- The impact of climate change on crop and livestock productivity is projected to be larger for tropical and subtropical regions such as Africa and South Asia, although there will be regional variations. Wealthy populations and temperate regions are less at risk, and some high-latitude regions may temporarily experience productivity increases, in part because of warmer temperatures and more precipitation. However, if society continues to emit more carbon dioxide and other greenhouse gases that cause climate change, even those regions will face damaging outcomes during the second half of this century.
- Climate change has important implications for food producers and consumers in the United States. The nation is likely to experience changes in the types and cost of food available for import. It can also expect to face increased demand for agricultural exports from regions coping with production difficulties.
- Climate change risks extend beyond agricultural production to critical elements of global food systems, including processing, storage, transportation, and consumption. For example, warmer temperatures can have a negative impact on food storage and increase food safety risks; higher sea levels and changes to lake and river levels can impede transportation.
- Risks to food security will increase with a higher magnitude and faster rate of climate change. In a worst-case scenario based on high greenhouse gas concentrations, high population growth, and low economic growth, the number of people at risk of undernourishment would increase by as much as 175 million by 2080 over today's level of about 805 million. This would reverse recent gains, as the number of people at risk of undernourishment has dropped from about 1 billion since the early 1990s.

Society can take steps to reduce the food system's vulnerability to climate change, ranging from more advanced growing methods to cold storage, improvements in transportation infrastructure, and other strategies. Such adaptations, however, may be difficult to implement in some regions due to availability of water, soil nutrients, infrastructure, funding, or other factors.

Depiction of global food supply.

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Population & Fires

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CISL DIRECTOR'S MESSAGE

Welcome to the FY2016 CISL Annual Report from Anke Kamrath, CISL's Interim Director.

It is my sad duty to report that NCAR lost a beloved and respected colleague when Al Kellie passed away unexpectedly in his sleep on 7 September 2016.

Al Kellie, SCD and CISL Director 1998-2016.

Al will be remembered for his considerable contributions to NCAR – especially his forward-looking stewardship of its high-performance computing resources – and for the way he truly cared for his staff both professionally and personally. Al joined NCAR in 1998 as Director of the Scientific Computing Division (now CISL). Under his leadership, NCAR transitioned from a parallel vector supercomputing environment to massively parallel clusters of microprocessors, delivering a staggering 30,000-fold increase in sustained computing capacity to the atmospheric and related sciences during his tenure.

In 2003 Al spearheaded NCAR's effort to design, fund, and construct a new high performance computing (HPC) center to support future generations of power-hungry, high-performance supercomputers. By 2009 this effort had matured into a successful proposal to the NSF for constructing the NCAR-Wyoming Supercomputing Center (NWSC) in Cheyenne, Wyoming. The NWSC became a case study in the international HPC community for its exemplary design and construction. Al was extremely proud of the award-winning NWSC when it opened in 2012, and his pride grew as CISL staff developed it and the research community used its resources to more fully realize its potential.

It is my honor to serve as CISL's Interim Director and to continue our

Anke Kamrath, CISL Interim Director

forward-looking work to meet new challenges. As a brief introduction, my name is Anke Kamrath and I joined CISL in July 2009. Since that time I have been a member of CISL's executive leadership team, working to support the Lab's vision for and excellence in serving the research community. I will continue serving in an interim capacity until a permanent CISL Laboratory Director is appointed.

I am now supporting NCAR and UCAR in three major roles. I will continue working as CISL's Director of the Operations and Services Division, and I will both oversee the Lab as a whole and serve as the Security Chief Information Officer (SCIO) for UCAR. Part of my work as SCIO will be to manage UCAR's progress toward full compliance with the Federal Information Security Management Act (FISMA).

My first priority is to move NCAR's newly installed supercomputer named Cheyenne into full production by January 2017. I am committed to continuing Al Kellie's series of successes by ensuring that the NWSC's second supercomputer is operational and advancing our science right on schedule. This annual report highlights some of the successes CISL has achieved during Al's final year as its Director. It is organized into three sections that begin with our Service achievements in cyberinfrastructure, user support, big data, and information technology. The Science section follows with reports on our data-focused research, numerical methods for modeling, and applied computational science research. Finally, CISL's Education efforts are described in the areas of integrating education into our research, training researchers in scientific computing, and reaching out to attract new and diverse talent to our scientific and technical enterprises.

Service

CISL's service highlight occurred in Cheyenne, Wyoming, where the NWSC facility was fully prepared and the Cheyenne system was installed and powered up before the end of the fiscal year, all while the Yellowstone system operated at full productivity without interruption. Our operational supercomputing environment includes the Yellowstone computer, the central disk storage system known as NCAR's GLobally Accessible Data Environment, two data analysis and visualization systems, the High Performance Storage System data archive, high-speed wide-area networking, and various high-performance data transfer and sharing services, all coupled by the many system and application software suites that allow our science to advance at an ever-faster pace. To prepare for the next generation of computing, CISL continued exploring new types of systems by operating and enhancing its HPC Futures Lab to assess new technologies that may be available in upcoming production computers. CISL's end-to-end workflow support for Earth System scientists includes comprehensive, targeted user support, an expansive and growing portfolio of Big Data services, enterprise IT support for all of NCAR and UCAR, and leadership in cyberinfrastructure initiatives from local to international levels. CISL staff produced significant progress in these areas, and overviews of this work appear in the first section of this annual report.

Science

CISL's science portfolio made numerous advances this year by combining petascale supercomputing resources with the latest computational science research in algorithms, mathematical techniques, and statistical methods applied to Earth System science. New scalable algorithms for data assimilation are being developed and used to support large atmosphere

and ocean prediction models in collaboration with scientists throughout NCAR. Strides in interpreting and using heterogeneous data continued throughout the year. Computing for climate models was accelerated through new algorithms and by exploiting emerging technologies such as coprocessors. CISL scientists also developed computationally efficient parallelizable data analysis techniques and data processing tools. And long-term research efforts are now succeeding in building uncertainty measures into climate models in ways that are useful for decision making and policy.

Education

CISL's education accomplishments include strong participation by new interns, students, and visiting scientists in workshops, seminars, and training programs that supplement education efforts throughout UCAR and at other institutions. Educational events continued to bring mathematicians and computer scientists to NCAR, and these led to collaborations, influenced graduate student research, and enriched our staff. Training in using HPC systems and CISL-developed data analysis and visualization tools developed more capable and effective researchers. And community outreach increased NCAR's connection with and maximized our impact on the university community, students, interns, and future employees. CISL's outreach efforts actively attracted qualified candidates – particularly those from diverse backgrounds – to our research enterprise and allowed us to enrich our workforce while increasing its diversity.

As you read about CISL's accomplishments, I hope you can appreciate the importance of the progress we are making and the pride we share in our work and the dedication of our staff.

‹ 2016 CISL Annual Report   up   Advance Earth System science through HPC and data services ›

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ADVANCE EARTH SYSTEM SCIENCE THROUGH HPC AND DATA SERVICES

Computing is a foundational element of scientific research, and CISL provides a portfolio of advanced computing and data services specifically tailored for the atmospheric, geospace, and related sciences communities. At its core, CISL is a laboratory dedicated to providing advanced cyberinfrastructure to advance world-class science.

CISL curates, manages, and archives a rich, growing set of digital collections to which it provides free and open access, and that attracts more than 12,000 individual researchers who annually download 1.5 petabytes of data through various pathways. Moreover, CISL creates essential, widely used software such as visualization and analysis tools; creates frameworks for implementing parallel modeling workflows; creates and operates science gateways; provides user support and training for all of these services; and integrates its resources and services with regional, national, and international cyberinfrastructure.

CISL services evolve in response to changes in the underlying computational technologies and the scientific demands of the community, informed by the research and development activities performed under CISL Strategic Goal 2.

CISL provides 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 FY2016 CISL continued to operate the petascale Yellowstone supercomputing environment at the NWSC, including the supercomputer, the 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.

CISL’s software CI capabilities continued to make important progress in FY2016, and overviews of these advances are provided in the sections below. Four years into Yellowstone’s production lifetime, CISL completed the NWSC-2 procurement effort that led to NCAR’s new supercomputing system named Cheyenne.

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

‹ CISL Director's Message up Acquire, deploy, and maintain CI resources ›

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ACQUIRE, DEPLOY, AND MAINTAIN CI RESOURCES

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 2,500 researchers from institutions throughout the U.S. and abroad.

The efficient design, operation, and maintenance of NCAR's HPC environment supports scientific productivity at research universities, NCAR, and other organizations, and CISL's ongoing leadership in providing discipline-focused computing services is a critical role for NCAR as a national center. Efficiently managing data is essential for progress on the grand challenges of numerically modeling the Earth System, and every user of CISL's HPC environment benefits from its data-centric configuration. Users can now arrange their workflows to use stored data directly without first needing to move or copy it. The design of the environment has proven to be efficient, reliable, and user friendly. Moreover, incremental refinements have improved operations and the user experience.

The supercomputing CI at the NWSC was being upgraded at the end of FY2016 with the addition of the 5.34-petaflops HPC system named Cheyenne, along with a 20-petabyte increment to the shared file system that has a 220 gigabyte-per-second bandwidth. These resources are scheduled to begin production in January 2017. They will augment the existing CI which includes Yellowstone, a 1.5-petaflops HPC system; GLADE, a 16.4-petabyte shared parallel file system; Caldera and Geyser, two separate data analysis and visualization (DAV) clusters featuring general purpose graphics processing units (GPGPUs); and HPSS, a disk- and tape-based archival system currently holding more than 66 petabytes of data. In addition to deploying the new CI resources, CISL is also is actively experimenting with its HPC Futures Lab, an infrastructure to support the testing of early-release HPC hardware and software.

CISL's goals and actions in this area directly support the broader goals of the NCAR Strategic Plan, CISL's Strategic Plan and the NSF's Cyberinfrastructure Framework for 21st Century Science and Engineering (CIF21 Vision). The NCAR Strategic Plan states that "High Performance Computing (HPC) is one of the foundational elements of NCAR's scientific research and publications." One of CISL's key strategic imperatives is advancing Earth System science by expanding the productivity of researchers through HPC and data services, so CISL provides and refines a portfolio of advanced computing and data services specifically tailored for the atmospheric, geospace, and related sciences communities. CISL services evolve in response to changes in the underlying computational technologies and the scientific demands of the community, informed by the research and development activities performed under CISL Strategic Goal 2.

Yellowstone and its associated complex of HPC systems and storage resources operated in full production status throughout FY2016. CISL will continue operating Yellowstone through calendar year 2017. The Cheyenne HPC system was installed and powered up at the NWSC by end-FY2016. Integration and testing efforts will be underway during Q1 FY2017 to ready the system for production by January 2017.

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

‹ Advance Earth System science through HPC and data services | up | Provide supercomputing resources ›

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PROVIDE SUPERCOMPUTING RESOURCES

The NWSC high-performance computing (HPC) environment includes petascale supercomputing resources, the Globally

Accessible Data Environment's (GLADE) centralized high-performance file systems, the NCAR HPSS data archive, and data analysis and visualization resources. CISL's Operations and Services Division operates these systems at the highest levels of availability and performance to enable the science, research, and discovery of the atmospheric and related sciences communities that are served by these resources. Initially placed into production in late 2012, the Yellowstone HPC system, along with its Geyser and Caldera data analysis and visualization systems, have been operated for nearly four years. During FY2016, these systems supported 528 million core-hours of computing for over 12.8 million jobs.

In the upcoming year, CISL's computational environment will be augmented with the new Cheyenne supercomputer that will provide more than three times the computational capacity of Yellowstone, plus additional data storage and archival resources. CISL will also begin the procurement process for an advanced data analysis and visualization platform to replace the Geyser and Caldera systems.

The 5.3 petaflops Cheyenne supercomputer, after installation at the NCAR-Wyoming Supercomputing Center (NWSC), is undergoing final check-out and testing and will begin user production in January 2017.

CISL's high-performance computing and storage environment efforts are focused on providing robust, reliable, and secure high-performance computing resources in a production research environment, and on supporting that environment for the thousands of users and hundreds of projects spanning NCAR, universities, and broader atmospheric science community. CISL continuously monitors system usage and performance, and it balances resource allocation through priority-based intelligent job scheduling, a well-tuned job queue structure, and single-job resource limits. CISL's commitment to a data-intensive computing strategy extends beyond the HPC/GLADE 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.

The efficient design, operation, and maintenance of NCAR's data-centric HPC environment supports scientific productivity at research universities, NCAR, and other organizations, and CISL's ongoing leadership in providing discipline-focused computing services is a critical role for NCAR as a national center. CISL also operates a supercomputer that provides real-time numerical weather predictions for the United States Antarctic Program, Antarctic science, and international Antarctic efforts.

The GLADE centralized file system supports the efficient management of data, which is critical for progress on the grand challenges of numerically modeling the Earth System, and every user of CISL's HPC environment benefits from its data-centric configuration. Users can now arrange their workflows to use stored data directly without first needing to move or copy it.

NWSC-2 procurement resources

On behalf of CISL, UCAR issued the NWSC-2 Request for Proposals in FY2015 for the acquisition of a new HPC resource to replace Yellowstone and for an augmentation of the GLADE environment. Awards were made in December 2015 for a new supercomputer, named Cheyenne, and for additional GLADE file systems. At end-FY2016, the 5.3 petaflops Cheyenne supercomputer was delivered, installed, and powered up at the NWSC and began final check-out and testing. Similarly, 20 petabytes of additional storage, with an aggregate bandwidth of 220 Gigabytes/second has been installed at the NWSC and is being integrated into the GLADE environment. These additional resources will become available for production use by January 2017.

Data-centric environment

CISL's Globally Accessible Data Environment (GLADE) provides centralized high-performance file systems and forms the hub of CISL's data-centric HPC environment. GLADE provides a shared, high-performance (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 (in time and energy) of moving data between systems and/or maintaining multiple copies of data. Temporary "scratch" spaces and longer-term "work" spaces are available to all users of the supercomputer systems, and long-term project space is allocated through the various allocation panels. GLADE also plays a growing role in hosting curated data collections from CISL's Research Data Archive (RDA), NCAR's Community Data Portal, the EOL Metadata Database and Cyberinfrastructure, and NCAR's Climate Simulation Data Gateway. During FY2016, CISL enhanced GLADE's network connectivity with 40 Gigabit-per-second Ethernet data-transport backbone. By the end of 2016, CISL will expand GLADE to a total data capacity in excess of 36 petabytes and provide over 220 Gigabyte-per-second aggregate bandwidth connectivity to the Cheyenne supercomputer.

High Performance Computing (HPC)

CISL continued operating the Yellowstone supercomputer, an IBM iDataPlex cluster with 4,536 nodes, 72,576 Intel Xeon E5-2670v2 (Sandy Bridge) processing cores, 145 terabytes of memory, and a peak processing power of 1.5 petaflops (1.5 quadrillion floating point operations per second). 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. When initially installed in 2012, Yellowstone was ranked as the 13th most powerful supercomputer in the world. In the HPC world, newer more powerful systems are continually displacing older systems on the TOP500 list, and by June 2014, Yellowstone was the 29th most powerful system on that list. It dropped to 49th place in June 2015, and by June 2016 it ranked as the 68th most powerful system.

The IBM iDataPlex supercomputer named Yellowstone has been the primary computational platform for nearly four years – providing a highly available, highly utilized HPC

The new Cheyenne supercomputer is an SGI ICE-XA cluster

with 4,032 nodes, 145,152 Intel Xeon E5-2697v4 (Broadwell) processing cores, 315 terabytes of memory, and a peak processing power of 5.34 petaflops. Similar to Yellowstone, Cheyenne's design and configuration will provide balanced I/O and exceptional computational capacity for the data-intensive needs of its user community. Cheyenne is expected to rank in the top 20 most powerful systems in the world when it is commissioned into production service in January 2017.

environment in support of NCAR and university science.

Data Analysis and Visualization

NWSC's HPC environment is completed by dedicated Data Analysis and Visualization (DAV) systems for analyzing computer-generated data, forecast model intercomparisons, and observational data analysis. NWSC's DAV resources are comprised of the Geyser, Caldera, and Pronghorn systems. Geyser and Caldera are specifically configured for tasks that utilize 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. 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; after decommissioning the Phi adapters it was repurposed to augment the Caldera system but without GPGPU accelerators. For more information, see the Data Analysis and Visualization section of this report.

Data Sharing Services

The NCAR Data Sharing Service continued to provide researchers a way to share large data sets with collaborators around the world using a simple web-based interface. Based on 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 access to GLADE file systems, data transport 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.

Antarctic Mesoscale Prediction System Support (AMPS)

CISL continued to operate the 84-node supercomputing cluster named Erebus, which is used exclusively by and in support of AMPS, an experimental, real-time numerical weather prediction system that produces twice-daily weather predictions for the Antarctic continent. Erebus delivered 8.6 million core-hours during FY2016, providing forecasts in support of the U.S. Antarctic Program flight operations and polar observatory, and to support research and education activities involving Antarctic meteorology.

CISL included an option in the NWSC-2 procurement for a new stand-alone system to replace Erebus, but upon evaluating the proposals, found it would be more economical to utilize the AMPS incremental funding to augment Cheyenne and dedicate the additional nodes to the AMPS efforts. During FY2017, CISL will assist AMPS in porting the forecast system to Cheyenne; once that is done, and after an operational series of forecasts are carried out in parallel with those on Erebus to certify Cheyenne's results, the Erebus system will be decommissioned and repurposed as part of CISL's High Performance Futures Laboratory.

Data archival services

The High Performance Storage System (HPSS) is an advanced, highly scalable and flexible mass storage system and archival resource that supports both NCAR's supercomputing environment as well as divisional servers run by other NCAR laboratories and UCAR programs. New HPSS hardware was installed at the NWSC to support the new supercomputing environment there, and the HPSS tape libraries in Boulder are now used to store critical data specified in the CISL Business Continuity plan. This disaster recovery service currently supports the RDA, NCAR's EOL, and UCAR's COSMIC program. HPSS data holdings at the NWSC stand at around 66 PB and 241 million files, with growth since Yellowstone began production averaging around 1.25 PB per month. After recent acquisition of two additional tape libraries at NWSC, the HPSS system has doubled its maximum data capacity from 160 to 320 petabytes. A major HPSS upgrade is underway and is scheduled to be completed in the second quarter of FY2017. For more information, see the Data archive section of this report.

HPC Futures Laboratory

CISL continued operating and enhancing its HPC Futures Lab that focuses on HPC research, which is relevant for improving the NCAR's HPC environment and helping CISL assess new technologies that may be available in future production 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. For more information, see the High Performance Futures Lab section of this report.

System specifications

The following table provides the technical details for the supercomputing systems maintained and installed by CISL during FY2016.

	Cheyenne	Yellowstone	Caldera	Geyser	Pronghorn	Erebus (AMPS)
System Type	SGI ICE-XA	IBM iDataPlex	IBM iDataPlex	IBM 19"rack	IBM iDataPlex	IBM iDataPlex
Primary Usage	Production high-performance computing	Production high-performance computing	Data analysis, visualization & GPGPU computing	Data analysis & visualization	Production computing	Antarctic Mesoscale Prediction System
Begin production	Jan 2017	Dec 2012	Dec 2012	Dec 2012	Dec 2012	Oct 2012
Target decommissioning date	-	end Dec 2017	-	-	-	mid 2017
Peak FLOP rate (TF)	5,342	1,510	21.8	14.4	37.7	28
Total number of nodes	4,032	4,536	16	16	16	84
Total memory (TB)	315	145	1.0	16	1.0	2.7
Primary node type	SGI IP-125	IBM dx360 M4	IBM dx360 M4	IBM x3850 X5	IBM dx360 M4	IBM dx360 M4
CPU type	Intel Xeon E5-2697v4	Intel Xeon E5-2670v2	Intel Xeon E5-2670v2	Intel Xeon E7-4870	Intel Xeon E5-2670v2	Intel Xeon E5-2670v2
CPU microarchitecture	Broadwell EP	Sandy Bridge EP	Sandy Bridge EP	Westmere EX	Sandy Bridge EP	Sandy Bridge EP
CPU frequency (GHz)	2.3	2.6	2.6	2.4	2.6	2.6
CPUs per node	2	2	2	4	2	2
Cores per node	36	16	16	40	16	16
Node memory capacity (GB)	3,168 @ 64 864 @ 128	32	64	1024	64	32
Node memory type	DDR4-2400	DDR3-1600	DDR3-1600	DDR3-1066	DDR3-1600	DDR3-1600
Interconnect network	Mellanox InfiniBand 4x EDR	Mellanox InfiniBand 4x FDR	Mellanox InfiniBand 4x FDR	Mellanox InfiniBand 4x FDR	Mellanox InfiniBand 4x FDR	Mellanox InfiniBand 4x FDR-10
Interconnect topology	9D enhanced hypercube	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
Interconnect ports per node	1	1	1	2	1	1
System bisection bandwidth (GB/sec)	>30,000	31,700	109	104	109	410
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	28	63	0.5	2	0.5	1

NWSC high-performance computing resources and their key attributes.

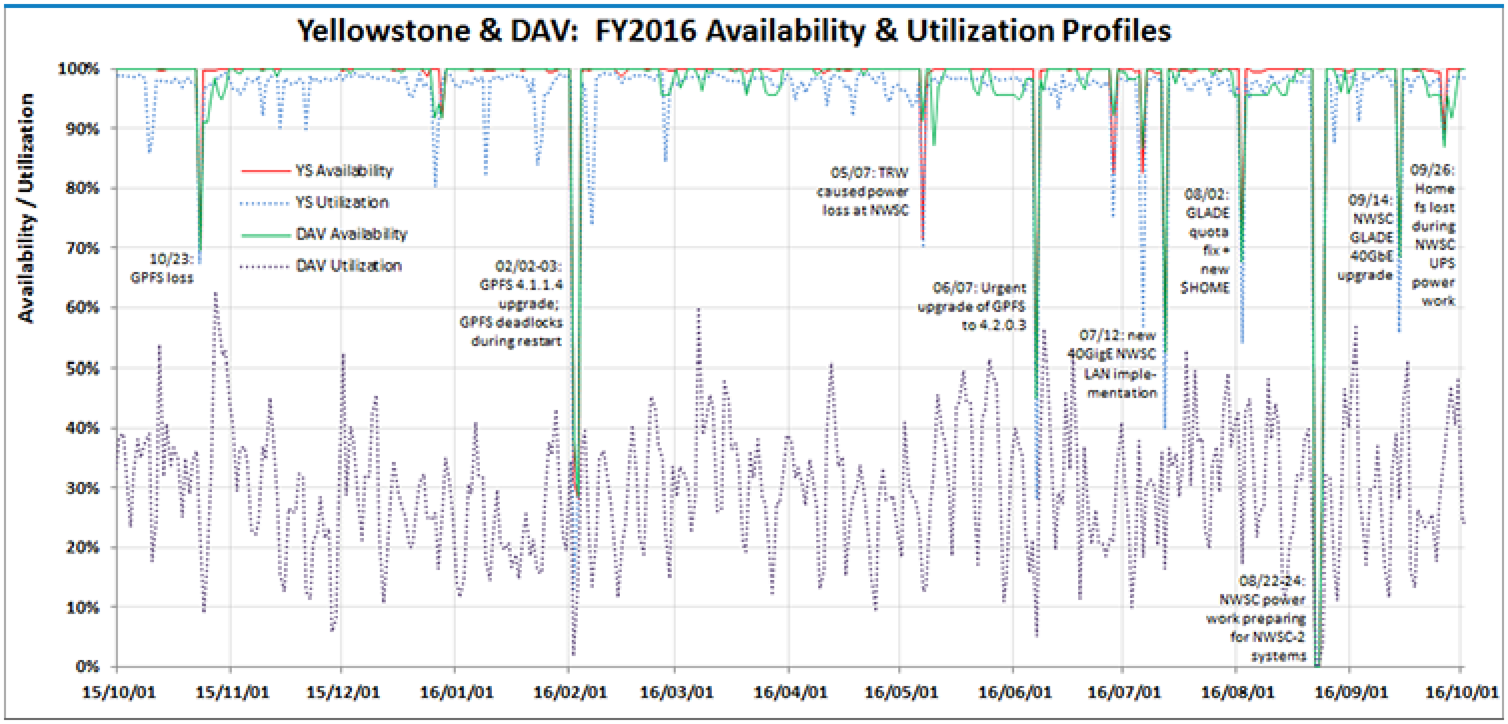
System reliability and usage

During FY2016, Yellowstone was highly available and utilized, with an average scheduled availability of 99.7% and user utilization of 95.2%, while the Caldera and Geyser Data Analysis and Visualization systems averaged 98.9% scheduled availability and 29.8% user utilization. The AMPS system, Erebus, was down only for scheduled NWSC work during infrastructure preparation for the new Cheyenne supercomputer, and it averaged 76.0% utilization. Similarly, the GLADE system was highly available. The following table provides key reliability and usage metrics for the NWSC resources during FY2016.

FY2016 Availability and Utilization Metrics	GLADE	Yellowstone	DAV	Erebus (AMPS)
Total user availability	99.11%	98.02%	97.31%	99.41%
Downtime: scheduled maintenance & environmental	0.85%	1.66%	1.56%	0.58%
Scheduled availability	99.96%	99.68%	98.87%	99.99%
Average user utilization	-	95.28%	29.80%	75.97%
Total CPU-hours	-	516,669,656	2,815,220	8,608,449
Total number of jobs run	-	4,780,290	4,201,171	3,831,780
Average job size (#CPUs)	-	1,569	9	224
Average CPU-hours per job	-	108.1	0.67	2.2

Average system availability and utilization during FY2016, along with some key usage and job metrics.

Stability and utilization of Yellowstone and the DAV resources reached new peaks this year. The figure below shows the availability and utilization profiles for FY2016, with annotation of those days where availability was less than 90%. Several of the incidents causing downtime during FY2016 were scheduled in advance, either for software upgrades, networking upgrades, or facility upgrades in preparation for the new NWSC-2 systems: Cheyenne and the GLADE-2 storage resources.



FY2016 availability and utilization profiles for the HPC (Yellowstone) and DAV (Caldera and Geyser) resources. Significant downtimes (daily availability of less than 90%) are annotated, and several were due to power outages and scheduled maintenance activities.

Funding

The NWSC environment, including HPC, GLADE, and DAV resources, was made possible through NSF Core funds, with supplemental support from the University of Wyoming. AMPS computing was supported by NSF Special funding.

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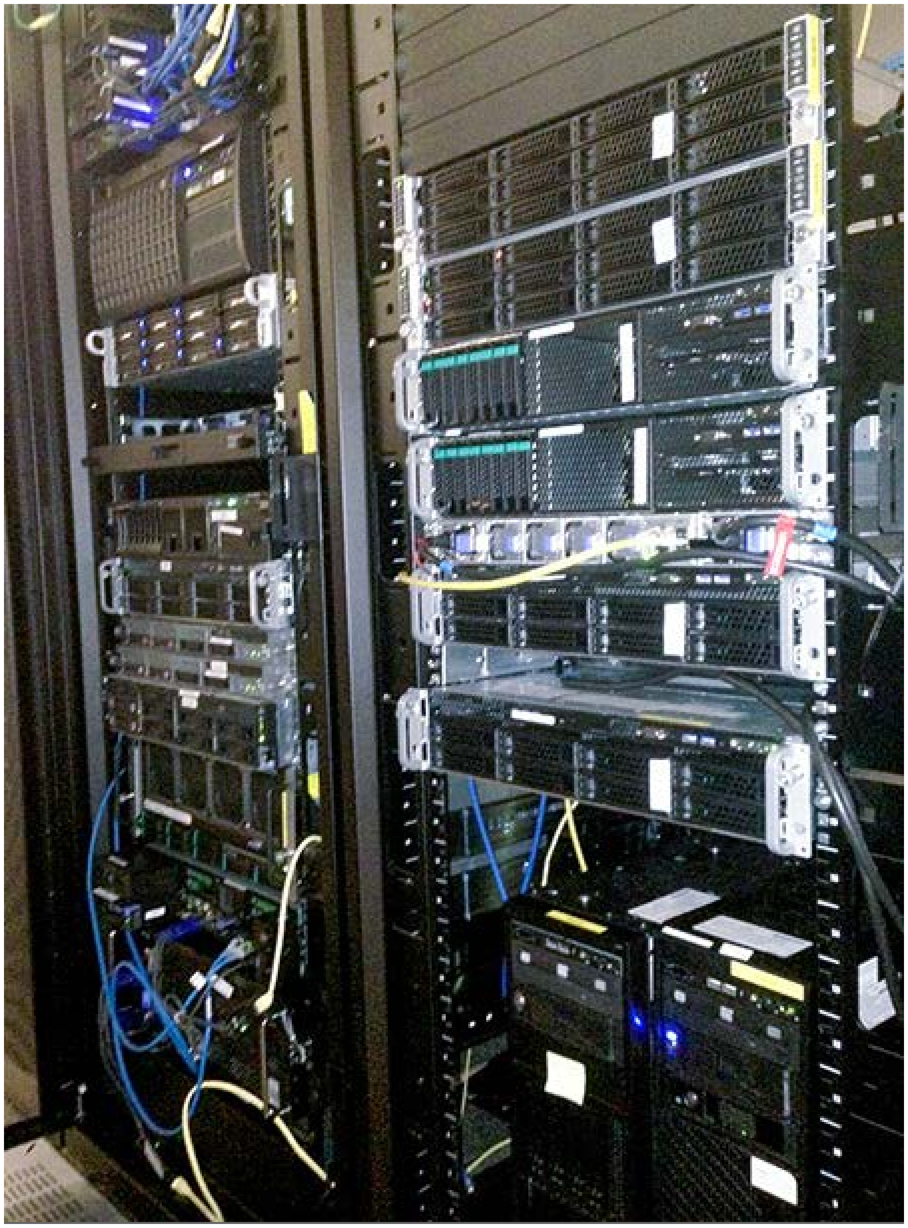
PROVIDE THE HPFL TEST AND EXPLORATION LABORATORY

Since 2014, CISL has operated its High Performance Futures



Two racks of hardware in the High Performance Futures Laboratory. The HPFL provides hardware and software infrastructure for testing and evaluating emerging technologies.

Laboratory (HPFL) which is comprised of small, experimental systems located both at the Mesa Lab facility and at the NWSC. The HPFL is a flexible, multi-system testbed where NCAR staff and collaborators can evaluate new hardware and software that represent experimental or emerging technologies and/or that may be part of future production systems. Initially focused on computational technologies, the HPFL was expanded during FY2016 to include storage, I/O, and data archive test resources.

The High Performance Futures Lab is intended to provide strategic opportunities for NCAR staff and collaborators to gain valuable experience with emerging hardware and software technologies, and CISL also uses it to study and mitigate risks arising from new technologies. New HPC and storage technologies such as high-performance stacked and non-volatile memory, and hybrid solid-state and non-volatile disk technologies are rapidly transforming the HPC and storage landscape. Such technologies are poised to transform system architectures by introducing additional layers of memory, a hierarchy of I/O devices, as well as tighter integration of those technologies with computing elements. CISL is using the HPFL and vendor partnerships, such as the SGI-NCAR Joint Center of Excellence and the Intel Parallel Computing Center, to learn how to apply these technologies effectively to atmospheric and geoscience applications and to meet the data requirements of future systems and applications.

The HPFL provides a ready-to-use environment where cutting-edge technology can be deployed and tested by system administrators, consulting staff, and computational scientists. 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- and I/O-intensive applications.

HPFL status

CISL continued operating and enhancing the HPFL during FY2016. By year end, the HPFL contained test platforms that included Intel’s new Xeon E5 v4 (Broadwell) and Phi (Knights Landing) processors, Mellanox EDR InfiniBand and Intel OmniPath high-speed interconnect technologies, 40-gigabit Ethernet, and SGI’s UV300 large-shared-memory system. Additionally, CISL added an I/O innovation component to the Lab that is focused on storage futures, I/O optimization, and better data-hosting services. This I/O component included SSD technology, Data Direct Networks (DDN) storage systems, and a test environment for new HPSS releases with HPSS on Linux and rolling upgrades to the NCAR HPSS archive.

HPFL software evaluation activities in FY2016 included testing of operating systems and their management (Salt, CentOS),

resource managers (SLURM, PBS Professional), MPI implementations (Intel MPI, OpenMPI, MPICH-3, and MVAPICH), containers (Docker), the Spectrum Scale (formerly GPFS) and Lustre parallel file systems, DDN's Infinite Memory Engine (IME), and an HPSS test environment. The HPFL also served as an initial NWSC-2 software test environment prior to the delivery of the NWSC-2 test system named Laramie.

HPFL and NWSC-2a/NWSC-2b procurements

New non-volatile memory and many-core technologies, some examples of which were tested in the HPFL during FY2016, are key components of the NWSC-2a and NWSC-2b procurements planned for the upcoming year. While NWSC-2a will be focused primarily on acquiring a production-quality data analysis and visualization platform to replace the existing Geyser and Caldera systems, it will also include GPUs, large shared-memory nodes for in-memory computation, and non-volatile memory, SSD, and/or burst-buffer hardware and software for accelerating the I/O operations critical to analyzing large datasets. The NWSC-2b procurement will look more toward an experimental computational-accelerator-based system utilizing many-core technologies. NWSC-2b will help NCAR evaluate the efficacy of alternate processor technologies for use by geoscience codes and to advance our understanding of how such technologies perform and can be managed in a semi-production computational environment.

Funding

CISL's HPFL is made possible by NSF Core funds and through partnerships with and equipment donations from leading HPC and storage vendors.

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PROVIDE CENTRALIZED HIGH-SPEED DATA STORAGE

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.

This photo shows the new GLADE-2 system that provides NCAR systems with an additional 20 petabytes of high performance centralized data storage. NCAR's two GLADE file systems now offer a total of 36.4 petabytes of storage for the Yellowstone and Cheyenne supercomputing environments.

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.

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 CMIP5 and the upcoming CMIP6. GLADE also advances CISL's computing imperative for facilities by demonstrating high-performance data services that are critical for the supercomputing resources that now operate at NWSC and will continue to be critical as next-generation resources begin production in early CY2017.

The GLADE environment has undergone several upgrades this year in preparation for the installation of NWSC-2 resources. All of the supporting infrastructure was upgraded for installing an additional 20 PB of storage in late 2016. All GLADE systems were upgraded to the current RedHat OS, and the GPFS file system was upgraded to 4.2.0 across all HPC resources. A new 40 Gb Ethernet I/O network was installed, and the GLADE-1 system was upgraded to 40 GbE. The new network infrastructure will allow GLADE-1 and GLADE-2 to be fully integrated and accessible to both Yellowstone and the new HPC resource, Cheyenne. Utilization of GLADE remains high with file systems reaching capacity several times 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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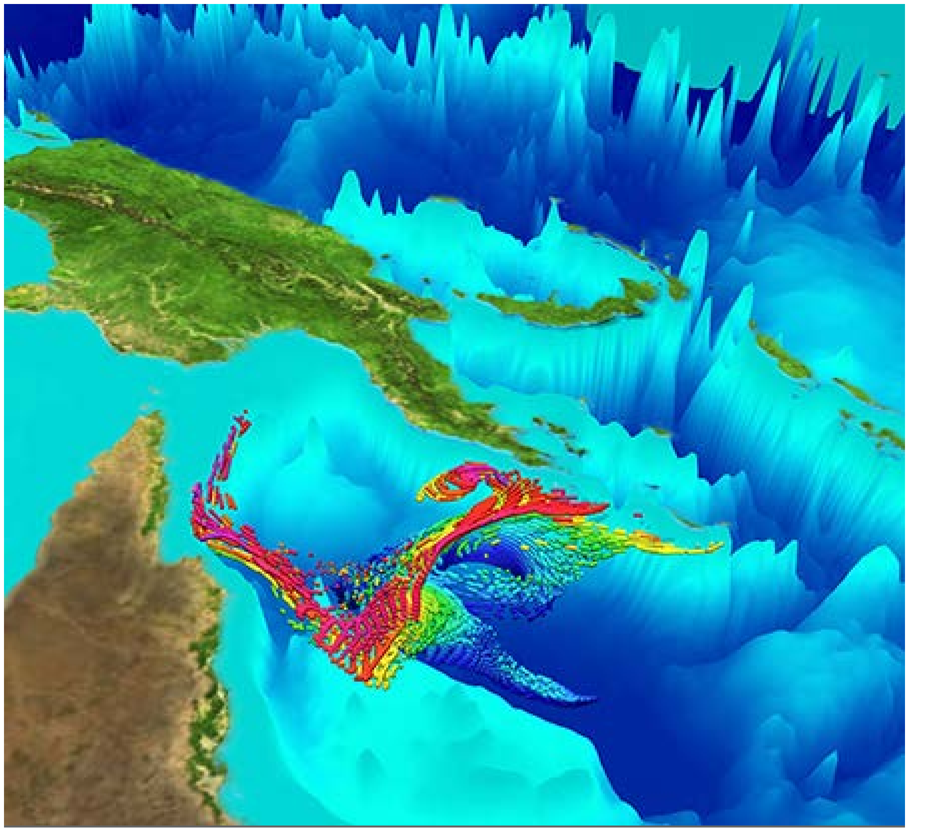
PROVIDE DATA ANALYSIS AND VISUALIZATION RESOURCES

NCAR's 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 figure is taken from an animation of the ocean flow dynamics that occur near the Great Barrier Reef near the northeast coast of Australia. It was produced using data from a model called CT-ROMS (Coral Triangle Regional Ocean Modelling System). CT-ROMS simulated 10 years of ocean activity in the Indonesian Throughflow, a region having the most complex ocean flow patterns in the world. The flow data are being used to better understand coral reefs through a metric called Potential Connectivity, which demonstrates how well coral reefs can re-seed their neighbors with larvae while they are being carried by these complex flow patterns. Understanding how reefs can regenerate each other has never been more imperative than it is right now because the most extensive coral bleaching event in recorded history is being observed at the Great Barrier Reef.

CISL provides a portfolio of advanced computing and data services specifically tailored for the atmospheric, geoscience, and related sciences communities. While computing is a foundational element of scientific research, the facilities to process, analyze, and visualize computationally generated and observational data are equally important in scientific discovery and facilitating the understanding of natural processes. CISL's DAV environment provides both hardware and software resources for developing and enhancing data analysis and visualization capabilities. Additionally, the DAV resources and CISL's software development efforts help scientists analyze and understand features in large and heterogeneous data sets by developing new methods and tools such as VAPOR to extract and visualize information from such data sets.

DAV hardware resources, metrics, and status

NCAR's DAV environment consists of two multi-node systems that began production service in late 2012. Each system is designed to complement the other in meeting the diverse needs of climate and weather DAV applications. The system named Geyser is targeted primarily at traditional interactive data set manipulation, data reduction, analysis, and visualization applications, and for large, data-intensive applications requiring graphical processing units (GPUs) and/or large shared memory. The system named Caldera is targeted for use by parallel graphics/visualization applications and computationally bound applications that can be accelerated via high-performance general-purpose graphics processing units (GPGPUs). Both DAV systems share a dedicated, high-bandwidth I/O network path to NCAR's 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) holdings.

Caldera is a 16-node cluster comprised of IBM dx360 M4 nodes that are identical to Yellowstone's compute nodes, except they are augmented with two computational accelerators, or general-purpose graphics processing units (GPGPUs). Each Caldera node contains two 8-core Intel Xeon E5-2670v2 (Sandy Bridge) processors, 64 GB of memory, and two NVIDIA Tesla K20X accelerators. Each K20X accelerator is capable of 1.31 teraflops of double-precision calculations or 3.95 teraflops of single-precision calculations. Caldera's peak double-precision floating point rate is therefore more than 47 teraflops. One hundred forty Yellowstone nodes are required to produce the same peak computation rate. After decommissioning the Intel Phi accelerators in the test system named Pronghorn, CISL repurposed twelve of its dx360 M4 nodes to augment Caldera's job scheduler queues for use by DAV jobs which do not require GPGPUs.

Geyser is a 16-node cluster comprised of IBM x3850 X5 nodes that are each equipped with a terabyte of memory, four 10-core Intel Xeon E7-4870 (Westmere) processors, 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 teraflops.

Unlike Yellowstone, which saw an average user utilization of over 95% during FY2016 and supports long-running batch jobs, the DAV platforms are designed for interactive applications and rapid job turnaround. Therefore, their average utilization is typically low, with bursts of high utilization. During FY2016, Caldera's average user utilization was 18.2%, while Geyser's average user utilization was 34.4%. While these figures are relatively low, they represent an increase in usage of 27% (Caldera) and 41% (Geyser) over the average user utilization measured in previous years, and the frequency of periods of high utilization increased dramatically during FY2016. CISL continues to monitor DAV workload and usage, and the observations are helping to guide requirements for future DAV systems.

CISL's monitoring of the Caldera system has shown that very few applications use the K20X GPGPUs. Since these computational accelerators are approximately an order of magnitude costlier than more traditional graphics processing units that are tailored to visualization and image rendering, CISL is re-evaluating the need for equipping systems with such high-end GPGPUs.

Additional details of the Geyser, Caldera, and Pronghorn systems are contained in the tables in the Production supercomputing section of this report.

DAV software

CISL continued enhancement work on its Visualization and Analysis Platform for Ocean, atmosphere and solar Researchers, which is an interactive 3D visualization environment for producing animations and still frame images. VAPOR is supported on and freely available for Linux and Windows systems. A major feature release of VAPOR (2.5) occurred during FY2016, and more new features will be made publicly available in the 2.6 release of VAPOR planned for November 2016. VAPOR developments in FY2016 provided high-resolution cartographic maps, 3D stereo rendering, parallel data conversion capabilities, new schemes for contouring, contour labeling, and coloring, data importers for the MPAS and ICON models, and a host of other changes and bug fixes. Additional developments included support for coupled model analysis, a more generalized wavelet-based progressive-access data format, enhanced plotting capabilities, animation encoding, and the release of an evaluation version of VAPOR3.

NWSC-2a procurement

Because the existing DAV systems are four years old, CISL will conduct the NWSC-2a procurement during FY2017 to acquire a production-quality data analysis and visualization platform that will replace the existing Geyser and Caldera systems. NWSC-2a will focus primarily on anticipated DAV workload requirements of the NCAR user community in the 2018-2022 timeframe (a companion NWSC-2b procurement will focus on the acquisition of a computationally accelerated platform). We anticipate that the NWSC-2a system will include GPUs, large shared-memory nodes for in-memory computation, and non-volatile memory, SSD, and/or burst-buffer hardware and software for accelerating the I/O operations critical to the analysis of large data sets. As of end-FY2016, CISL expects the new NWSC-2a system to be placed into production in early 2018.

Funding

NCAR's DAV environment and services are supported by NSF Core funds including CSL funding. VAPOR is funded by the National Science Foundation (Grants 03-25934 and 09-06379, ACI-14-40412) and by the Korea Institute of Science and Technology Information (KISTI).

‹ Provide centralized high-speed data storage up Provide a capacious and reliable data archive ›

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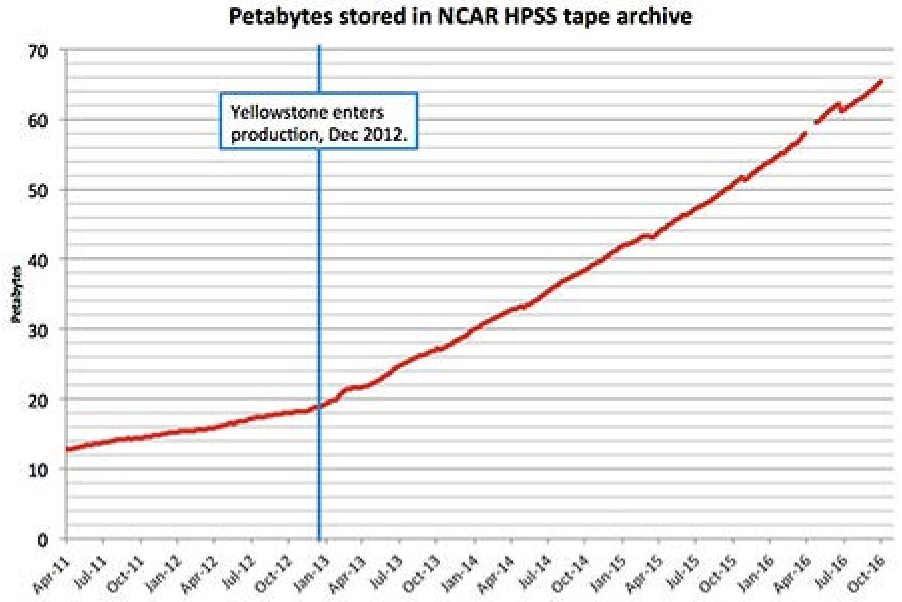
PROVIDE A CAPACIOUS AND RELIABLE DATA ARCHIVE

The High Performance Storage System (HPSS) is an

advanced, highly scalable and flexible mass storage and archival resource that supports both NCAR's supercomputing environment as well as divisional servers run by other NCAR laboratories and UCAR programs. CISL also uses the HPSS to support disaster recovery for irreplaceable data by maintaining HPSS infrastructure at the NCAR Wyoming Supercomputing Center (NWSC) in Cheyenne, Wyoming and at the NCAR Mesa Lab in Boulder, Colorado. The tape libraries in Boulder are used to store critical data specified in the CISL Business Continuity plan. This disaster recovery service currently supports the RDA, NCAR's EOL, and UCAR's COSMIC program.



This chart shows the growth since early 2011 of the HPSS archive located at the NCAR-Wyoming Supercomputing Center. The vertical blue line marks the date that the 1,504-teraflops computer Yellowstone entered production alongside the 77-teraflops computer Bluefire.

Tailored to the needs of the Earth System science community, this capacious and reliable data archive is a strategic component in the cyberinfrastructure that CISL provides and maintains to expand the productivity of the research community. CISL's ongoing leadership in providing discipline-focused computing and data services is a critical role for NCAR as a national center.

The HPSS system is maintaining a steady growth rate: Data holdings in FY2016 grew by nearly 15 PB of new data and an additional 25 million files. Holdings as of October 2016 stand at around 66 PB and 241 million files, with growth since Yellowstone began production averaging around 1.25 PB per month. After recent acquisition of two additional tape libraries at NWSC, the HPSS system has doubled its maximum data capacity from 160 to 320 PB. Further augmentation of the archival system has included purchases of a newer, faster metadata server and additional data movers to support the increase in load from the new Cheyenne system and the overlap period with Yellowstone. In addition to these improvements a major HPSS upgrade is underway, scheduled to be completed in the second quarter of FY2017.

To meet the increased data load from the new Cheyenne system, analysis and projection exercises were conducted to size an augmentation of the current HPSS equipment. Based on this analysis and consideration of projected technology advances, CISL is planning to extend the current archival system subcontract, procuring next-generation tapes and drives that will significantly increase total HPSS capacity and throughput via both augmentation of existing resources as well as re-use of existing tapes at higher capacities and bandwidth, thus preserving existing capital investment and substantially reducing overall cost.

The NCAR HPSS is managed by CISL under the UCAR/NSF Cooperative Agreement and is supported by NSF Core funds and CSL funding.

‹ Provide data analysis and visualization resources up Provide support services to all users of CISL resources ›

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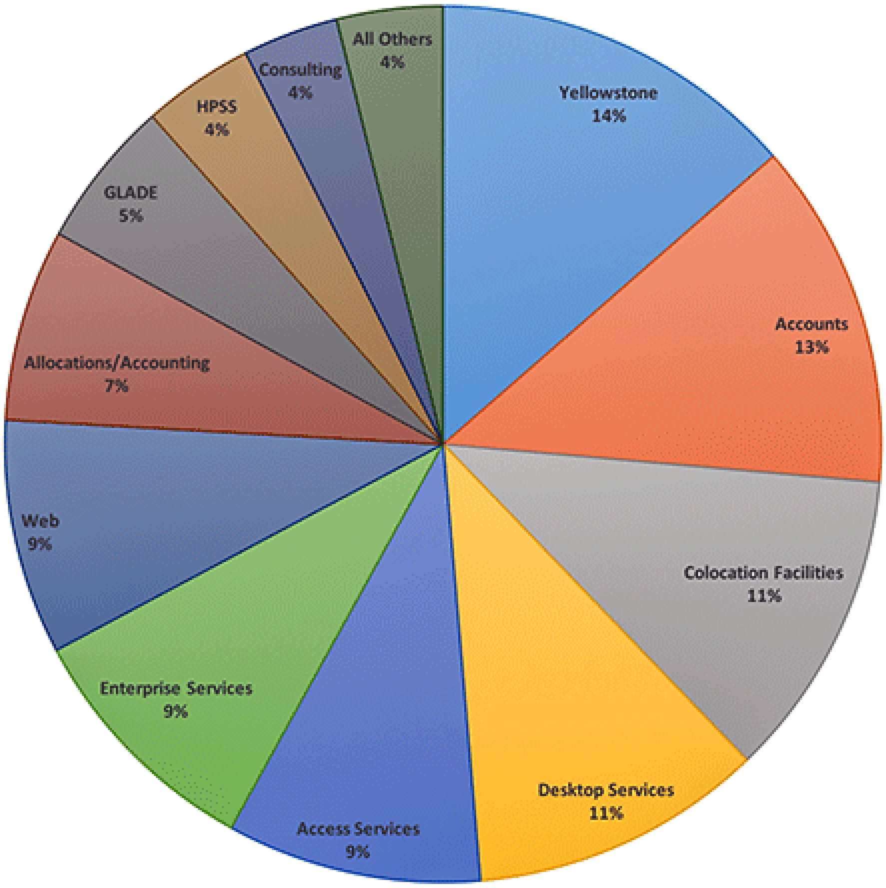
PROVIDE SUPPORT SERVICES TO ALL USERS OF CISL RESOURCES

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.



The CISL Help Desk received 10,250 ExtraView tickets in FY2016 and directed more than half to the appropriate service groups in CISL. The CISL User Services teams closed 4,700 support requests after interacting with service groups as needed.

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 FY2016.

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 FY2016, CISL user services began offering access to the CMIP Analysis Platform – a new service that will allow university researchers to tackle a broader range of climate analyses, began the groundwork associated with the deployment of the next-generation Cheyenne environment, 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.

CISL's strategic commitment to support services includes 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.

CISL tracks user support activity for this growing community using an ExtraView trouble ticket system. In FY2016, the ticket system recorded 10,843 tickets to the CISL Help Desk, a 5% decrease from the FY2015 total. The average number of log entries per ticket was 4.50, and communication with users was highest on complex cases. Of the total tickets submitted, the Help Desk team closed 2,754 tickets in an average of 3.61 days (median, 0.73 days), or 230 per month on average. In the same period, Consulting Services staff resolved 1,617 more-complex requests with an average response time of 24.3 days (median, 7.7 days). An additional 329 user support tickets that were fielded related primarily to managing allocations and accounting, with an average response time of 6.29 days (median, 0.87 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.

‹ Provide a capacious and reliable data archive | up | Provide a computing environment tailored to user needs ›

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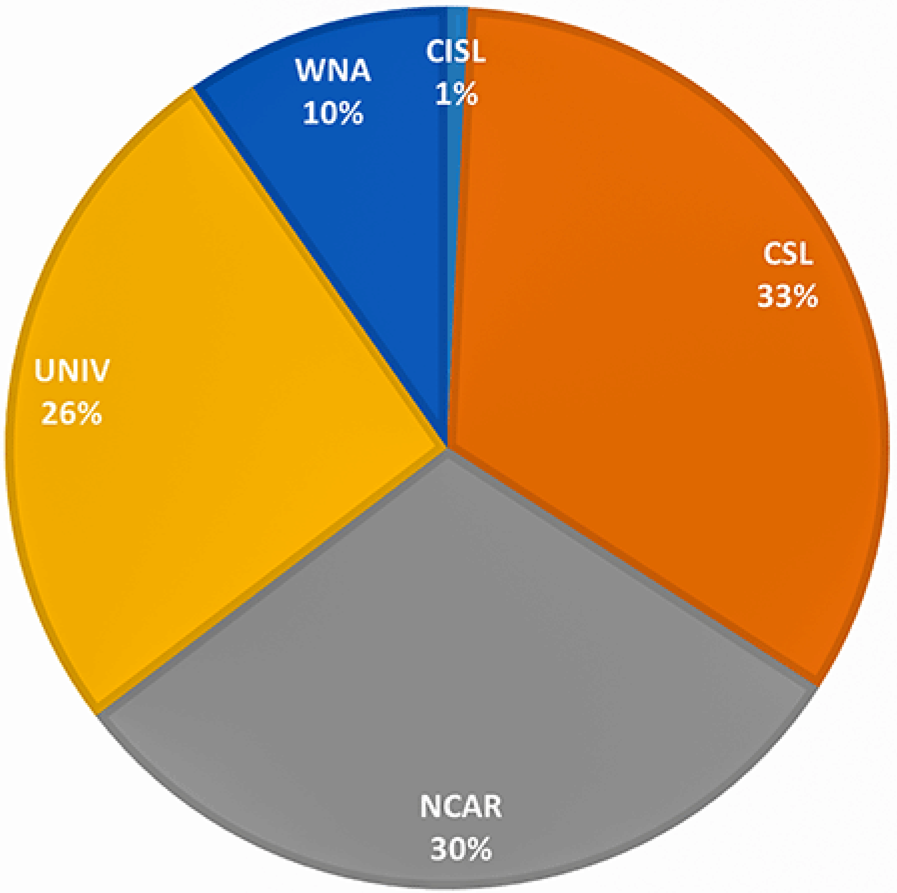
PROVIDE A COMPUTING ENVIRONMENT TAILORED TO USER NEEDS

CISL'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 CISL's resources, capabilities, and services in response to those needs. In FY2016, these user communities included more than 1,700 users at more than 260 universities and other institutions who



The FY2016 usage of Yellowstone by CISL's major user communities showed continued strong use by both the University and the Wyoming communities, bringing the actual usage very close to the targets for each group.

benefited from using CISL's high-performance cyberinfrastructure (CI) and services. More than 600 new users joined the CISL computing community in FY2016.

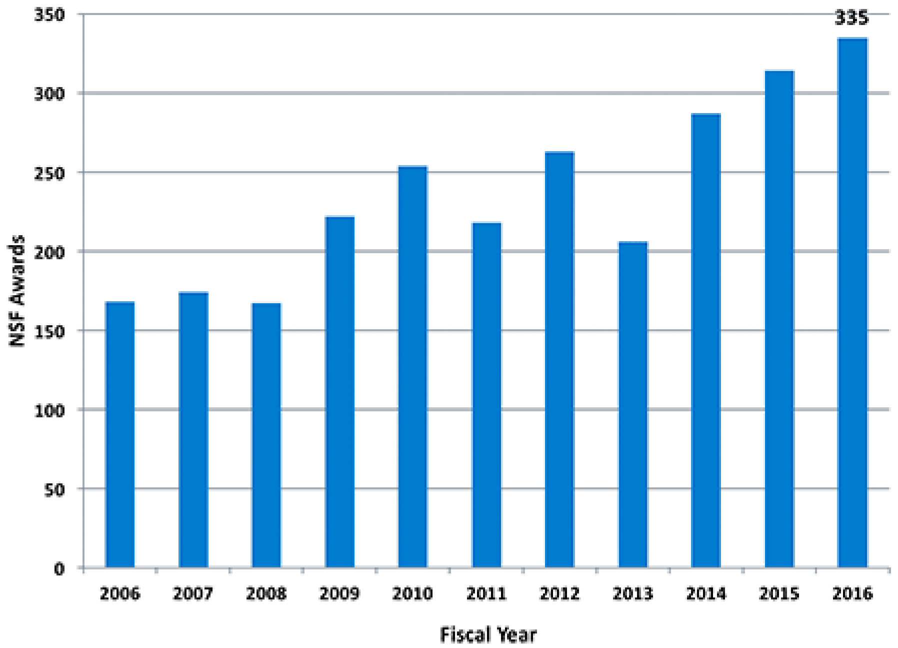
A discipline-specific approach to supercomputing allows CISL to tailor system design and services for our user communities while satisfying the highly specialized technical requirements of scientific applications such as climate system models. In FY2016, CISL announced and deployed the CMIP Analysis Platform as an allocated and supported service for users interested in climate model intercomparisons. This new platform allows users to conduct large-scale analyses on a "lending library" of published CMIP5 data. More than 30 allocation requests have been received since January 2016.

With respect to supercomputing services, more than 70% of CISL's HPC system use is related to running NCAR-developed climate and weather applications, and this well-defined workload allows CISL and NCAR scientists to optimize the most heavily used models and applications on current and future systems. It also ensures that model development and research in Earth System processes can occur in a controlled yet responsive environment where researchers can prepare complex models and perform the computationally demanding tests required to validate them.

The size, breadth, and disciplinary pursuits of the CISL user communities offer perspectives on the scientific impact enabled by CISL's HPC, data analysis, and archival resources. These user communities reported nearly 500 publications and 70 dissertations and theses resulting from CISL HPC support in FY2015 (the timeframe of our most recent survey). Scientifically, our user communities span 17 areas of interest in the atmospheric and related sciences.

CISL 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 FY2016, CISL continued to manage several allocation processes to distribute resources and ensure access by the most meritorious projects.

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 2015 and April 2016 combined, the CHAP reviewed 98 requests for 345 million core-hours on the Yellowstone



CISL allocations to university researchers have supported the scientific objectives of more than 150 different NSF awards each year for the past decade. In FY2016, active projects supported more than 330 unique NSF awards.

system. In addition, university researchers submitted 230 small allocation requests, and this indicates a growing demand for resources well beyond Yellowstone's current capacity.

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 FY2016, active projects supported more than 330 unique NSF awards, and 840 university projects were open during the year on CISL resources (an 8% increase over FY2015).

A comparable portion (29%) of Yellowstone is also allocated to NCAR researchers to support the computational needs of the NCAR laboratories, including NCAR Strategic Capability (NSC) projects. Requests for these large-scale projects were reviewed in October 2015 and April 2016 by a panel of NCAR computational scientists and approved by the NCAR Executive Committee.

About 28% of Yellowstone is available to the CSL at NCAR; in FY2016, 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 January and June 2016. In FY2016, the WNA awarded 42.7 million core-hours to 13 large projects, and supported 17 small allocations; 27 different WNA projects used nearly 54 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.

‹ Provide support services to all users of CISL resources   up   Support strategic use of CISL resources ›

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SUPPORT STRATEGIC USE OF CISL RESOURCES

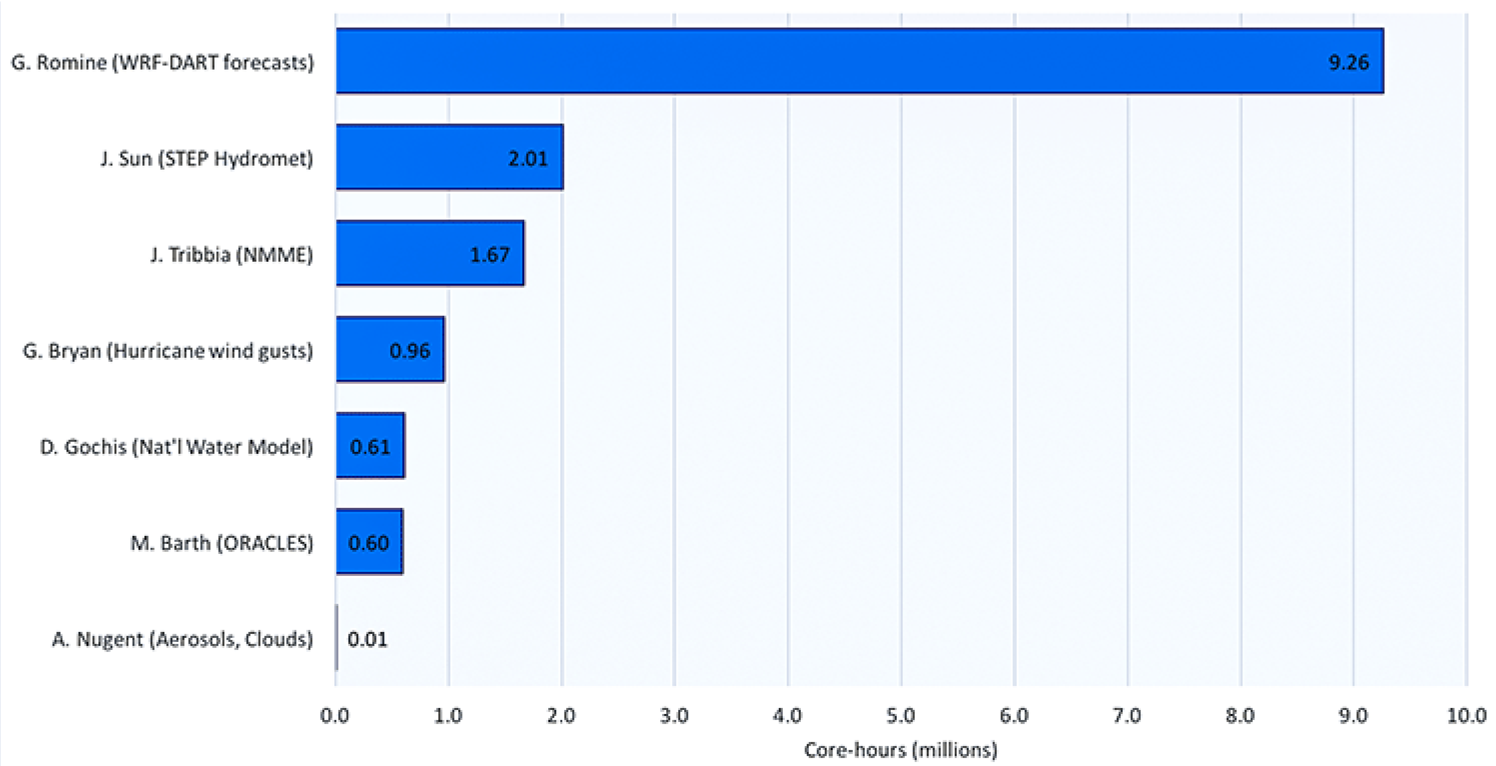
The CISL production supercomputing environment supports special computational campaigns for ongoing and short-term computational projects, all via a priority-based and near-real-time job scheduling mechanism. These campaigns are managed to minimize the impact on the production computing delivered to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

This table lists the special computational campaigns supported by CISL during FY2016.

FY2016 Special Campaign	Project Lead	Begin	End

Aerosols in Shallow Tropical Convection: Impact on Cloud Microphysics and Precipitation	A. Nugent	5-May-15	30-Nov-16
ORACLES Campaign	M. Barth	4-Aug-16	31-Oct-16
Research and Development of the National Water Model Using the Community WRF-Hydro Modeling System	D. Gochis	5-May-16	31-Dec-16
Advanced study of wind gusts in hurricanes using large-eddy simulation	G. Bryan	25-Feb-16	30-Sep-16
North American Multi-Model Ensemble (NMME) Phase II seasonal system	J. Tribbia	15-May-15	30-Sep-17
2016 STEP Hydromet Project Year 3	J. Sun	9-May-16	30-Sep-16
Real-time high-resolution ensemble analyses and forecasts of high-impact weather with NCAR's DART facility and WRF model	G. Romine	1-May-15	30-Apr-17

Among these projects, the STEP Hydromet real-time experiment, a collaborative effort among the MMM, RAL, and EOL labs at NCAR, was conducted during the summer months in the Front Range hydromet testbed. The experiment started in the summer of 2014, repeated in 2015, and was conducted again in summer 2016 with an expanded scope. The main objective of the 2016 experiment was to demonstrate and test the end-to-end integrated hydrometeorological system developed by the STEP scientists. The end-to-end system involves analysis of high-resolution observations, data assimilation using WRFDA, new model-based nowcasting system VDRAS, qualitative precipitation forecasting (QPF) with WRF, and the coupled hydrological model WRF-Hydro.



Yellowstone core hours dedicated to special computational campaigns during FY2016. CISL works to accelerate scientific discovery through numerical simulation by providing a portion of its HPC systems to special campaigns.

With the upcoming arrival of the Cheyenne cluster in 2017, NCAR is once again preparing to support its Accelerated Scientific Discovery (ASD) initiative, which provides large-scale computational resources to a small number of projects for a short period following acceptance of a new HPC system. In support of NCAR's supercomputing strategy, the ASD program offers researchers a unique opportunity to quickly complete large-scale experiments that can lead to scientific breakthroughs of value to the entire community. These large projects also test the capability of the new system and help system administrators ensure that the supercomputer runs reliably at scale and under high utilization. ASD project allocations are balanced between university researchers and NCAR scientists, and proposed ASD projects were reviewed and recommended at the end of FY2016.

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.

‹ Provide a computing environment tailored to user needs   up   Optimize model performance for current and future supercomputers ›

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OPTIMIZE MODEL PERFORMANCE FOR CURRENT AND FUTURE SUPERCOMPUTERS

In FY2016 CISL continued to augment its efforts to optimize NCAR codes, and it focused 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 Explore many-core and accelerator-based architectures.

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 that requires careful parallel programming to properly utilize, and the introduction of heterogeneous architectures composed of both conventional processors and accelerator coprocessors.

Strategic Parallel and Optimization Computing (SPOC) initiative

In FY2016, CISL's SPOC initiative continued 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:

- In FY2016, a CSG-CGD collaboration optimized CSLAM, a new transport scheme being implemented within the spectral element dynamical core of CAM (CAM-SE). CSLAM targets model runs with a large number of tracers, and prior to optimization, CAM-SE-CSLAM outperformed traditional CAM-SE only when using more than 40 tracers in a test configuration. The SPOC effort focused on improving serial code performance by optimizing loop structures, improving memory access patterns, and reorganizing code for better vectorization. In the end, they moved the crossover point from the original 40 tracers to 18 tracers, surpassing the initial goal of 30 tracers.

- With SPOC support, two former SIParCS students hired as student assistants for User Services have continued to pursue WRF optimizations. In one project, a student continued investigating the effects of domain decomposition and especially processor binding and hybrid parallelism (MPI and OpenMPI) to WRF scaling. The other student developed performance optimization code changes to WRF advection, demonstrating very significant speed-ups in synthetic kernels. She is now working to apply those changes to the production code.

- In a related vein, along with the procurement of the Cheyenne system, NCAR and SGI also formed a Joint Center of Excellence focused on optimization and performance improvement activities in FY2016. Through these efforts, NCAR and SGI will collaborate to optimize the operation of the Cheyenne system; to port, tune, and optimize applications for the Cheyenne environment; and to prepare NCAR models and the SGI hardware and software ecosystem for future and emerging HPC technologies.

- 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, CISL hosted vendor-led training events, one by Intel about their analysis tools and compilers, and another by Allinea that introduced their debugging and profiling tools.

The SPOC initiative is supported by NSF Core funds.

‹ Support strategic use of CISL resources | up | Sustain and enhance the NWSC ›

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SUSTAIN AND ENHANCE THE NWSC

CISL built the NCAR-Wyoming Supercomputing Center (NWSC) to provide advanced high-performance computing (HPC), data storage, and data analysis capabilities for many years into the future to maintain NCAR's leadership position in geosciences computing capability and capacity. CISL regularly enhances the NWSC while maximizing its efficiency, sustainability, and usability. The NWSC is designed to meet the rapidly growing 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

Members of the NWSC Infrastructure Support Group are shown installing new electrical transformers. These transformers supply 208-volt power to the GLADE-2 and NWSC-2 test equipment.

predictive power, and longer simulation times. The NWSC faces its next big test in 2016 as the incoming supercomputer named Cheyenne will increase the electrical load by almost 2 MW. That additional load should make it possible to meet or exceed the facility's design energy efficiency.

The NWSC is fully aligned with NSF's vision for 21st-century cyberinfrastructure and directly contributes to the nation's 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."

All planning for installing and integrating the incoming 5.3-petaflops HPC system Cheyenne was completed in FY2016. A design-build contract was awarded to Saunders Construction Inc. Design efforts were complete by spring 2016, with construction documents sufficient for permits in the summer. Fit-up efforts began in earnest in late summer with a majority of the work complete by September. During September the NWSC accepted delivery of the Cheyenne supercomputer, disk storage equipment for the GLADE-2 file systems, and two automated data storage modules for enhancing the tape archive.

The operational expenses and HPC fitup for NWSC during FY2016 were met using NSF Core funds.

‹ Optimize model performance for current and future supercomputers   up   Operate the NWSC efficiently and reliably ›

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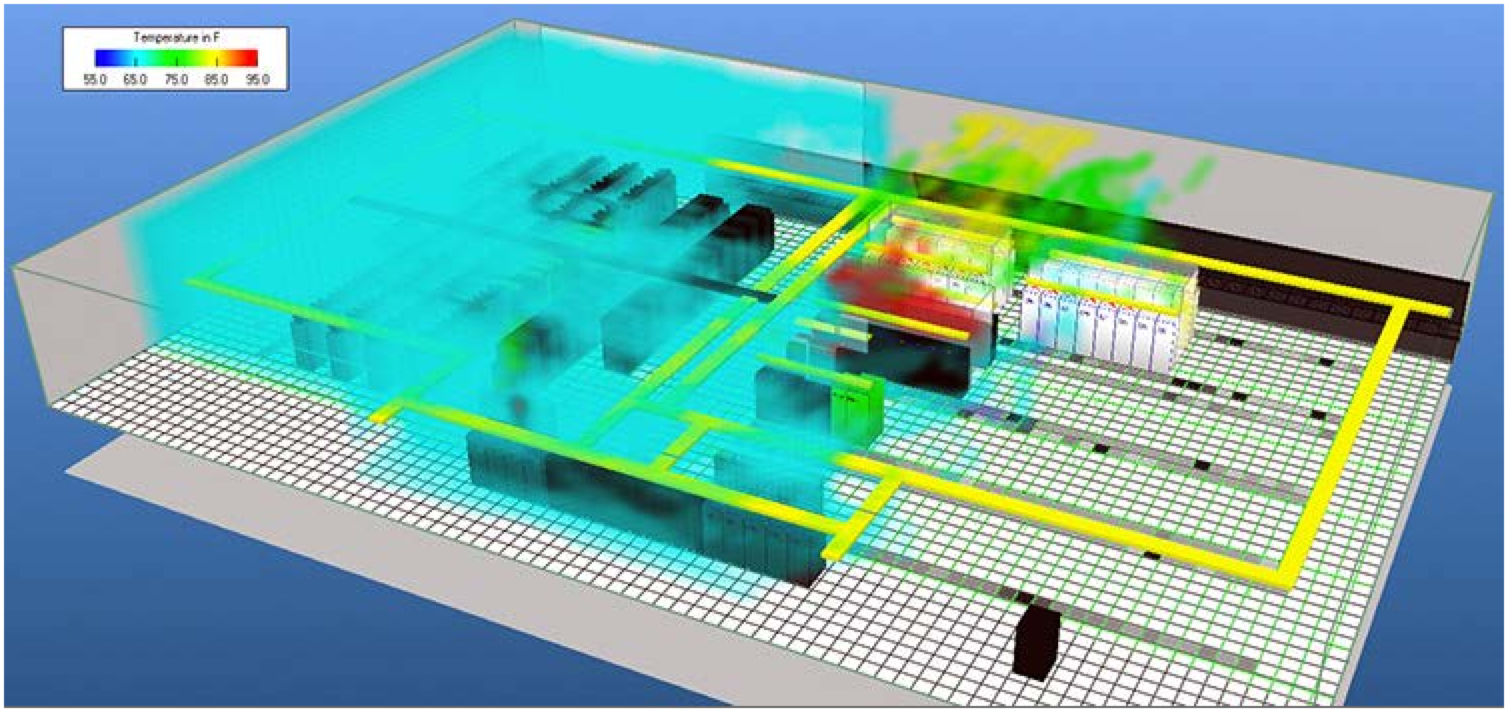
OPERATE THE NWSC EFFICIENTLY AND RELIABLY

CISL will continue improving NWSC efficiency as measured by metrics such as its power utilization efficiency (PUE). Over the next five years, CISL expects to incrementally improve the NWSC's exemplary PUE. Since 2013, the facility has performed exceptionally well and achieved many of its design goals for efficiency, maintainability, and reliability. In particular, NWSC's design encompasses a number of energy-saving features representing the state of the art in efficiency and sustainability, and these features reduce operating costs significantly below those of traditional computing facilities. The design for NWSC assumed a 4-MW IT load and projected a design Power Utilization Effectiveness (PUE) of 1.08. With the facility at only 1.7 MW, it has frequently achieved a PUE of 1.11–1.15. The NWSC faces its next big challenge in 2016: the incoming Cheyenne supercomputer will increase the electrical load by almost 2 MW. With that additional load, it should be possible to meet or exceed the design PUE of 1.08. NWSC optimization and maintenance continues with lessons learned and minor modifications to reduce energy costs and improve efficiency.



The figure shows a three-dimensional temperature representation of the NWSC produced by a commercial Computational Fluid Dynamics application named TileFlow. A student assistant updated this work and provided a much more detailed model that we use to evaluate equipment installation scenarios and ensure that the NWSC operates as efficiently as possible.

When the petascale Yellowstone supercomputer was installed at the NWSC, NCAR fulfilled a top imperative of its previous strategic plan to meet the rapidly growing HPC needs of Earth System scientists. The effort reflected strong engagement by all stakeholders in a private-public partnership that included UWyo, the State of Wyoming, Cheyenne LEADS, the Wyoming Business Council, and NSF. NCAR's addition of the Cheyenne supercomputer extends our ability to meet researchers' growing needs into the future.

During summer FY2016 CISL employed a Mechanical Engineering intern from California Polytechnic State University to update and modernize the computational fluid dynamic models for all NCAR computing facilities. She performed a major update that produced the most detailed models to date of the NWSC. These models inform and allow the NWSC to optimize airflow performance and minimize operational costs.

Our ongoing collaboration with the University of Wyoming (UW) to evaluate and prototype automated continuous commissioning techniques is currently on hold for two reasons. SIParCS interns from last year worked with the software being proposed by UW and found a number of challenges with implementing the software at the scale of the NWSC. Secondly, the project funding anticipated by UW collaborators did not materialize.

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

‹ Sustain and enhance the NWSC   up   Provide the community with Big Data services ›

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PROVIDE THE COMMUNITY WITH BIG DATA SERVICES

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 many petabytes of data available on NCAR's cyberinfrastructure.

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 12,500 unique users acquire 2.2 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).

Digital Asset Service Hub: The Digital Asset Service Hub (DASH) is being implemented by NCAR's cross-organization Data Stewardship Engineering Team (DSET). DASH will provide a comprehensive central system and the information resource for searching and discovering digital assets held by groups throughout NCAR. DASH will increase Big Data services' scientific value and impact on the research community. It will also provide guidance on best practices for organizing Big Data within the organization.

Data Assimilation Research Testbed (DART): Data assimilation (DA) is a key tool for Earth System science that allows models to be confronted with observations. DA is essential for making forecasts for all components of the Earth System at all space and time scales. DART is a software facility for ensemble data assimilation that allows uncertainty quantification, which is essential to many prediction and scientific goals.

DART software: DART software supports community researchers and improves their prediction skill for and understanding of the Earth System. This software helps researchers collaboratively develop and apply data assimilation methods across a wide range of geophysical problems.

Data gateways: Data gateways provide diverse scientific communities with access to data-sharing infrastructure. CISL gateways span climate science, regional climate change, arctic science, solar science, digital preservation, and international efforts to develop metadata and knowledge infrastructure.

Advanced visualization services: CISL staff work closely with individual scientists to develop engaging and informative visualizations that are used for research, scientific briefings, presentations at conferences, publication, and outreach to NCAR visitors. CISL also explores new technologies and visualization techniques to examine how they can be applied to advance geoscience research.

Data analysis and visualization software: CISL's portfolio of data analysis software 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.

Reliable, long-term, customized support for scientific advancement defines the overarching merit of CISL's integrated

computing and data services. CISL provides a portfolio of advanced data services specifically tailored for the atmospheric, geospace, and related sciences communities. Stewardship of valuable reference data collections and operation of petascale computing environments are fundamental underpinnings for NCAR's pursuit of the Grand Challenges identified in its strategic plan, as are the activities to create the coordinated, next-generation portfolio of Big Data services. The criticality of these services is embodied in CISL's strategic imperative to "Develop and sustain advanced computing and data system services" and its imperative to "Provide the community with Big Data Services." As with all CISL services, data services evolve in response to changes in the underlying technologies and the scientific demands of the community, informed by the research and development activities performed under CISL Strategic Goal 2.

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

‹ Operate the NWSC efficiently and reliably up Expand the content of and access to the RDA ›

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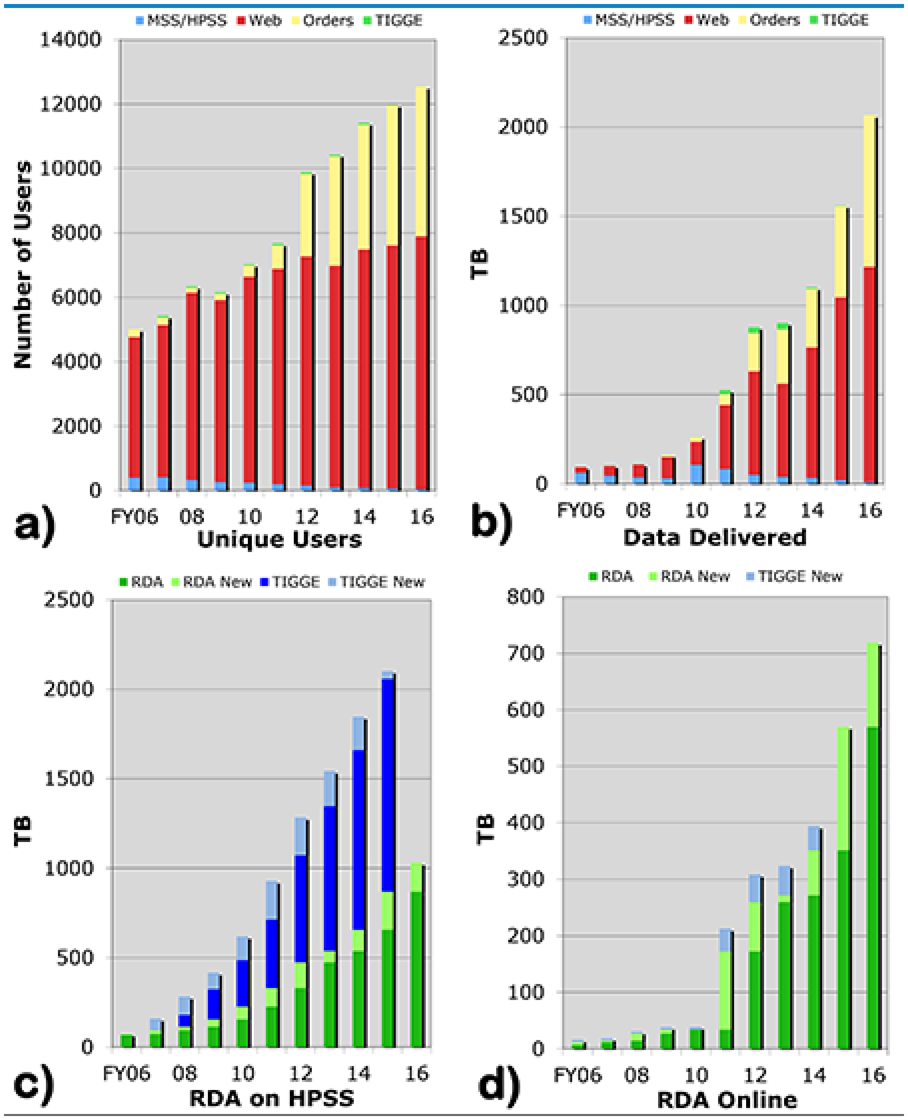
EXPAND THE CONTENT OF AND ACCESS TO THE RDA

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 data sets 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 frequently accesses it. To meet research community needs, the RDA continuously adds new and augments existing data content. Access is also improved with new tools, web services, and HPC-driven workflows that extract data specified by the users from multi-terabyte data sets. The RDA is nationally and internationally respected for its staff, data management practices, consulting services, and ability to positively affect outcomes in the data domain. This position is advantageous to building collaborations that continually strive to provide better scientific data resources and access.

All efforts to improve the RDA focus on enhancing the productivity of the weather and climate research communities. The RDA strives to minimize the data work burden for the researcher by hosting the needed reference data sets with personal consulting services, and it provides easy access pathways including locally to the CISL HPC from a directly connected central file system, via the Web through UIs and standard APIs that support machine-to-machine interoperability, and by creating customized data packages on demand for individuals from large and heterogenous collections. The RDA is also valued for the professionally curated and stewarded data collections that are preserved for the long-term, are citable, support reproducible science, and help NCAR meet Federal requirements for open access to data.



These charts show the data access and growth metrics for the RDA during FY2006-2016: a) The number of unique RDA users specified by access pathway: the NCAR HPSS, publicly available web servers, and one-time special requests (orders) prepared for individual users. 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. Note that services related to TIGGE were terminated in 2016.

In FY2016, over 12,500 unique persons were provided about 2.2 petabytes of data through various primary access pathways: the NCAR HPSS, public servers on the web, and one-time special requests prepared for individuals. The total number of unique users increased steadily from 2012 through 2016 (see chart a). One-time requests (orders) include subsetting, format conversion, and restaging files from the HPSS to disk. Data delivered by full file downloads on the web increased 100 terabytes and orders gained 300 terabytes in 2016 (chart b). CISL is making it easier for users to access terabyte-sized archives on their own. Orders were automatically prepared for over 4,600 individuals, and they received about 850 terabytes of data. Web users form the largest group, with 7,800 people downloading over 1.2 petabytes of data.

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 access from the HPSS (tape-based) has dropped to less than 10 terabytes, and anecdotally, our local users are pleased. These metrics indicate that the RDA is an important and growing data resource for a broad community.

The RDA content expanded by 160 terabytes in FY2016 (chart c). The complete RDA is now over 1.0 petabytes, and over 700 terabytes of it is readily available via GLADE (chart d). The THORPEX (THe Observing system Research and Predictability EXperiment) Interactive Grand Global Ensemble (TIGGE) archive was removed from the RDA causing the dramatic drop in overall size observed in 2016 (chart c). 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 data sets, and stewardship improves the documentation, creates systematic organization, applies data quality assurance, assigns DOIs, and develops user access. Many routine tasks and background infrastructure developments are necessary to maintain the RDA. Major accomplishments for FY2016 include:

- On an hourly to monthly basis, updates are made to observational, analysis, and reanalysis data sets from NOAA. These are supplemented with similar updates for ECMWF and JMA products.

- Expanded automated systems that use CISL HPC and GLADE to give users better access to terabyte-sized data sets. More than 75,000 individual data requests were processed resulting in a net data volume reduction of 98% relative to source archive file size.

- RDA's data-transfer services were fully Globus GridFTP enabled. This integration included a convenient identity-provider layer so that users can log in with their RDA credentials to manage Globus-based data transfers of RDA data. In addition, the RDA's user "dashboard" feature allows users to view all Globus shares granted to them and provides a direct link to the Globus interface to initiate a data transfer. Over 5.6 million files totaling 125 TB were transferred by RDA users via Globus.

- Added significant data assets to the RDA:

    - The International Comprehensive Atmosphere Data Set Release 3
    - NCAR MMM 10-member, 3-km, real-time ensemble prediction system
    - Cross-Calibrated Multi-Platform Ocean Surface Wind Vector Analysis Product V2
    - An Ensemble of Atmospheric Forcing Files from a CAM reanalysis
    - EarthScope USArray Transportable Array (TA) Surface Pressure Observations
    - Coordinated Ocean-ice Reference Experiments - Phase II
    - ECMWF IFS CY41r2 High-Resolution Operational Forecasts
    - Arctic System Reanalysis 30km Monthly Means
    - Expanded Thematic Realtime Environmental Distributed Data Services (THREDDS) Data Server (TDS) access to 49 popular GRIB and NetCDF formatted data sets, 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 63 data sets
    - Increased formal data citation potential by assigning and maintaining DOIs on 79 RDA data sets

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

‹ Provide the community with Big Data services up Lead NCAR's Data Stewardship and Engineering Team ›

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LEAD NCAR’S DATA STEWARDSHIP AND ENGINEERING TEAM

To support a large and expanding scientific community, NCAR has been openly sharing a significant amount of its digital assets, including publications, data sets, software applications, and models. Spread across the organization, these various digital assets support the atmospheric and related sciences needs of universities, NCAR, and the broader geosciences community. User surveys have confirmed the value of these digital assets and indicated that broader and easier access would be helpful. These findings along with federal and agency mandates for open data sharing have prompted NCAR to create the Data Stewardship Engineering Team (DSET).

With membership from each NCAR Laboratory, the NCAR Library, and UCAR Community Programs, DSET is tasked with designing and implementing an integrated system to allow comprehensive search and discovery of digital assets across the organization. The IT implementation will adhere to community-recognized metadata standards, integrate across existing data services systems, and augment systems that are underutilized and may not have the operational capabilities to preserve digital assets for the long term. This upcoming search and discovery system – along with supporting consulting services, guidance for grants requiring Data Management Plans, assistance for assigning DOIs to digital assets, and training for best practices in data management – will form the Digital Asset Services Hub (DASH) as a whole for the organization. CISL’s experience with IT infrastructure and data repository management has positioned it to be a leader in the NCAR-wide DSET and the subsequent development of DASH.

DASH, as designed and implemented by the DSET, will provide a comprehensive central system and the information resource for searching and discovering the digital assets held by groups throughout NCAR, thereby increasing NCAR’s scientific value to and impact on the research community. The IT foundation for DASH uses CI and skilled personnel in CISL to develop, maintain, and operate atmospheric and related science-specific data services for the NCAR organization. Cross-organization metadata support is delivered by personnel in EOL.


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DASH - GETTING STARTED

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- Consultation with Data Curation & Stewardship Coordinator
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- Getting Assets into DASH
- Software and Tools

CONTACT INFORMATION

- Contact DASH
- Background for DASH (DSET)
- UCAR/NCAR Policies

HOME » DATA PORTALS

Digital Asset Services Hub (DASH)

Discovery . Access . Use . Data Services

The Digital Asset Services Hub (DASH) is dedicated to provide **support**, **engagement**, and **training** for UCAR/NCAR's digital assets, including datasets, publications, software, and models. The services and resources made available through DASH focus on supporting these UCAR/NCAR community's digital assets in order to make them available to the broader scientific community. DASH is is created and maintained by the Data Stewardship Engineering Team (DSET).

Overview - DASH Services & Resources

There are currently six DASH Services & and Resources areas that are under development.

- Training and Education Materials & Best Practices
- Consultation with Data Curation & Stewardship Coordinator
- Frequently Asked Questions (FAQs)
- DASH Search and Discovery
- Getting Assets into DASH
- Software and Tools

Training and Education Materials & Best Practices

- Learn about Data Management Plans and related policies/requirements.
- Access Data Management Plan Template and Sample.
- Find out how to obtain a Digital Object Identifier (DOI).

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Home page of the Digital Asset Services Hub (DASH) as of end-FY2016.

DASH is made effective by framing its IT infrastructure and services to support the asset providers and meet their needs. DASH’s services include: Data Management Plan (DMP) templates and guidance, monitoring of DMP goals for successful grants to assist with accountability to Federal mandates, improved user interfaces through usability assessments studies, and a dedicated point of contact and consulting service for the organization.

NCAR has an inventory of more than 100 digital assets that include software, publications, documentation, model codes, and sets of data files that are managed as a single entity or collection. Since late 2015, the DSET has been making good

progress toward its purpose of providing comprehensive digital asset search and discovery capability across the organization. This progress has been enabled and facilitated by regular meetings, volunteer support from each NCAR Laboratory, and some dedicated staff support. Two related DSET technical initiatives are also ongoing: development of a digital asset metadata and the DASH scientific data management system. The metadata specification is based on ISO 19115 standards with elements that enable DOI assignment through DataCite’s registry service. These metadata are being preserved in the new scientific data management system that is based on CKAN, an open-source software that will be modified to meet NCAR needs. As such the system is the metadata repository, supports search and discovery, and will be an access point for metadata sharing with outside organizations (e.g., EarthCube). User access will be through both user and application programming interfaces (UI and API).

In the next phase of development, the system will be augmented with data storage for projects that are not served by other repositories. Beginning in July 2016, a new Data Curator and Stewardship Coordinator role was added to this effort. The Coordinator provides educational materials for NCAR to prepare consistent Data Management Plans (as required for grant proposals), guidance on metadata standards and repository options related to DASH, consulting for data providers and users seeking digital asset information, and other support services aligned with the DSET goals. The DASH is the network location where all DSET-related services will be located. It is currently under development and will exhibit rapid improvement and public availability in the coming year.

The first prototype DSET system will demonstrate digital asset search and discovery spanning NCAR, all Laboratories, the Library, and UCP. Test-user feedback and lessons learned will lead to metadata and system refinements, followed by large-scale metadata insertion, user interface and API improvements, and finally open service to the public. The holistic view of digital assets provided by DSET developments will greatly improve the experience of our broad and growing user community. We expect our users to offer recommendations and guidance that we will use to enhance the system. Successful completion of these near-term goals will also lay the foundation for collaborations outside NCAR, which include Internet interoperable (machine-to-machine) access to more data, and the federation and sharing of NCAR resources with peer organizations and research communities like those organizing around EarthCube efforts. DSET progress can be tracked on the DSET project website.

The DSET and DASH are supported by NSF Core funds.

‹ Expand the content of and access to the RDA up Advance the application of ensemble Data Assimilation ›

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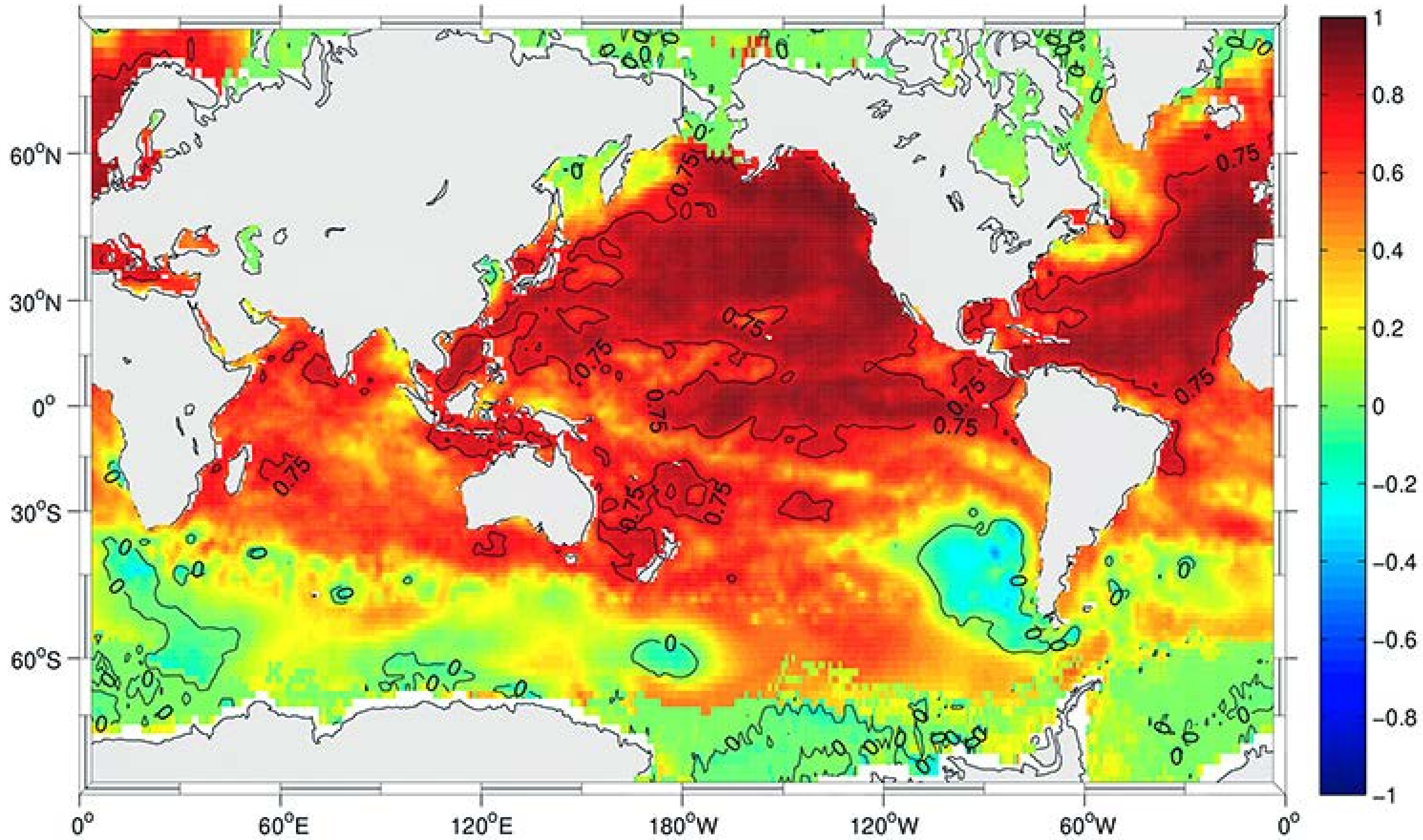
ADVANCE THE APPLICATION OF ENSEMBLE DATA ASSIMILATION

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. With DART, modelers and experimenters can use state-of-the-art DA algorithms to build forecasting systems and diagnose both models and observation systems with a minimum investment in software and algorithm development. DA experts can use DART as a framework for building and testing new algorithms with both simple and sophisticated models. Finally, DART fosters a community of users, supported by the DART development team, who collaborate scientifically and contribute important new capabilities to the facility.



This plot shows the anomaly correlation for sea surface temperature (SST) between a coupled DART/CESM reanalysis and the HADISST product for 1970-1981. Red colors indicate that the reanalysis agrees well with the independent estimates of SST (which were not assimilated by DART) from HADISST. Data from this reanalysis provides information for improved localization of observation impact in strongly coupled DART/CESM assimilations and could also act as initial conditions for CESM hindcasts.

Data assimilation is a key tool for Earth System science that allows models to be confronted with observations. DA is essential for making forecasts for all components of the Earth System at all space and time scales. DA also provides a tool for identifying deficiencies in models and observing systems. The ensemble DA tools provided by DART allow uncertainty quantification which is essential to many prediction and scientific goals. Facilitating the use of DART by scientists helps to achieve CISL's strategic goal to "Advance Earth System science by expanding the productivity of researchers through high-performance computing and data services".

Interfaces between DART and new models continue to be developed. During the past year, work began on interfaces for the CESM/CICE sea ice model, the WACCM-X high top atmosphere model, a second version of the ROMS ocean model, the OpenGGCM ionosphere-mesosphere-thermosphere model, and the PARFLOW watershed flow model. Interfaces were completed for the CM1 convection-resolving model, the FEOM ocean model, and a new version of the COSMO regional atmosphere model. Additional support for estimating sources and sinks of trace gases in both CAM and WRF/CHEM was developed in collaboration with ACOM and Berkeley. The real-time WRF/DART assimilation system continued to run, making use of the new memory-scalable version of DART. A number of enhancements were made to DART systems for CESM including a survey of DART optimization parameters with CAM in preparation for a decadal atmosphere reanalysis, and tuning of the localization of the impact of observations in coupled CAM/POP assimilations in collaboration with CGD.

Data assimilation research in IMAGe is supported by NSF Core funding plus Grant 16-013 from the University of New Hampshire's Open Geospace General Circulation Model program, Grant N0014-15-1-2300 (subaward A15-0093-S001-P0567931) from the DOD Office of Naval Research's National Oceanographic Partnership Program, and Grants OCE149559 and OCE1243015 from the National Science Foundation program Decadal and Regional Climate Prediction using Earth System Models.

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computational methods for Earth System models

- Reach out to new generations of scientists through education

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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

STRATEGIC PLANS

- CISL Strategic Plan
- NCAR Strategic Plan

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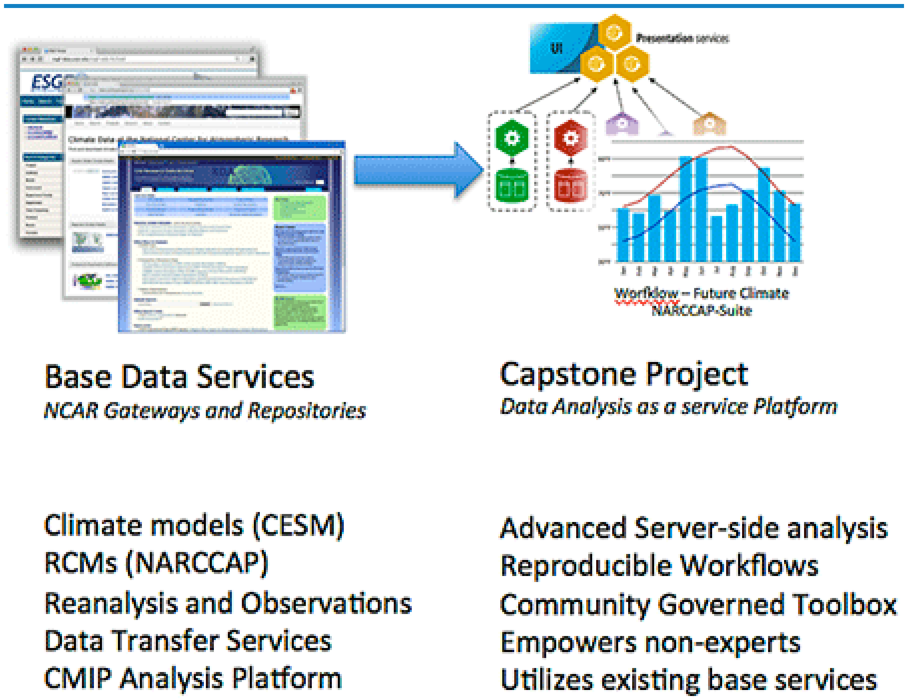
PROVIDE SCIENCE GATEWAYS AND DATA-SHARING SERVICES



CISL services provide access to shared data management and data use cyberinfrastructure for diverse scientific communities with over 2,000 active users monthly. New projects, such as Capstone, are under development bringing advanced analysis capabilities to current and new user communities utilizing the extensive base services CISL manages.

CISL builds and operates science gateways, data services, and data tools that provide diverse scientific communities with access to data-sharing infrastructure. Our projects span climate science (e.g., the Climate Simulation Data Gateway and the Coupled Model Intercomparison Project (CMIP) Analysis Platform), 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).

CISL serves data to the community through data gateways over high-speed wide-area networks and via high-speed disk and near-line tape systems. The CMIP Analysis Platform provides a one-stop shop for analysis and visualization of CMIP data on CISL's DAV resources. The Data Sharing and Data Transfer services are built on Globus services and provide high performance access to NCAR services and data. CISL is working to expand our data services with new web-based capabilities (e.g., server-side analysis, microservices, and specialized queries) to enhance the overall usability and impact of these services and data assets as well as other data resources across NCAR.

Science gateway advances, open data access, and end-user support allow scientists and wide-ranging data consumers to spend less time handling and preparing data and more time on their research.

Scientists increasingly want to openly access data products and use cyber-resources via web- and grid-based environments such as science gateways or virtualized environments such as clouds. Such environments can increase scientific productivity by abstracting away a large set of arcane, machine-specific knowledge, allowing scientists to focus on their science. Here, the challenge for CISL and other HPC organizations is to provide a new layer of virtualized services to support research communities – on a fixed budget. These services should scale with demand and operate seamlessly across multiple, heterogeneous, and potentially distributed computing systems. Such requirements present profound technical challenges. For example, while cloud technologies are being rapidly adopted in the enterprise computing sector, the parallel performance of large-scale applications running on cloud platforms remains poor.

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 Climate Simulation Data Gateway, ESGF, WMO, Data Sharing Services, new projects such as

Capstone, 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.

Climate Simulation Data Gateway

CISL operates the Climate Simulation Data Gateway that provides data discovery and access services for global and regional climate model data, knowledge, and software. The Climate Simulation Data 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 Climate Simulation Data 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. This resource is heavily used by over 1,000 users monthly and each month delivers over 30 terabytes of scientific data to the community.

Accomplishments in FY2016 include expanded open access to NMME and other select datasets, expanded OpenDAP services on openly accessible data and a re-worked publishing workflow built to improve performance of large-volume and large-velocity data collections.

CMIP Analysis Platform

Most academic researchers do not have the resources to download, store, and analyze large portions (often tens or hundreds of terabytes) of the two petabytes of data published worldwide from Phase 5 of the Coupled Model Intercomparison Project (CMIP5). This challenge will be exacerbated in Phase 6, with data volumes expected to be 10 or 20 times larger than in CMIP5. For CMIP6, NCAR alone is projecting it will generate 5 PB of data or more. To address these barriers, NCAR has deployed a CMIP Analysis Platform opportunity to support analyses on a "lending library" of CMIP5 data. The CMIP Analysis Platform integrates published CMIP5 data and a suite of human and software support services overlaid on NCAR's operational analysis and disk storage environment.

We are prototyping the analysis platform within the existing Yellowstone environment and populating the analysis platform with high-value CMIP5 data sets to demonstrate the feasibility of the concept and to better understand user needs, the support effort required, and the demands on the compute, storage, and software environment. Announced to the user community in January 2016, the CMIP Analysis Platform has already been requested by a number of users, and several terabytes of data have been added. The platform has also been integrated with CISL's support environment to allow us to track requests.

NCAR Data Sharing Service

The NCAR Data Sharing Service leverages the capabilities of Globus Plus to increase customization options for storage as well as data sharing. Globus Plus refers to a feature that allows researchers to share data with colleagues outside of their home institutions, greatly facilitating collaborative work. 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 while leveraging the network bandwidth of NCAR's data transfer nodes.

Usage of the Data Sharing Service continued to grow in FY2016 with expansion of the space available for the sharing service. We are currently serving 96 TB of data through the service.

Data Transfer Services

The NCAR Data Transfer Services, built on Globus services, provide parallel data transfer tools with direct access to all GLADE-hosted data. 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. Through the use of dedicated data transfer nodes, users can easily transfer data within NCAR and to peer institutions through the use of Globus online web-based services or scripted data transfer mechanisms.

The data transfer services were moved to new nodes and to a new 40-gigabit Ethernet network environment in FY2016. The new nodes support Globus transfer services along with traditional gridFTP, scp, sftp, and bbcp services as well as access to the HPSS system for users without an HPC account.

Capstone: Data Analysis as a Service Platform

Although climate and weather information is vital to research and decision-making in a wide variety of societally important contexts, it is difficult for scientists, resource managers, and concerned citizens to access and share the expert knowledge required for analyzing and drawing conclusions from weather and climate data. Common barriers to effectively using climate data use are the time, resources, and expertise required to discover, access, and process climate data for analysis. Massaging data in this way is time consuming, requires special, discipline-specific knowledge, may involve protracted email conversations with busy human experts, and is potentially error prone and difficult to reproduce. Further, the requisite deep knowledge of these analysis techniques is often encoded in software, and not in the published literature.

To begin addressing these issues, we are pursuing an integrated data analysis system that will provide server-side analysis of both model output and observational data. Capstone has the ambitious goal of addressing the data analysis needs of a diverse set of users (e.g., climate scientists, researchers and engineers from other disciplines, resource managers, and citizen scientists) who may lack some of the necessary knowledge or resources to do so on their own. To do this, Capstone is being designed to offer remotely accessible, server-side computational services for data processing and analysis using a community-governed toolbox of (micro)services.

Capstone accomplishments in FY2016 include exploration and development of an initial cloud-based prototype by a SIParCS student team during summer 2016. This early work is based on a broad review of existing technologies and approaches, including those by peer research centers. An early implementation plan has been prepared, and we are pursuing funding and partnership opportunities.

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.

Accomplishments in FY2016 include refinement of an automated archive export and storage process using Amazon AWS services. The ACADIS data repository was successfully transitioned to management by NCEAS/NCEI in FY2016.

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. Roughly 2,200 registered CDP users are discovering, accessing, and using 8,000 collections representing over 6.5 terabytes of managed data holdings.

In FY2016 we researched, identified, and deployed prototype replacement technology for the CDP services. Technology direction decisions were based on input from active CDP data providers, prototype technology deployments, and the NCAR Data Stewardship Engineering Team (DSET). In FY2016 we continued to provide operational support, security upgrades, and critical bug fixes for the CDP services.

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 FY2016, CISL continued developing a new web-based dashboard tool for system monitoring and federation-wide reporting and capacity planning. We expanded our Chronopolis production node with a new 375 TB storage system and deployed a test node to support project performance testing goals. CISL continued to provide operational support of the NCAR storage node that currently manages 25 terabytes and over 2.3 million managed objects.

Funding

The Climate Simulation Data Gateway and CDP are 100% supported by NSF Core funding. The CMIP Analysis Project is funded by NSF Special funds. The Data Transfer Services and Data Storage Service are 100% Core funded. Chronopolis is supported by special funds from the Chronopolis project. We are actively pursuing funding for the Capstone project.

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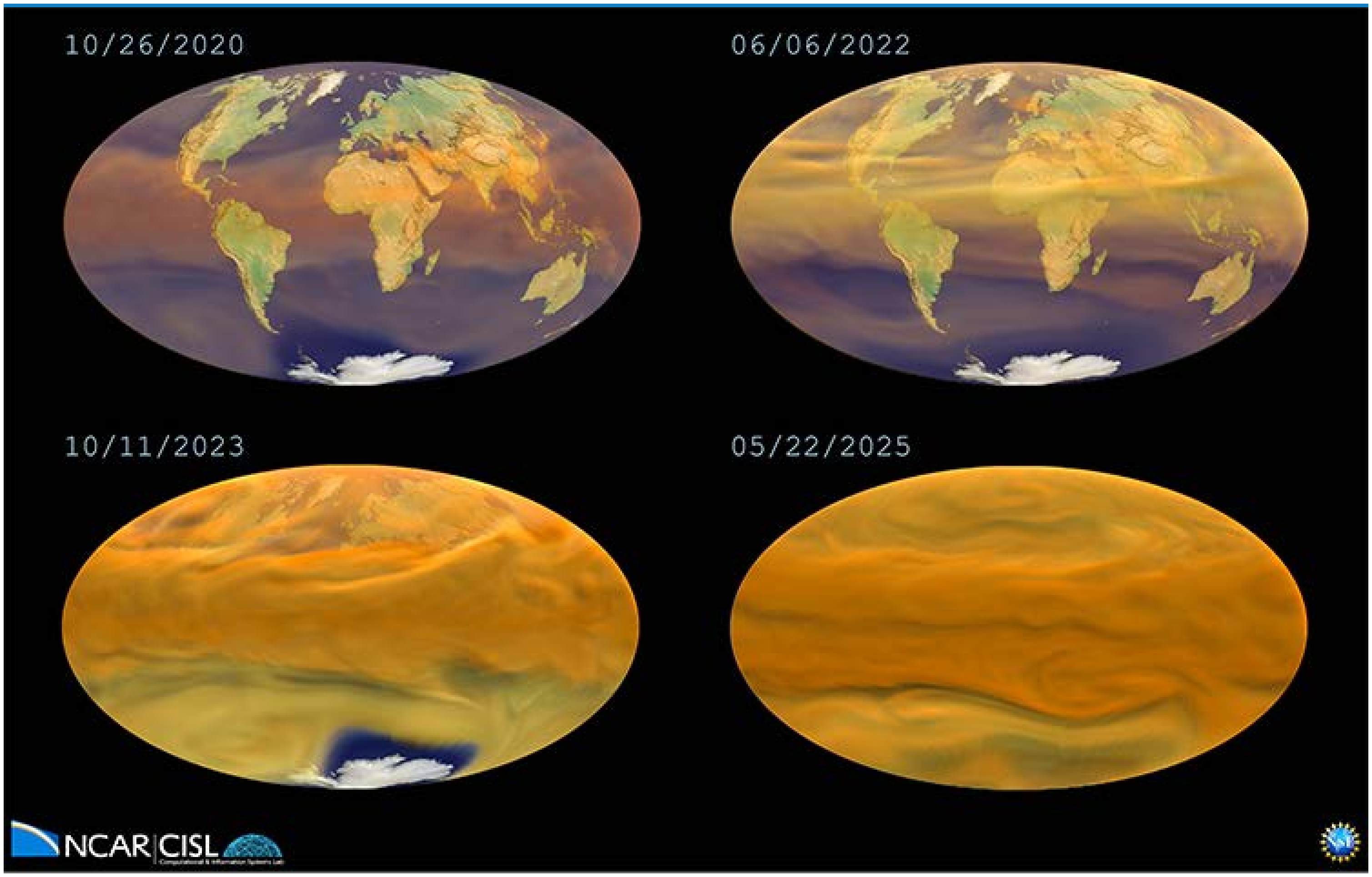
PROVIDE ADVANCED VISUALIZATION SERVICES

CISL develops tools, software, and Big Data services to help scientists better understand and communicate scientific findings to their peers, stakeholders, and the general public. In particular, CISL staff work closely with individual scientists to develop engaging and informative visualizations that are used for research, scientific briefings, presentations at conferences, publication, and outreach to NCAR visitors. Additionally, CISL regularly explores new technologies and visualization techniques to examine how they can be applied to advance geoscience research and E&O opportunities.



This image shows the global dispersion of sulfate aerosols that result from continuous sulfur injections into the stratosphere, derived from simulations performed for a climate engineering project led by Jadwiga Richter (CGD) and Simone Tilmes (CGD). The visualization demonstrates how sulfate aerosols are distributed with time in the upper Earth's atmosphere, in an attempt to counteract the effects of global warming. Computer simulations like this allow us to conduct climate engineering experiments that cannot be done in the real world. —Visualization by Matt Rehme (CISL).

CISL offers a portfolio of visualization resources including CISL-developed visualization tools – such as the NCAR Command Language (NCL) and VAPOR – as well as other state-of-the-art third party visualization systems that are leveraged to create efficient workflows and customized visualizations to meet the Big Data visualization needs of the researcher. Earth System science is advanced and research productivity is enhanced by this service that helps researchers create informative and educational visualizations for which they may not have the time, skills, or tools to develop.

Examples of visualization services provided to the scientific community in FY2016:

Geoengineering visualization provided to Jadwiga Richter (CGD) and Simone Tilmes (CGD) for presentation to the director and deputy director of the Defense Science Office at the Defense Advanced Research Projects Agency (DARPA) to summarize results of a seedling project and to propose a future effort on climate intervention research.

- CESM visualization of Justin Small's (CGD) sea surface height and latent heat flux correlations for a seminar presentation.
- CESM temperature anomaly visualization for Warren Washington (CGD) that compares 2012 and 2090 global anomalies and was submitted to Argonne for inclusion in their Supercomputing Conference (SC2015) booth.
- A series of climate change visualizations for Clara Deser (CGD) and Marty Quinn (Plymouth University) as part of an interactive educational exhibit that uses sound and visualization to interpret climate change.
- Flight path visualization of the ORCAS field project for Matthew Long (EOL) and Britton Stephens (EOL).
- A series of visualizations showcasing flow dynamics of the CT-ROMS model, which describes the interconnectivity of coral reefs in the western Pacific that suffered an unprecedented bleaching event in 2016. The model is developed and researched by CGD under researchers Joanie Kleypas, Frederic Castruccio, and Dianne Thompson. Work was accepted into to the XSEDE 2016 showcase and featured in a news article by *Science Node*.

Other FY2016 visualization and collaboration research and advancements include:

- Implemented virtual and augmented reality apps to make geoscience data more engaging and accessible to the general public.
- Developed new Autodesk Maya routines for improving runtime efficiencies and volume-rendering capabilities of high-resolution scientific data.
- Installed and tested the Scalable Amplified Group Environment (SAGE2) tool with the University of Wyoming Shell Visualization Center for conducting collaborative research to enable distributed scientific teams to work together more effectively.

This project is supported by NSF Core funds with supplemental funding provided by NCAR's Climate and Global Dynamics (CGD) laboratory.

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ENHANCE DATA ANALYSIS AND VISUALIZATION SOFTWARE

Presentation of award to the winner of the VAPOR visualization contest organized by the Korean Institute of Science and Technology Information (KISTI) at the Korean Supercomputing Conference. Nearly 20 students in the atmospheric sciences participated in the contests.

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 interactively analyze and interpret results arising from numerical modeling. 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 both qualitative and quantitative data analysis. The VAPOR package has a community of over 8,000 registered users worldwide, and to date has been cited over 280 times.

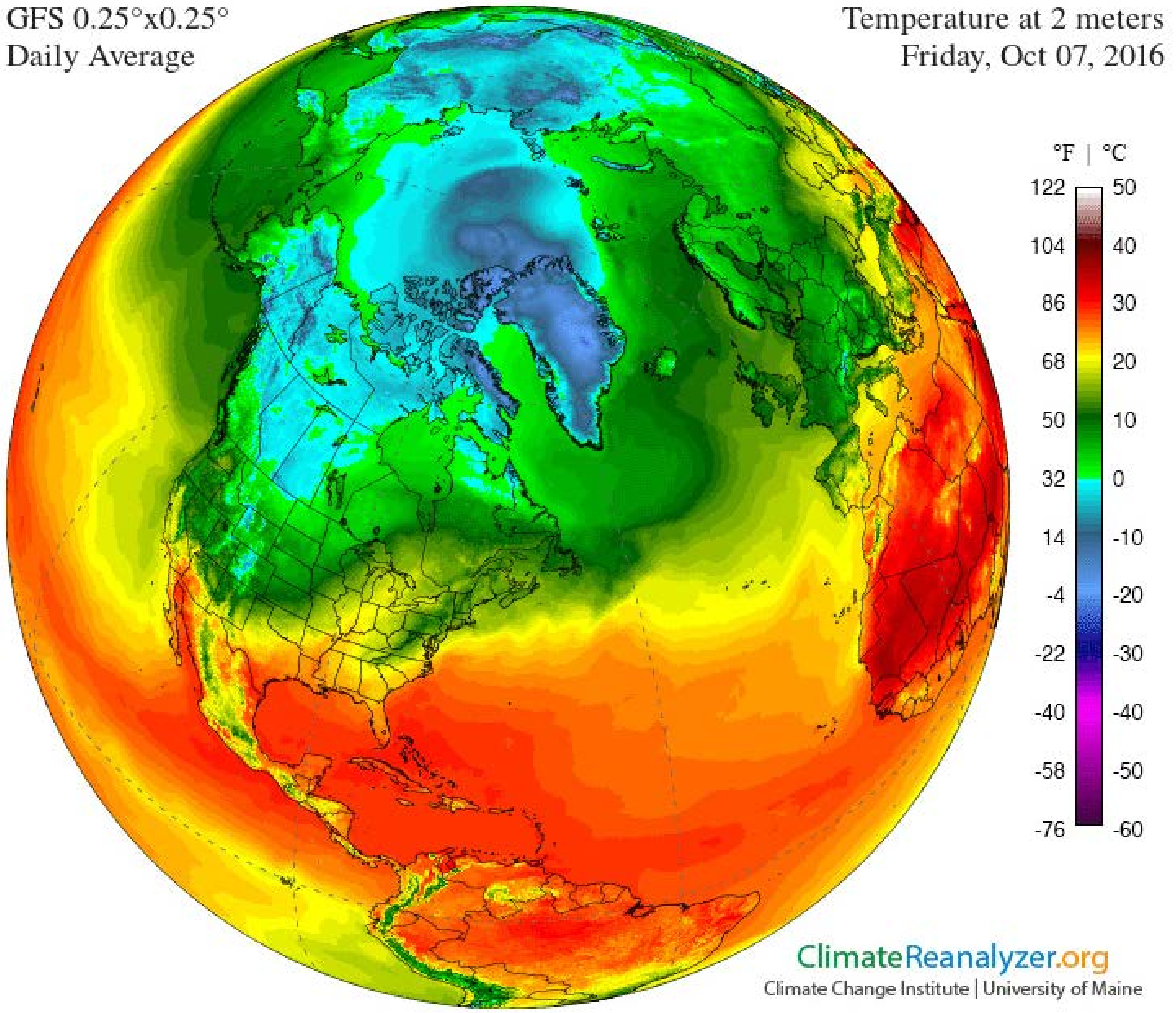
NCL is an open source data analysis and visualization environment developed in close collaboration between CISL, NCAR climate modeling and weather research groups, and the university and broader geoscience communities. PyNIO and PyNGL are Python modules based on NCL's file input/output and visualization capabilities. WRF-Python is a new package that provides a comprehensive Python interface to the WRF-ARW computational and visualization capabilities in NCL. These science-driven, well-supported, free tools enable scientists to effectively read, analyze, and visualize a wide variety of complex geoscientific data formats on a variety of computing platforms. NCL has been embraced broadly across the international geoscience community spanning research, education, operational, military, government, and commercial organizations. It is used for creating publication-quality visualizations, analyzing climate model data, and real-time data display at operational centers. The Python tools are aimed at exposing NCL's unique capabilities to a mainstream language that has widespread adoption in the scientific community. In the period October 2015 to September 2016, NCL was downloaded 20,398 times with a monthly average of 35,220 unique visits to its website. Beta versions of PyNGL and PyNIO were downloaded about 2,350 times.

A CISL strategic goal is expanding the productivity of researchers in the atmospheric, geospace, and related sciences through advanced computing and data services. VAPOR's Big Data capabilities make it unique among advanced visualization tools and satisfy a critical need for computational geoscience, particularly in the areas of weather prediction, climate, and ocean modeling. NCL and related Python tools address disparate and evolving research issues in the climate, atmospheric, and oceanographic community, for example, the effects of heat waves, droughts, and evapotranspiration on humans and agriculture. Scientists can produce results more quickly and effectively because these tools facilitate decision making, improve understanding, and stimulate insights from data sets that are being produced in varieties and volumes far exceeding anything they've ever had to manage before.

VAPOR's FY2016 efforts were again focused primarily on meeting the contractual obligations of grants from the Korea Institute of Science and Information Technology (KISTI) and the NSF. The KISTI award funded the development of numerous enhancements to VAPOR's suite of visualization tools such as support for calculation and display of basic data statistics; closer integration with Python in the form of plotting capabilities enabled with the widely used Matplotlib module; and animation encoding. These new features will be made publicly available in Release 2.6 of VAPOR planned for November

2016. Additionally, the KISTI grant supported ongoing efforts to support coupled model analysis. A two-year NSF SSI2 grant was completed with all milestones successfully met, the most notable of which was the refactoring of VAPOR's wavelet-based, progressive-access data format – the VAPOR Data Collection (VDC) - to improve its generality and hasten its adoption by other data analysis packages. Toward that end the new data format has been integrated into partner UCSD's bioimaging package, QUEST, and nascent efforts were begun to add support for the VDC in CISL's NCL package. In addition to meeting contractual obligations, the VAPOR team completed and released an evaluation version of VAPOR3. VAPOR3 represents a complete refactoring of the VAPOR code based aimed at addressing many of the limitations of the original design.

A major new version of NCL is well underway, with over 80 new functions for extreme value statistics, heat stress, crop and evapotranspiration, bootstrap estimates, and meteorology, new graphical capabilities based on high user demand, critical updates to the internal map database, major overhauls to the file I/O library, and significant speed-up of popular computational routines. A release is expected in November 2016. At the beginning of FY2016, CISL hired two software engineers to further its Python integration efforts with NCL. This resulted in the completion of two long-standing milestones: the creation of a WRF processing Python package which uses “xarray” as its core data model, and the integration of our Python tools and NCL under the Conda package manager, making these tools significantly easier to install. WRF-Python is in use by friendly testers, with an expected release date of December 2016. Both PyNGL and PyNIO had beta releases in FY2016, with major releases expected in early FY2017.



Climate Reanalyzer, developed by Sean Birkel, a Research Assistant Professor at Climate Change Institute / University of Maine, is a platform for visualizing a variety of weather and climate datasets and models. The site includes maps, time series, and correlation interfaces for several monthly reanalysis models, maps for CFSR daily reanalysis, maps for monthly 4km PRISM U.S., and an interface for plotting data from the Global Historical Climatology Network (GHCN). Visitors to Climate Reanalyzer include researchers, teachers, students, and climate and weather enthusiasts. Images from Climate Reanalyzer regularly appear on blogs and weather and climate-related news media. Data processing and graphics on Climate Reanalyzer are done almost entirely from scripts written in NCL.

The VAPOR project is supported by NSF Core funds, a subaward from the University of California at San Diego, NSF 54067252, and a grant from the Korean Institute for Science and Technology Information. The NCL and related Python tools project is supported by NSF Core funds.

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ADVANCE ENTERPRISE IT AT NCAR AND UCAR

Surrounding NCAR's computational and data services is an IT enterprise with many cross-cutting issues that must be managed across organizational boundaries. These include processes for adopting technology to maintain interoperability, responsibility for the collective cybersecurity posture of NCAR/UCAR, and coordinating network infrastructure.

Developing an enterprise architecture (EA) has been foundational to our approach to enterprise IT. EA is the discipline of translating an organization's vision and strategy into effective business practices combined with information technology infrastructure to support those practices. The EA is a joint effort between CISL/OSD and UCAR Finance and Administration, and it supports the strategic plans of both UCAR and CISL. A separate standalone IT UCAR Strategic Plan was finalized, and it is summarized in the graphic below.

This is a summary of UCAR's Information Technology strategy for the next two years.

There were many advances in enterprise IT during FY2016. Cybersecurity efforts saw a formal rollout of FISMA (Federal Information Security Management Act) with the goal of FISMA Low certification for the general organization and FISMA Moderate for projects requiring this higher level of cybersecurity. Cybersecurity achievements include establishment of a Security Chief Information Officer with the CISL Director serving in this role, establishment of a new corporate Policy 1-7 outlining governance for cybersecurity, creating a FISMA/Cybersecurity Risk team, publishing the NSF strategic security plan and policies, coordinating FISMA project responses, and deploying continuous monitoring processes. Other enterprise IT accomplishments include networking enhancements at the NWSC to support the new Cheyenne supercomputer and at NCAR's Mauna Loa Solar Observatory to upgrade their Wide area network for new instruments. The uninterruptible power supply at the Mesa Lab Computing Facility was upgraded with a right-sized system that improves the system's efficiency by 13 percent.

This effort is supported primarily by UCAR indirect funds. FISMA efforts also receive project funding to cover the costs for FISMA certification above the “low” level. The MLCF renovation was funded by NSF Special funds.

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PROVIDE NETWORKING SERVICES

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.

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.

CISL plans, engineers, installs, operates, maintains, develops strategy, and performs research for fast, reliable, and flexible networks that support data services at the campus, metropolitan, regional, national, and international levels. 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.

At its core, CISL is a laboratory dedicated to providing advanced cyberinfrastructure to propel world-class science. CISL services evolve in response to changes in the underlying cyberinfrastructure technologies and the scientific demands of the community.

NETS pursued these Local Area Network (LAN) and general support projects in FY2016:

- UCAR network infrastructure re-cabling
- WASP inventory system
- Geographic Information System (GIS)
- Softphones
- Voice over Wifi
- Cellular support
- ML Room 034 remodel and NETS shop relocation
- Network monitoring
- Netflow
- Extraview
- Filemaker
- Business continuity
- Everbridge Emergency Notification System (ENS)
- UPS
- Grounding
- Wireless networking
- Voice Over IP (VoIP)
- Collocation Facilities Management (CFM)
- CO2 Monitor networking
- EOL field project wireless testbed
- HAO High Altitude Chamber
- ML Climate Exhibits
- ARUBA Clearpass design
- MLDC (ML-29) infrastructure design
- Cisco VG320 voice gateway upgrade
- IPv6 UCAR deployment
- Spring and fall power downs
- Equipment maintenance
- Budget support
- Purchasing support
- HAO MLSO LAN upgrade design and implementation
- OpenDCIM
- Patchmanager
- NWSC Module A & B design

- NWSC2 procurement
- Maintenance of NETS servers
- Replaced Smartsheets with Google Docs
- Migrate to CISL domain
- CISL and NCAR Director's Office Chromebox deployments
- Unidata move inside security perimeter

NETS pursued these Metropolitan Area Network (MAN) projects in FY2016:

- Boulder Point-Of-Presence (BPOP)
- Boulder Research and Administration Network (BRAN)
- BRAN Vassar Fiber Cut
- SHEPC inter-building cabling and agreement
- BRAN Table Mesa Flood Mitigation

NETS pursued these Wide Area Network (WAN) projects in FY2016:

- Front Range GigaPoP (FRGP) ongoing management and engineering
- Bi-State Optical Network (BiSON) ongoing management and engineering
- DREAM 20G upgrade
- 100G NWSC/FRGP path
- New FRGP participants:
    - The State Higher Education Policy Center (SHEPC), incorporated under Colorado law by three nonprofit corporations: National Center for Higher Education Management Systems (NCHEMS), State Higher Education Executive Officers Association (SHEEO), and the Western Interstate Commission for Higher Education (WICHE)
    - Jefferson County School District
    - Johnson and Wales University
- Internet2 Gender Diversity Initiative Co-chair
- Internet2 Network/Connector Liaison
- XSEDE
- Western Regional Network (WRN)
- WRN NOAA support
- NOAA Research Network (NWAVE)
- NOAA FRGP TIC design and implementation
- 910 colocation renewal
- Level3 Fiber Lease Renewal
- Colorado Department of Transportation (CDOT) Higher Education Fiber Agreement
- The Quilt Project – National Regional Networks Consortium
    - Jeff Custard – Executive Committee/Chair until 2/19/16
    - 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
- CSU-P NSF CC* 10G research lambda
- Added two CSU-FC 10G lambdas
- BPoP TCOM Upgrade
- ADVA ALM Testbed
- Submitted NSF CICI Rocky Mountain Regional Internet Security Collaboration (RMRISC) Proposal - not funded

NETS pursued these special projects in FY2016:

- NSF RMCMOA CC*IIE Grant and WINS Supplement
    - Two RMCMOA workshops
        - LBNL CIRA Report on Engaging Researchers
    - Women in IT Networking at Supercomputing (WINS) awarded five women to attend and participate in SCinet and

    SC 15
    - No Cost Extension to 2/28/17
    - Change of Scope
- NSF WINS Three-year Proposal - unsolicited
    - Evaluated 33 submissions
    - Awarded eight women to attend and participate in SCinet and SC 15
- Westnet meeting support
    - January 2016
    - June 2016

NETS will continue to provide support and enhancements for all of these essential networking services.

Detailed project descriptions appear below for three of these projects: NWSC data center network design and implementation, Mauna Loa Network collaboration known as MLONET, Fiber expansion (Level3 fiber lease renewal, CDOT fiber lease agreement, SHEPC fiber build).

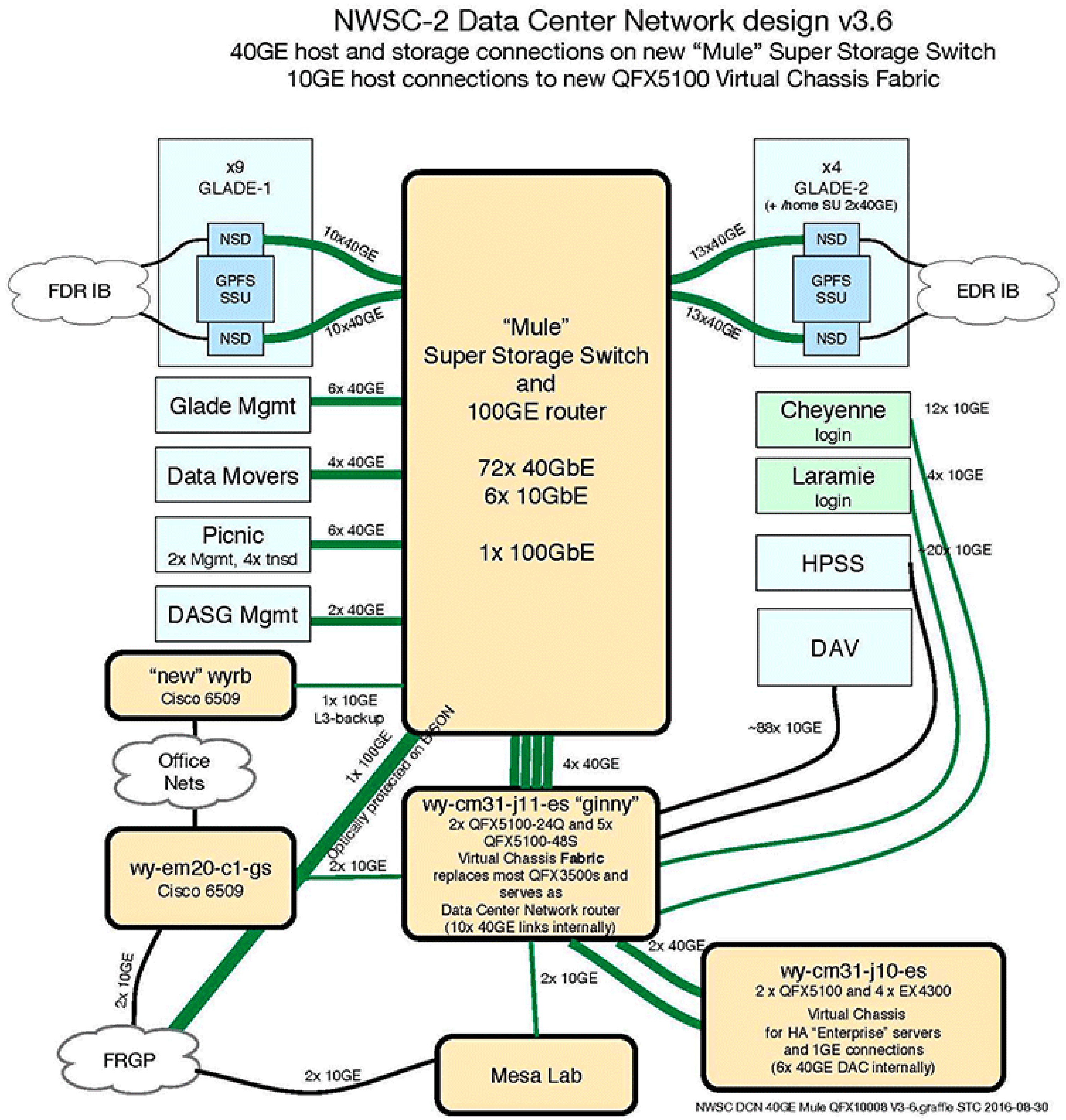
NWSC data center network design and implementation

This is an ambitious phased project to install a Juniper QFX10008 (Mule) capable of 40 and 100 Gbps and upgrade all Juniper 3500s to much more capable Juniper QFX5100s.

This project was planned in 2015 and was completed in fall 2016. This is a full refresh of the data center network to support the new supercomputer, Cheyenne, and the new GLADE storage and analysis system.

The NETS team replaced eight QFX3500 switches with QFX5100s, added an additional five QFX5100s to meet the requirements of the project, and added 240 10 Gbps ports. In its current configuration, Mule can provide up to 100 40 Gbps ports and two 100 Gbps ports, scaling up to 96 Tbps of throughput. NETS worked closely with DASG to procure, design, and install the QFX10008 Mule to provide 40 Gbps Ethernet connections between 20 “old” GLADE-1 and 32 “new” GLADE-2 hosts.

Using a phased approach, the NETS team created two virtual chassis and also replaced the Cisco 1 Gbps switches in the data center with Juniper EX4300s. Most of the computing devices in the data center require redundant connectivity. Using virtual switches in the design allows these devices to connect to two or more switches, which provides a more resilient network, mitigates outages caused by any individual device, and allows component upgrades with less downtime. During the project phases, NETS, CASG, and ISGC teams moved over 500 ports from old equipment to the new network.



This diagram shows the high-level design for the NWSC data center network upgrade.

Mauna Loa Network collaboration known as MLONET

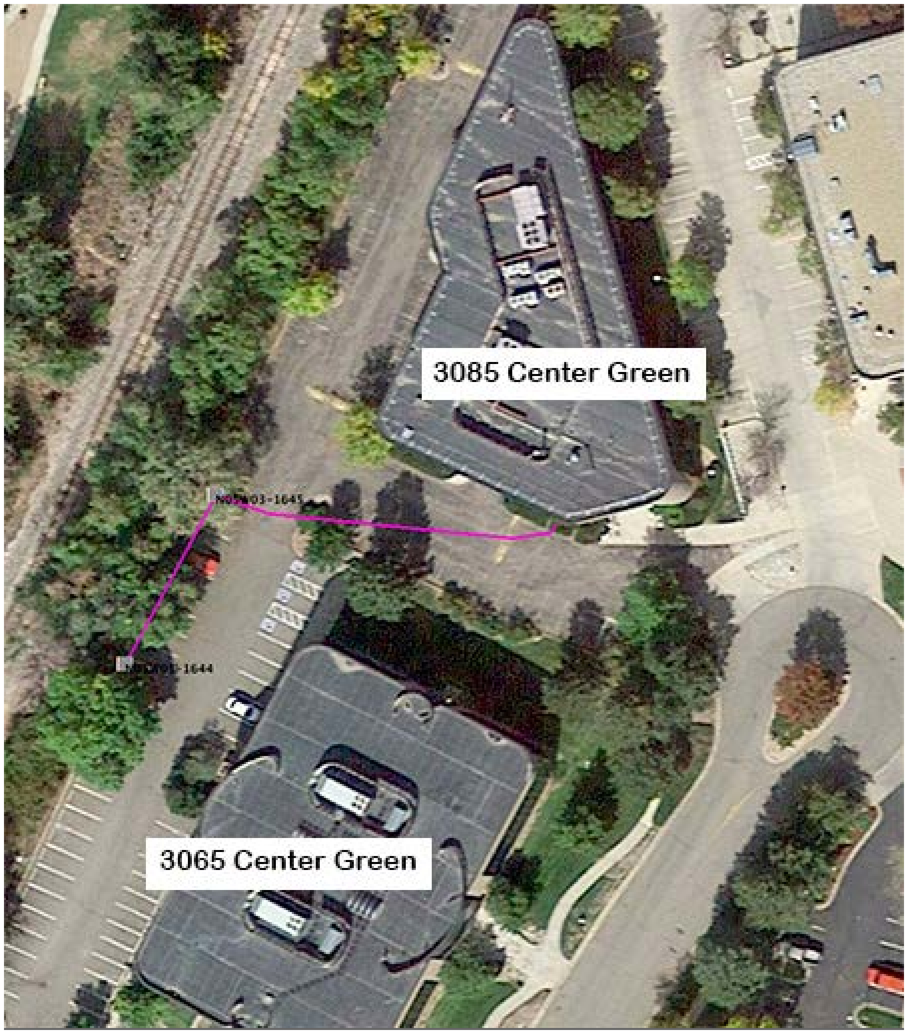
MLONET is a joint project between the University of Hawaii (UH), NCAR/UCAR, and NOAA to upgrade the WAN for instruments housed on Mauna Loa, Hawaii, including the HAO Mauna Loa Solar Observatory (MLSO). This project is funded in part by NSF award ACI-1541471 "CC*DNI Instrument: High Performance Reliable Network Access to Mauna Loa Observatory Science Instruments" in the amount of $398,207 awarded to UH with support from NCAR/UCAR and NOAA.

Mauna Loa has suffered with costly and inadequate networking for many years, and the difficult-to-reach location limits the networking options and increases the cost. The MLONET team evaluated options, reviewed the high-speed wireless design, and managed the installation of the system that has gone active. In addition, the NETS team took advantage of a facility upgrade project at MLSO to design and install a new Juniper router/switch, new LAN cabling and wallplates, a new wireless LAN system, and new fiber optic networking to tie into the new WAN wireless system. This upgrade moves the MLSO network to NETS standards and increases WAN bandwidth from 100 Mbps to 400 Mbps. This has been an excellent collaboration between UH, NOAA, NETS, and HAO.

Images of LAN and WAN networking equipment and infrastructure used in the Mauna Loa Network collaboration.

Fiber expansion (Level3 Fiber Lease renewal, CDOT fiber lease agreement, SHEPC fiber build)

Extensive expansion and renewal of WAN fiber optic cabling has taken place this year. Owned/leased fiber optics are the preferred method of constructing LAN, MAN, and WAN networks. NETS has been able to greatly expand the amount of fiber owned or on long-term lease for the use of NCAR/UCAR, the FRGP, and BiSON. NETS completed a very long negotiation with Level3 to renew valuable fiber leases with no cost increase. These paths provide critical physical network segments on the BiSON and UCAR networks. NETS has worked for a number of years to establish a relationship with the Colorado Department of Transportation (CDOT), which controls extensive fiber optic cabling in the state and federal right of ways. The partnership has been solidified after the signing of a 10-year agreement for multiple fiber paths



Fiber pathway connecting SHEPC to the UCAR Center Green 2 fiber.

including Boulder to Golden on US 93, Boulder to Denver on US 36, Denver to Stateline on I-25, and select paths in Pueblo for the use of CSU-Pueblo. NETS also succeeded, after a long negotiation, in partnering with the City of Boulder for a right of way between the SHEPC facility on Center Green and CG2. This allowed SHEPC to join the FRGP.

Funding

NETS activities are primarily supported through UCAR Communications Pool indirect funds, the FRGP/BiSON, NSF Core funds, and NSF awards ACI 1440642 and ACI 1640987.

‹ Advance enterprise IT at NCAR and UCAR up Formalize and enhance UCAR's cybersecurity capabilities ›

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FORMALIZE AND ENHANCE UCAR’S CYBERSECURITY CAPABILITIES

UCAR’s information technology (IT) environment is a large and diverse set of compute, data, web, and network servers. These systems comprise vital scientific research platforms as well as business application systems. Over the next five years CISL will introduce new security practices aligned with community best practices, such as those defined by the Federal Information Security Modernization Act (FISMA).

The CISL Director has been delegated the role of Security Chief Information Officer (SCIO) by the UCAR President’s Council and as defined in Corporate Policy 1-7. While managed by CISL, the Office of SCIO oversees and manages information security and privacy for the UCAR/NCAR/UCP enterprise. The SCIO inventories all UCAR systems and related information and manages security controls using federal information-processing standards and guidelines adopted by the National Institute of Standards and Technology (NIST) in accordance with the FISMA. The Cybersecurity, Risk, and Compliance (CRC) team oversees alignment to regulatory requirements and IT audit functions.

The SCIO delegated responsibility for implementing a security strategy with prevention, detection, and response components to the Security Engineering Group (SEG). Working with the SEG is the Computer Security Advisory Committee (CSAC) – senior system administrators from across the organization – to balance the organization’s collective cybersecurity needs with those of the divisions and programs.

Providing secure IT systems within CISL and across UCAR supports CISL’s computing imperatives to provide supercomputing resources, Big Data services, and enterprise information technology for UCAR, NCAR, and the Earth System sciences. Formalizing and enhancing cybersecurity capabilities is also an action item in CISL's strategic plan. 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.

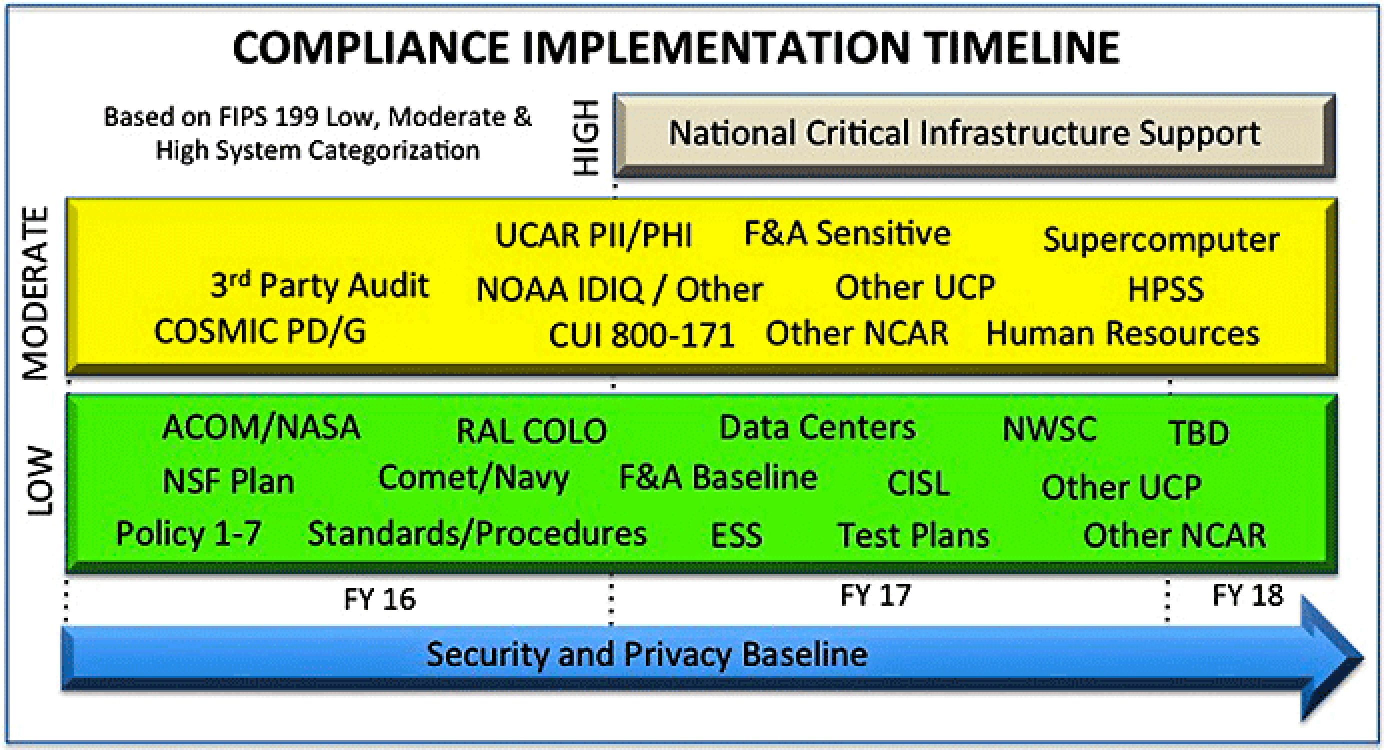
In FY2016, UCAR formed the Office of the CIO’s Cybersecurity Risk and Compliance (CRC) team that revised and is implementing the UCAR Strategic Security Plan for NSF. This founding plan guides our cybersecurity efforts and becomes the baseline strategy that the rest of UCAR can leverage. The plan is organized around a set of guiding principles intended to balance UCAR’s mission-critical needs for unfettered processing power and stability in the computing environment with the need to address modern cybersecurity challenges including external malicious attacks and internal resource constraints. The plan is aligned to the top 10 cybersecurity objectives identified by the Office of Management and Budget to Congress of the Federal Information Security Modernization Act (FISMA II).

Cybersecuity accomplishments in FY2016 include:

- Established a formal governance model with authority and roles clearly identified through new UCAR corporate policy 1-7 that created the enterprise-wide Office of Chief Information Officer for Security.
- Adopted industry best practices with appropriate examinations of assumptions and revision to fit with UCAR’s open scientific mission, as reflected in 17 UCAR security standards with associated procedures based on NIST Special Publication 800-53, Revision 4.
- Mitigated new or expanded risks based on our professional judgment in comparison to risks we currently accept or for which we provide compensating controls.
- Resolved to build in security early in the process of planning and implementing projects and programs. As projects move forward, continual effort is devoted to a comprehensive and proactive security component.
- Established review processes in coordination with UCAR Contracts for procuring cloud services.

- Managed the first third-party IT audit of security and privacy practices funded by a NOAA contract for FISMA compliance.

Cybersecurity at NCAR is supported by a combination of NSF Core funding and UCAR Communications Pool indirect funds. Portions of the effort for the COSMIC II program were funded by project-specific funds from NOAA.



This compliance timeline illustrates planned activities and portions of the organization that will be working with the compliance team to implement security best practices. Risk assessment and continuous monitoring of activities will become a cornerstone of the cybersecurity approach consistent with the security plan.

‹ Provide networking services   up   Deliver modern IT infrastructure, services, and platforms ›

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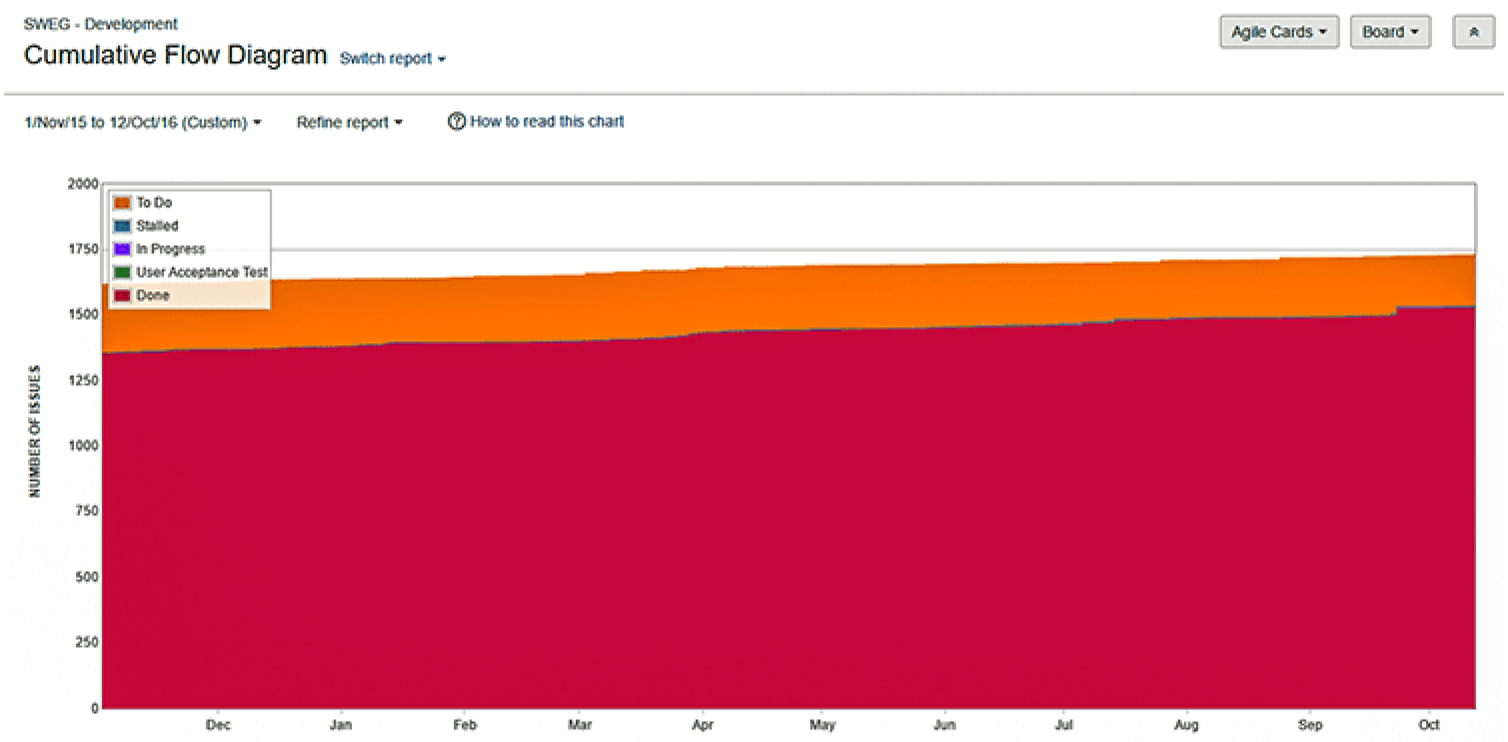
DELIVER MODERN IT INFRASTRUCTURE, SERVICES, AND PLATFORMS

CISL supports the hardware and software infrastructure for many of UCAR's information technology (IT) services (e.g., Domain Name Service, Active Directory (AD), web content management system, software revision control systems, and systems administration support). CISL will evolve these services to enable platform-as-a-service models; enhance and enable storage, data protection, and archive services; and provide and promote virtualized computing services. CISL will

also identify, promote, and implement common software development tools (e.g., GIT, Wiki, and automation tools).

CISL’s expertise and synergy in designing and provisioning cyberinfrastructure is essential to effectively managing and operating enterprise IT, supercomputing, cybersecurity, and communication services. The rapid pace of change in IT positions enterprise IT as a key enabler for scientific productivity.



This figure shows a cumulative flow diagram from JIRA illustrating progress on feature enhancements and bug fixes for SAM and other tools that SWEG is working on. This metric shows that the overall trend is appropriate with new work being accomplished at an expected pace without a huge jump in work in the “To-Do” category.

CISL continues to provide an organizational leadership role in an Identity and Access Management (IAM) effort. During FY2016 CISL's Enterprise Infrastructure Operations (EIO) group upgraded and configured the three high-availability Active Directory domain controllers. These systems are the foundational building block for a unified IAM service. Additional pilot work proved the viability of Active Directory Federation Services (ADFS) to enable cloud-based authentication services. Finally, CISL, RAL, and other parts of UCAR partnered in moving over 90% of the laptop and desktop infrastructure to utilize AD authentication methods.

During FY2016 SWEG has continued to deliver services supporting overall UCAR IT services as well as NCAR’s HPC services. SWEG has also worked across the organization to migrate users from Subversion to GitHub as the baseline version control system. GitHub represents a more modern approach that enables both self-service capabilities for developers but also enables broader visibility and collaboration tools for our open source software projects. At the end of FY2016 we had 487 software repositories and over 250 users, representing the largest single source catalog of software at UCAR|NCAR. SWEG continued to support Drupal as the content management platform for the organization. SWEG began the first steps of implementing a Drupal cloud-hosting pilot, aimed at delivering higher availability with more efficient development workflows. SWEG also engaged in a project with UCAR Communications for developing and implementing a modern replacement theme for *AtmosNews*. SWEG continued in its support of PeopleDB, in particular the integration with AD to support automated account-creation workflows. SWEG also continued the ongoing development SAM. In particular this

year, SAM was integrated with the XSEDE XRAS system to streamline the allocation request process as well the the required enhancements to support the new supercomputer Cheyenne.

EIO also configured a VMware vSphere environment that will host UCAR services such as DNS, FTP, DHCP, etc., to run on a common hypervisor and reduce complexity in the enterprise environment. The vSphere environment will also allow UCAR staff to run additional virtual machines in the future when it will be offered as Infrastructure as a Service (IaaS). The vSphere environment was set up as multiple clusters allowing general use virtual machines (VMs) to be run on one cluster, administrative VMs to run on a second cluster, and sensitive systems to run on separate clusters as an enhanced security feature. The vSphere environment is configured to interact with AD for authentication to reduce the number of passwords UCAR staff need to remember.

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.

‹ Formalize and enhance UCAR’s cybersecurity capabilities | up | Host NCAR/UCAR computers at MLCF ›

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HOST NCAR/UCAR COMPUTERS AT MLCF

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. To achieve energy and other efficiencies, CISL is consolidating computer

rooms across the organization. CISL along with UCAR Facilities Management, Safety, and Sustainability (FMS&S) has a comprehensive plan to refurbish and operate the MLCF as a centralized co-location facility for the growing numbers of smaller-scale systems deployed across NCAR, UCAR, and member universities. CISL expects this effort to require about three years.

The MLCF continues to be a key part of the CISL cyberinfrastructure strategy. Critical data sets and data services are replicated between NWSC and MLCF, providing a robust infrastructure to ensure our stewardship of important data sets. For NCAR more broadly, the MLCF hosts systems for key scientific programs and applications. Finally, the strategy to refurbish MLCF allows UCAR to phase out support for multiple smaller facilities and enhance the energy efficiency of the organization, reduce costs, and maintain responsible environmental stewardship.

CISL and FMS&S completed cost estimation, phasing, construction documents, and specifications for the MLCF in FY2016. CISL and FMS&S are now in the initial proposal phase soliciting proposals from general contractors for phase one construction.

CISL worked with FMS&S to install a modern Uninterruptible Power Supply (UPS) system that is right-sized for the MLCF. The new UPS system utilizes new Energy Saver System (ESS) technology that improves the facility’s UPS efficiency to 98% (from 85% in the older system), and eliminates nearly all of the electrical losses common with older UPS technology.

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

‹ Deliver modern IT infrastructure, services, and platforms up Lead and participate in the CI community ›

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LEAD AND PARTICIPATE IN THE CI COMMUNITY

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.

CISL's strategy is to engage the community in numerous activities to advance high performance computing (HPC), data storage, and networking technologies, and to improve regional, national, and international cyberinfrastructure. These activities are aligned with NCAR's leadership role as a Federally Funded Research and Development Center (FFRDC).

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.

‹ Host NCAR/UCAR computers at MLCF up Lead regional CI engagements ›

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LEAD REGIONAL CI ENGAGEMENTS

CISL will actively initiate and lead networking partnerships and collaborations and engage in regional HPC activities such as the Wyoming-NCAR Alliance, the Rocky Mountain Advanced Computing Consortium (RMACC), and the Pacific Research Platform. In networking technology, CISL will provide the technical leadership for operating several regional networks

The participants in the first Women In Networking at SC (WINS) discuss a diagram of the network on display at SC15. The networking equipment they helped install and operate appears behind the clear panels at the SCinet installation in the exhibit hall.

that are tightly integrated with national networks. Examples include the Front Range GigaPop (FRGP) and the Bi-State Optical Network (BiSON).

CISL's strategy is to engage the community in numerous activities to advance high performance computing (HPC), data storage, and networking technologies, and to improve regional, national, and international cyberinfrastructure (CI). NCAR's CI partnership strategy is to engage research CI communities in activities that complement NCAR's goals and mission, that broadly advance HPC, data storage, and networking technologies, and that improve regional, national, and international CI. All of these activities are aligned with NCAR's leadership role as a Federally Funded Research and Development Center. Further, this work also addresses CISL's imperative to broaden participation in technology, education, and applied research.

Information technology is a fast-paced business, driven by exponential growth in the capabilities of the underlying technologies, so it requires an agile approach to the partnerships surrounding it. Consequently, partnerships in computational science and technology at NCAR have typically grown up from the challenges created by emerging, disruptive technologies. Two key components of NCAR's partnership development strategy are technology tracking and applied research. The former activity alerts the lab to emerging challenges, while the latter enables the lab to exploit them as opportunities. Knowledge gained from both serves as a guide to help direct and prioritize CISL's research and development partnerships and to realize its goals in operational systems.

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 support 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, the Colorado Department of Transportation (CDOT), and the National Research and Educational Networks (RENs) consortium named The Quilt. These collaborations and networks are all designed to provide NCAR/UCAR and other regional institutions 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, supercomputing environment, and its 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 FY2016, CISL concluded its collaboration with the University of Colorado at Boulder and the University of Colorado at Denver on a Major Research Instrumentation project that brought Janus, a 184-TFLOPS supercomputer to the CU Boulder campus. In addition, the Colorado School of Mines (CSM) moved its IBM supercomputer named “BlueM” out of the Mesa Lab Computing Facility, as part of preparations for upgrading the Mesa Lab Data Center (MLDC).

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 provided in Explore many-core and accelerator-based architectures.

Rocky Mountain Advanced Computing Consortium

The Rocky Mountain Advanced Computing Consortium (RMACC) is a collaboration among academic and research institutions located throughout the intermountain states. Its mission is to facilitate widespread effective use of regional high performance computing. In FY2016 CISL continued its participation in RMACC, collaborating in areas such as education, outreach, training, and HPC research. Each year RMACC holds an HPC Symposium that provides opportunities for professional development via scientific and technical presentations and training lectures. CISL helps organize and plan the Symposium. RMACC also showcases student research through a student poster competition at the symposium. CISL's SIParCS students did very well again, winning three out of the top four posters recognized by RMACC. The RMACC community also considers other collaborative measures to benefit the regional development of HPC, such as writing joint infrastructure proposals and having a Consortium booth at the IEEE Supercomputing Conference.

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 (RMCMOA).” 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, CI, and 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 Colorado, New Mexico, Idaho, Utah, and Wyoming.

During the two-year award term, the project team conducted four regional workshops for smaller institutions. The workshops 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 were held in FY2015. The third, held in January 2016 at the University of Arizona in conjunction with Westnet and the Westnet CIO Meetings, focused on lessons learned in previous NSF CC* awards and goals from NSF for future CC* solicitations especially for small schools. The fourth and final workshop was held in conjunction with the RMACC Symposium in August 2016 at the Colorado State University in Fort Collins. This workshop focused on strategies for engaging researchers and current network performance and troubleshooting techniques. A formal Lawrence Berkeley National Laboratory (LBNL) Cooperative Institute for Research in the Atmosphere Requirements Review was produced as an example of the researcher engagement process and results.

The team consulted 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. CISL has also collaborated through the RMCMOA grant, with the other five regional awardees in The Quilt including presentations on the effort at Internet2, NSF PI, and Quilt Meetings.

CISL also submitted and was awarded a supplement to the RMCMOA 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 received funding to participate in the 2015 Supercomputing Conference (SC15 was held in FY2016) while gaining valuable hands-on training in building one of the world's premier IT networks.

The five awardees worked directly with the volunteer workforce that builds and operates the dedicated high-performance research network known as SCinet. It comes to life for the duration of the Supercomputing Conference 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.

The RMCMOA grant has received a No Cost Extension to 2/28/17, which will allow three WINS SC15 awardees to return to participate in SCinet and SC16 and will allow RMCMOA participants to return to the January 2017 Westnet CIO and Westnet meetings.

Women in Networking at SC

The University Corporation for Atmospheric Research (UCAR) and The Keystone Initiative for Network Based Education and Research (KINBER) together with the Department of Energy's (DOE) Energy Science Network (ESnet) received a three-year

grant from NSF to continue the successful WINS pilot program. Aimed at increasing hands-on training opportunities for women in the Information Technology, the team has created the Women in Networking at SC (WINS) program. Funded through a grant from the National Science Foundation (NSF) and directly from DOE, the 2016 program funds eight early-to-mid-career women in the research and education (R&E) network community to participate in the setup, build, and live operation of SCinet, SC's ultra-high-performance network that supports large-scale computing demonstrations. SC is considered the premier U.S. conference on HPC, networking, data storage, and data analysis and is attended by over 10,000 of the leading minds in these areas of research.

Marla Meehl and Jason Zurawski (on left) and Mary Hester (far right) were instrumental in making the WINS program possible. Here, they visit the new NCAR booth at SC15 with the five WINS recipients: from left, Sana Bellamine, Kathy West, Amy Liebowitz, Debbie Fligor, and Megan Sorensen.

Internet2 Gender Diversity Initiative

Internet2 began the Gender Diversity Initiative (GDI) in 2013 as a community-driven effort to increase diversity in advanced networking community at all stages of professional development, because I2 believes that a more diverse and inclusive community is a stronger one and will generate better solutions, tools, and results for the many people we serve around the world. Marla Meehl from NETS has co-chaired the GDI Steering Committee since its inception with Laurie Burns McRobbie from Indiana University. At each Internet2 Global Summit and Technology Exchange, the Diversity Steering group of the Gender Diversity Initiative chooses one or more awardees to attend the meeting. The Goals of Gender Diversity Initiative are to:

- Provide a national forum for discussion and sharing of best practices in improving gender diversity in technical fields, particularly advanced networking.
- Explore and support specific projects that have application to the membership community at large.
- Partner with other national organizations engaged in similar work, such as the National Center for Women in Technology (NCWIT), Society of Women Engineers (SWE), and other organizations with a national scope.
- Communicate regularly to the membership and the public on effective approaches and progress toward improved diversity.

Funding

CISL’s work in this area is supported by NSF Core funding, NSF MRI grant CNS-0821794, NSF ACI 1440642, NSF ACI 1640987, and UCAR non-federal funds. UCAR Indirect funds supported the operating costs of the colocated BlueM computer

system.

‹ Lead and participate in the CI community up Lead national CI engagements ›

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LEAD NATIONAL CI ENGAGEMENTS

CISL makes significant contributions to U.S. cyberinfrastructure and maintains a strong presence in national CI development projects, including both HPC and networking. Working with national entities broadens NCAR's impact by fostering the maturation of national HPC CI, leveraging national resources and partnerships to tackle

national problems, and this work is a natural and mutually beneficial component of a national center's role.

The CISL exhibit booth at the SC15 conference in Austin, Texas.

XSEDE program and Service Provider Forum

In FY2016, the NSF's eXtreme Science and Engineering Discovery Environment (XSEDE) successfully proposed and was continued with a second five-year award. As part of the new award, NCAR expanded its participation in XSEDE by increasing its participation in XSEDE's Extended Collaborative Support Service. CISL's David Hart took on the role of director for XSEDE's newly formed Resource Allocations Service.

CISL continues to be engaged as an active member of the XSEDE Service Provider (SP) Forum as a Level 2 SP. NCAR integrates its networking, data transfer, and science gateway services at the NCAR-Wyoming Supercomputing Center (NWSC) with the XSEDE environment. NCAR provided a 10-Gbps networking link to XSEDEnet through June 2016, supporting high-performance access to the 16-PB GLADE file system for users having both NCAR and XSEDE accounts. XSEDE network access is now provided via Internet2.

NCAR remains active in coordinating training, education, and outreach goals with other XSEDE SPs. CISL's VAPOR team, for example, contributed a VAPOR training course for XSEDE users in FY2016. CISL staff also attended and contributed as part of the program committee for the XSEDE16 annual conference in Miami. Hart has also been designated the general chair for the 2017 conference, preparations for which began in FY2016.

National networking projects

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.

UCAR is a collaborator on the recently funded Pacific Research Platform (PRP). A series of ultra-high-speed fiber-optic cables will weave together a cluster of West Coast university laboratories and supercomputer centers as part of a five-year, $5 million dollar grant from NSF. The network is meant to keep pace with the vast acceleration of data collection in fields such as physics, astronomy, and genetics. The PRP 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. UCAR has installed a PRP FIONA node at the NWSC and is working with climate scientists to utilize the data node.

CISL's involvement with national networking consortia also includes Internet2, NOAA's science network NWAVE, and the Department of Energy (DOE) Energy Science Network (ESnet). These are the premier U.S. 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.

ACM/IEEE Supercomputing conference participation

CISL is 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 also participates each year at the Supercomputing Student Job Fair, 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, the fastest and most innovative computer network in the world; at SC15, SCinet delivered more than 1.6 terabits (or trillion bits) per second of network bandwidth to exhibitor booths, allowing them to demonstrate the latest HPC-enabled research – from genomic analyses to multi-gigabit simulations.

Other initiatives

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.

CISL staff members also 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. Many of CISL's national leadership activities are funded by NSF Core funds. XSEDE is funded through a five-year grant from the NSF Advanced Cyberinfrastructure division.

‹ Lead regional CI engagements | up | Lead international CI activities ›

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2016 CISL ANNUAL REPORT

- CISL Director's Message
- Advance Earth System science through HPC and data services
  - Acquire, deploy, and maintain CI resources
  - Provide support services to all users of CISL resources
  - Sustain and enhance the NWSC
  - Provide the community with Big Data services
  - Advance enterprise IT at NCAR and UCAR
  - Lead and participate in the CI community
    - Lead regional CI engagements
    - Lead national CI engagements
    - Lead international CI activities
    - Partner with vendors to provide technology for NCAR science
- Improve mathematical and computational methods for Earth System models
- Reach out to new generations of scientists through education

2016 NCAR ANNUAL REPORT

LEAD INTERNATIONAL CI ACTIVITIES

CISL 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.

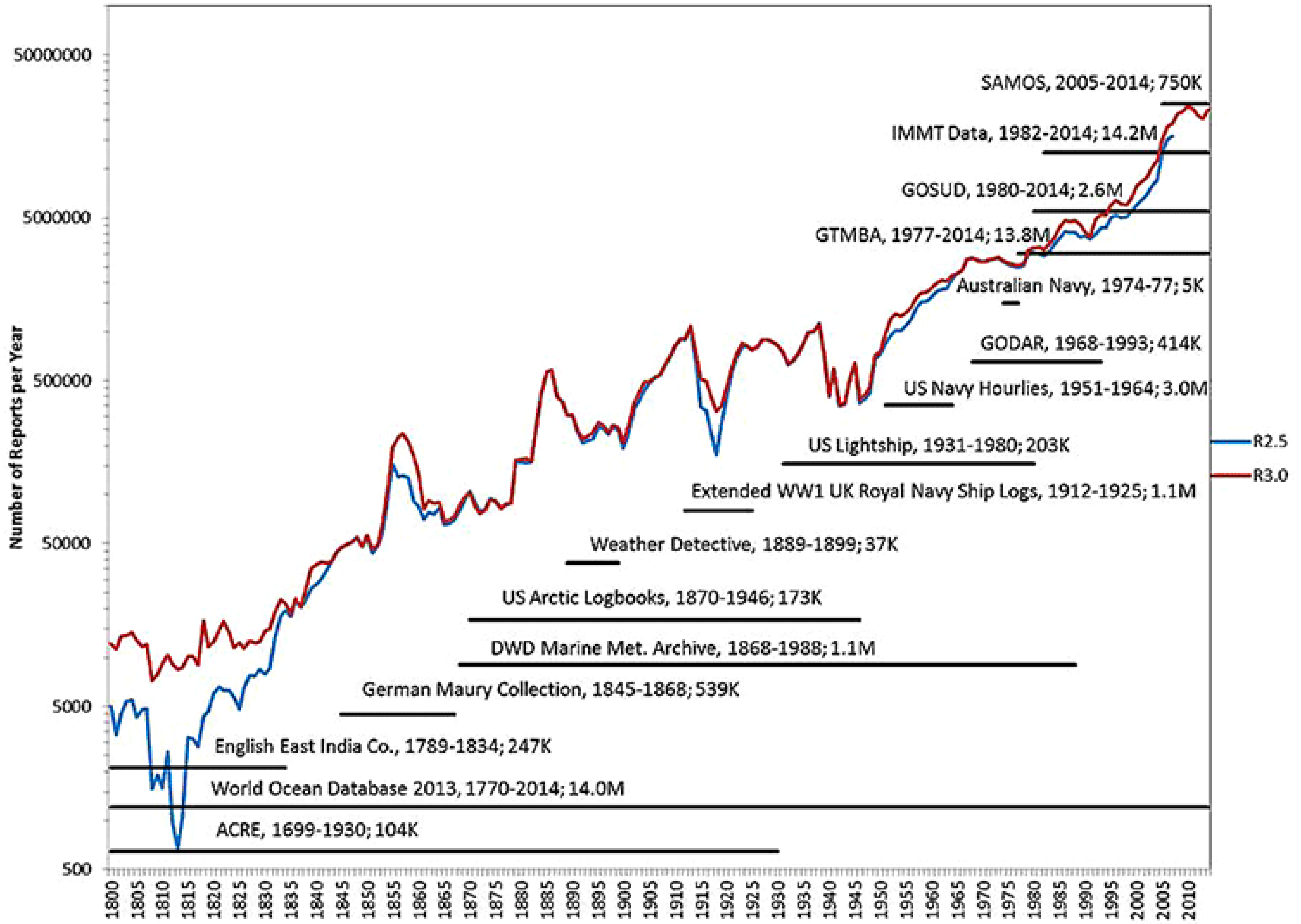
CISL shares its strong technical competencies in supporting international developments, advisory functions, best practices,

capacity building, and research projects. CISL provides technical leadership to international activities such as the WMO's Global Information System (WIS), engages in formal data exchanges and data provisioning agreements with international peer centers in supercomputing, climate, and weather, and with international projects such as the Earth System Grid Federation, provides software to a worldwide community, and hosts international meetings focused on advancing climate, weather, and computing research.

CISL's partnership strategy is to engage research CI communities in activities that complement its goals and mission, that broadly advance high performance computing (HPC), data storage, and networking technologies, and that improve international CI. The bi-directional sharing aligns with NCAR's leadership role as a Federally Funded Research and Development Center (FFRDC), keeps the organization in a world leadership position, and impacts international achievements through collaboration with peer groups.

Research Data Archive

There are several noteworthy formal international data exchange agreements associated with 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. Having the data directly available to the HPC environment makes it efficient for our community to use these high-volume resources. CISL reciprocates by preparing observational datasets and delivering them to support future reanalysis efforts, e.g., the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). Overall, the RDA is an internationally recognized source for over 10 reanalysis collections, all at the highest resolutions available.



Major historical digitized and external archive data sources were added to ICOADS Release 3.0, for 1800-2014. Horizontal black lines illustrate the time ranges of the original data sources, which are also shown in the source label along with the number of reports. The annual numbers of reports are plotted as curves, blue for the previous Release 2.5 (extended by NCEP NRT data for 2008-14), and red for Release 3.0. Data coverage prior to 1800 is sparse, and that following 2007 continues to grow annually.

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. CISL is a primary partner in the ACADIS effort which provides data management support for NSF-sponsored Arctic research including Arctic Observing Network (AON) data for the International Polar Year (IPY). This significant data repository, representing over 3,800 irreplaceable datasets, was successfully transitioned to NCEAS management this year. 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.

Data analysis and visualization tools

CISL's data analysis and visualization tools (e.g., NCL, PyNGL, and VAPOR) are widely used in centers and universities

around the world. CISL continued leading an ongoing collaborative research agreement with the Korean Institute for Science and Technology Information (KISTI) to enhance CISL's open source VAPOR package. In collaboration with KISTI, a number of new analysis capabilities were added to the VAPOR package, including integration with the Python Matplotlib module; support for basic statistics; and support for visualizing data generated by the FVCOM ocean model. One KISTI scientist accomplished the latter during a two-month summer visit to NCAR.

CISL released a beta version of NCL with numerous specialized functions for addressing the effects of heat waves, droughts and evapotranspiration on humans and agriculture. NCL and Python efforts were closely integrated through the alpha release of a new WRF Python analysis module, beta releases of both PyNGL and PyNIO, and the distribution of all software under the Conda package manager. NCL training was expanded to include various Python modules, reaching over 150 students in various workshops, short courses, and tutorials.

Intel Parallel Computing Center for Weather and Climate Simulation

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 it relied heavily on NCAR staff for technical support of the project.

Fortran standards

CISL participates in International Standards (ISO) activities to contribute to the development of the Fortran programming language. A CISL staff member serves as chair of the U.S. Fortran Committee. This participation allows programmers at NCAR to track and influence Fortran's development. With NCAR models facing future HPC resources with 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 hosted the joint meeting of the international and U.S. Fortran committees at the Mesa Lab in June 2016.

International Computing in Atmospheric Sciences workshop

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. The next iCAS meeting will held again in 2017, and planning was begun in FY2106. 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.

World Meteorological Organization Information System

CISL contributes to developing the World Meteorological Organization (WMO) Information System (WIS). Under the auspices of the United Nations, the WMO is designing, developing, and deploying WIS as a next-generation globally federated information system for weather, climate, hydrology, oceanography, and many other disciplines. CISL is involved in the management and technical direction of WIS and has contributed ideas, strategies, and services developed through our work with CDP, ESG, and ACADIS.

Funding

RDA activities are 100% Core funded. The collaborative research agreement with KISTI is funded 80% by KISTI, with 20% of its support from NSF Core funding. ESG, CDP, and NCL activities are 100% Core funded. ACADIS is funded 100% by NSF Special funds. WMO activities are 100% Core funded.

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PARTNER WITH VENDORS TO PROVIDE TECHNOLOGY FOR NCAR SCIENCE

CISL maintains close contacts with High Performance Computing (HPC), networking, and related vendors as a way of providing information to them regarding the computational requirements of the Earth System sciences and to track technology. To this end, CISL maintains 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 occasionally makes sole-source purchases or receives loaner equipment or software products from vendors for evaluation and testing purposes under these agreements.

CISL's HPC Futures Lab is an important facility that houses much of this equipment, thus enabling CISL to efficiently manage the complex task of keeping abreast of technological developments and innovations. Many of these relationships with vendors go deeper, developing into partnerships with shared R&D goals and benefits. More details appear in the Research and technical collaborations section of this annual report.

These activities are supported with NSF Core funds.

‹ Lead international CI activities up Improve mathematical and computational methods for Earth System models ›

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STRATEGIC PLANS

CISL Strategic Plan

NCAR Strategic Plan

PREVIOUS CISL REPORTS

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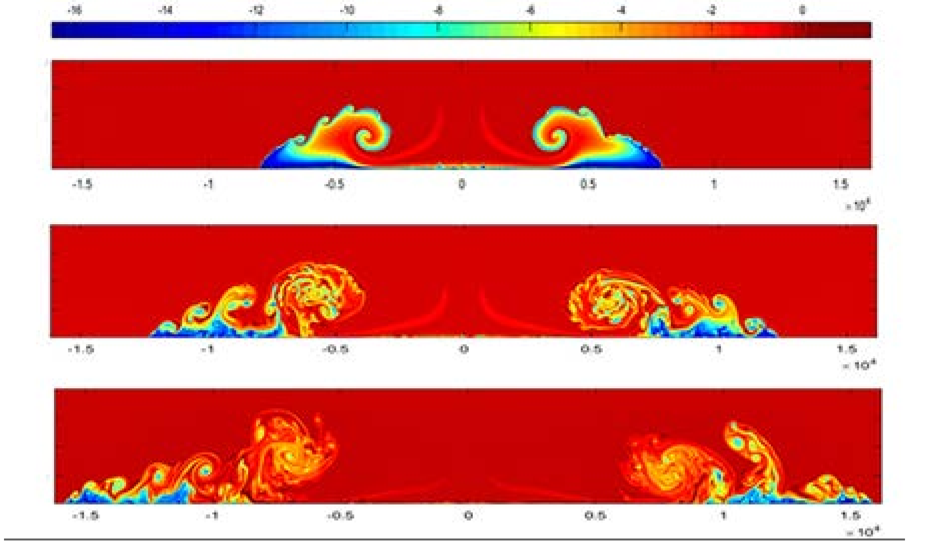
IMPROVE MATHEMATICAL AND COMPUTATIONAL METHODS FOR EARTH SYSTEM MODELS

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.

Guided by the NCAR strategic plan, CISL research improves predictions of weather and climate and estimations of their



This simulation of atmospheric flow at a high resolution shows the time evolution of the potential temperature of a traveling cold density current along the ground. The two-dimensional Navier-Stokes equations were solved at 25-meter resolution in the turbulent regime, with the viscosity being that of air at 15 degrees C. An algorithm for solving this test case was developed in CISL and uses radial basis functions (RBFs) to generate accurate and

impacts. CISL tackles the challenges of developing new data-centric approaches, combining numerical models with observations, interpreting heterogeneous data, and quantifying the uncertainty in predictions in ways that are useful for decision making and policy. CISL also adapts scientific computing in innovative ways like accelerating computation through new algorithms and exploiting new technologies such as coprocessors. This basic computational and data science research supports NCAR's first strategic imperative, and it also benefits the community model development central to NCAR's Imperative 3. Finally, CISL research on the use of new architectures and technologies plays a central role in NCAR's Strategic Imperative 4, developing new computational resources.

compuationally efficient discretizions of the deriviative operators. This research advances NCAR's modeling capabilities for resolving small-scale convection relevant to severe storm prediction.

The goal of CISL's research activities is to sustain progress in the Earth System sciences by combining powerful supercomputing resources with the latest computational science research in algorithms, mathematical techniques, and statistical methods. CISL helps produce significant and transformative impacts on geoscience by aligning its computational resources with the research objectives of NCAR's other laboratories and the requirements of data-centric science.

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

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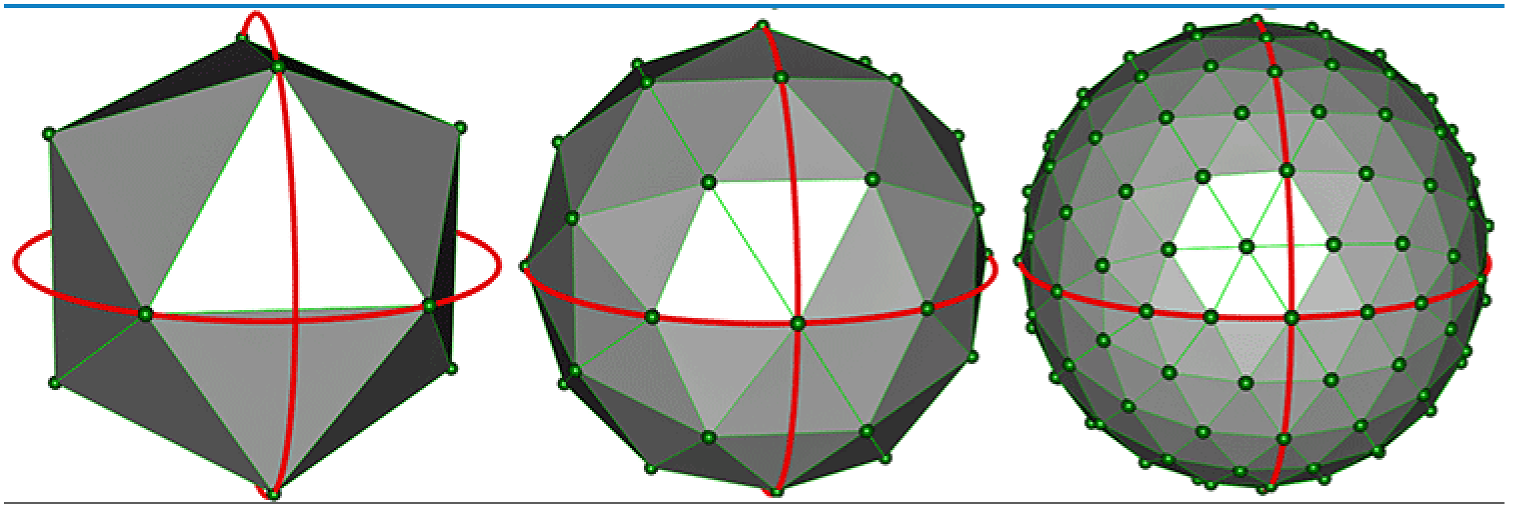
ADVANCE DATA-CENTRIC RESEARCH

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 large numerical experiments and to interpreting the wide range of small but vital historical data sets that document past climate and important geophysical processes. Also of note are the massive data archives from remotely sensed and *in situ* instruments.

Accordingly, CISL takes a broad view of data including: traditional observations from instruments, outputs from models,

and derived "data products" from analyses. In the past, HPC in the geosciences has focused on modeling. CISL research also focuses on how data transformation and data analysis also benefit from HPC resources.



This graphic shows three levels from a multi-resolution node distribution for the sphere to be used for fitting remotely sensed CO_2. The first three levels of nodes (green points) are used for a spatial statistics model on the sphere and a companion spatial analysis. This research represents the interplay, common in CISL, of developing new algorithms that exploit computational resources, address the specific needs of geophysical research, and are widely disseminated to the community as open source software. This green points locate the centers of basis functions that can represent global fields and global data sets in a way that preserves spherical geometry. For reference, the equator and prime meridian (red) are located on each plot, and the shaded triangles indicate how the different levels are related by subdividing each triangular face into four smaller triangles with three new points. The basis functions in this model consist of bump-shaped functions centered on these node points and are *zero* beyond a certain range. As the number of levels increases, more complex structure for a field on the sphere can be represented, and the LatticeKrig spatial method is based on this scheme for assigning node points. This approach is efficient for interpolating and smoothing data because it takes advantage of sparse matrix algebra throughout its computations. Preliminary timing results for the sphere suggests that for 10,000 observations, it can provide a factor of 10 or more speedup over standard 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. All of these areas require the additional research of developing algorithms and workflows that scale to the large parallel computational architectures available to the geosciences.

In general the need for innovative data analysis tools – especially for larger data volumes (e.g. Big Data) – is an implicit theme underlying nearly all of NCAR's strategic imperatives.

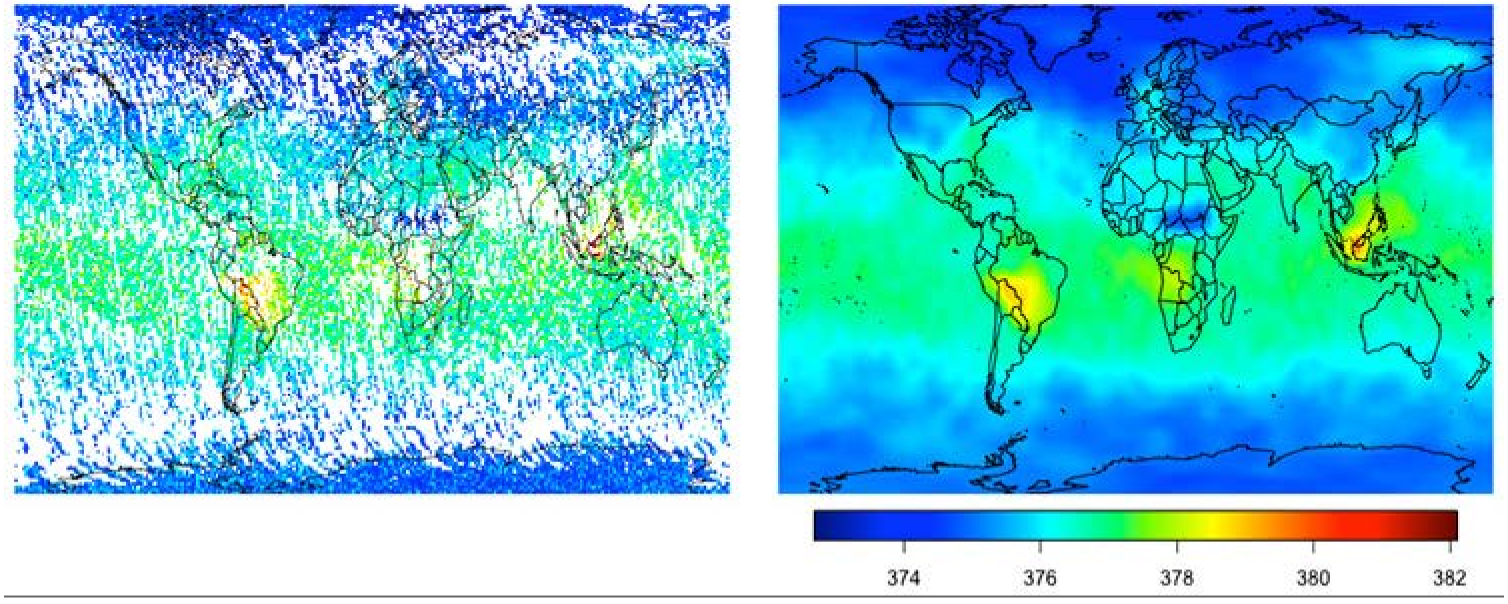
Specifically, however, this data science research supports NCAR's first strategic imperative as it relates to basic research in *data science* and also to the fourth subsection of Impertive 4. Both of these imperatives relate to the challenge of tailoring data methods to meet the unique needs of the geosciences community. This research also fits into the community model development that is central to NCAR's Imperative 3. This activity has the important role of confronting models with observations and fashioning data products that use the best statistical methods for model validation and diagnostics.

Finally, we note that providing the best data tools for analysis, efficient work flow, and data reduction is aligned with the goals of Imperative 4.

Some highlights for data science research during this period include:

- The Data Assimilation Research Testbed has been improved to be more scalable in terms of memory. This allows for ensemble data assimilation for models with larger state vectors and is important to address assimilation for higher-resolution versions of weather models such as WRF and MPAS, and for coupled climate models such as CESM.
- The basic statistical computations needed for analyzing spatial data has been optmized to use multiple GPUs and processors. This parallelization can give a factor of 70 speedup for critical computational steps, and it supports a useful increase the size of data sets that can be analyzed using standard methods.
- A parallel algorithm has been devised to address the statistical computations for finding signals of climate change in observational data. A novel feature of this work is to remove some of the arbitrariness of deciding how many basis functions (i.e., empirical orthogonal functions) are used to represent the climate signal.
- Initial experiments have been completed as part the North American portion of the Co-ordinated Regional Climate Downscaling Experiment (NA-CORDEX). Runs exploring the robustness to different regional resolutions (25 km versus 50 km) suggest that the differences in the 50-km simulations driven by the two different global models are as great as the differences between the resolutions when a regional model (RegCM4) was driven by the MPI global model. This kind of factorial-designed experiment helps to set ranges on the uncertainty of regional climate projections based on a multi-model ensemble.

Funding for these projects and related research is listed in each of the following sections.



These two figures show the raw CO_2 observations (left) typically of a remotely sensed data product and the estimated complete surface (right) using a spatial method based on the LatticeKrig model. Approximately 32,000 observations and 13,000 basis functions at four levels of resolution (3–6) are used in the statistical model.

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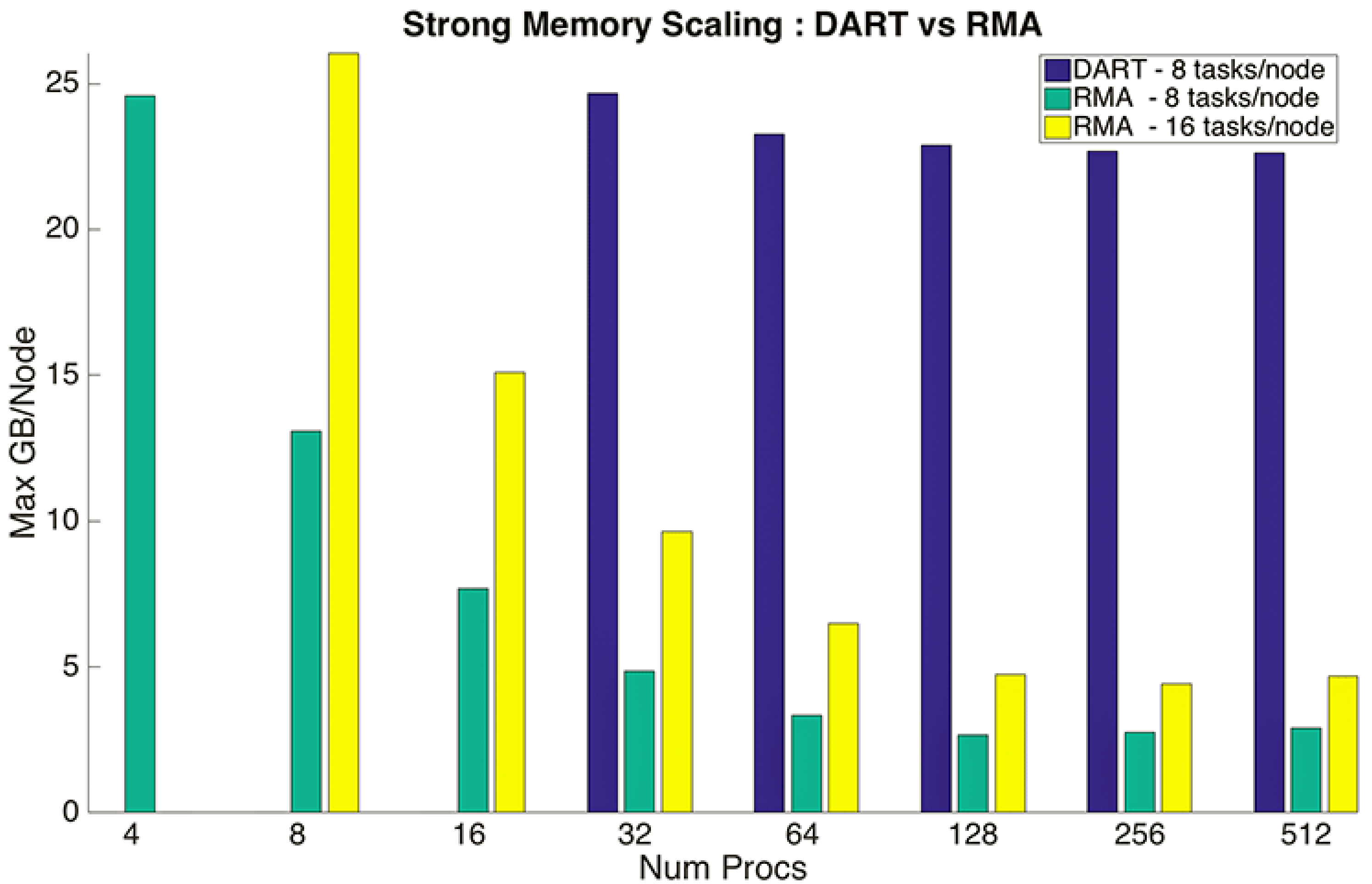
ADVANCE DATA ASSIMILATION SCIENCE

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.

DART provides ensemble data assimilation (DA) tools that use state-of-the-art statistical methods for combining model forecasts with observations to produce initial conditions for forecasts along with estimates of uncertainty. DART tools can also diagnose and improve both models and observing systems. The use of ensembles of forecasts means that DART applications are among the largest and most computing intensive in the geosciences, so effective use of supercomputing facilities using advanced scalable algorithms is essential. All of these aspects of DART are key to meeting CISL's strategic goal to "Enhance the effective use of current and future computational systems by improving mathematical and computational methods for Earth System models and related observations" and in particular the imperative to "advance data-centric research."



This chart shows the total amount of memory required on a Yellowstone node to run DART with a 50-member ensemble for a WRF model that has 184 million model-state variables. The default version of DART can only be run with 8 processes per node because of its large memory footprint. The new version has good memory scalability with the amount of memory decreasing as the number of processes increases, and allows more efficient use of Yellowstone since 16 processes can be run on each compute node. This allows DART to work with much larger models while using computing more efficiently.

Work to develop a memory-scalable version of DART has continued, and this includes exploring the impact of distributing model metadata across processors. Nine large models including CESM components, WRF, and MPAS have now been converted to work with the new DART version. Improved efficiency for DART with CESM models is being developed in collaboration with CGD by avoiding redundant initialization for ensemble forecasts using the CESM coupler. In addition, a more efficient version of DART for coupled CAM/POP data assimilation has been completed and is being tested by CGD scientists. New forward operators and improved methods of assimilating satellite retrieval profiles of chemical constituents have been developed and tested in collaboration with ACOM. With help from MMM, a version of DART that replicates the

capabilities of the NOAA operational ensemble Kalman filter with WRF has been completed and used to understand differences between the capabilities of the two systems for operational predictiton. New algorithms for explicitly estimating correlated observational errors have been developed in collaboration with RAL, and this led to significant improvement when assimilating surface observations and satellite radiances in idealized tests. A novel DA methodology, pseudo-orbit DA was implemented in DART in collaboration with the University of Chicago and Oxford University and is being tested with idealized models.

Data assimilation research in IMAGe is supported by NSF Core funding plus Grant 16-013 from the University of New Hampshire's Open Geospace General Circulation Model program, Grant N0014-15-1-2300 (subaward A15-0093-S001-P0567931) from the DOD Office of Naval Research's National Oceanographic Partnership Program, and Grants OCE149559 and OCE1243015 from the National Science Foundation program Decadal and Regional Climate Prediction using Earth System Models.

‹ Advance data-centric research up Develop statistical methods to interpret data and improve models ›

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DEVELOP STATISTICAL METHODS TO INTERPRET DATA AND IMPROVE MODELS

Traditional tools for data analysis in the geosciences are effective for homogeneous data sets and summarizing unambiguous features. They tend to break, however, when applied to combine sparse and heterogeneous observations or to quantify the uncertainty in estimated features or in derived fields. Bayesian statistical models provide a framework to produce blended and gridded data products and also to attach uncertainty measures to the results. These tools from statistical science, however, must be adapted to handle the larger data volumes typical in geophysical problems.

This work fills a vital need to interpret geophysical data using contemporary statistical science and drawing on machine learning from computer science. The benefits include better insight into hidden features of large data volumes and improved interpretation through adding measures of uncertainty. It supports CISL's strategic goal to enhance the effective use of current and future computational systems. Specifically, this work strategically combines applied statistical science with supercomputing resources to sustain progress in the Earth System sciences.

The accomplishments described below are some of projects that have been advanced during this period, and they illustrate the diverse ways that data science is applied to NCAR's scientific problems.

Climate informatics

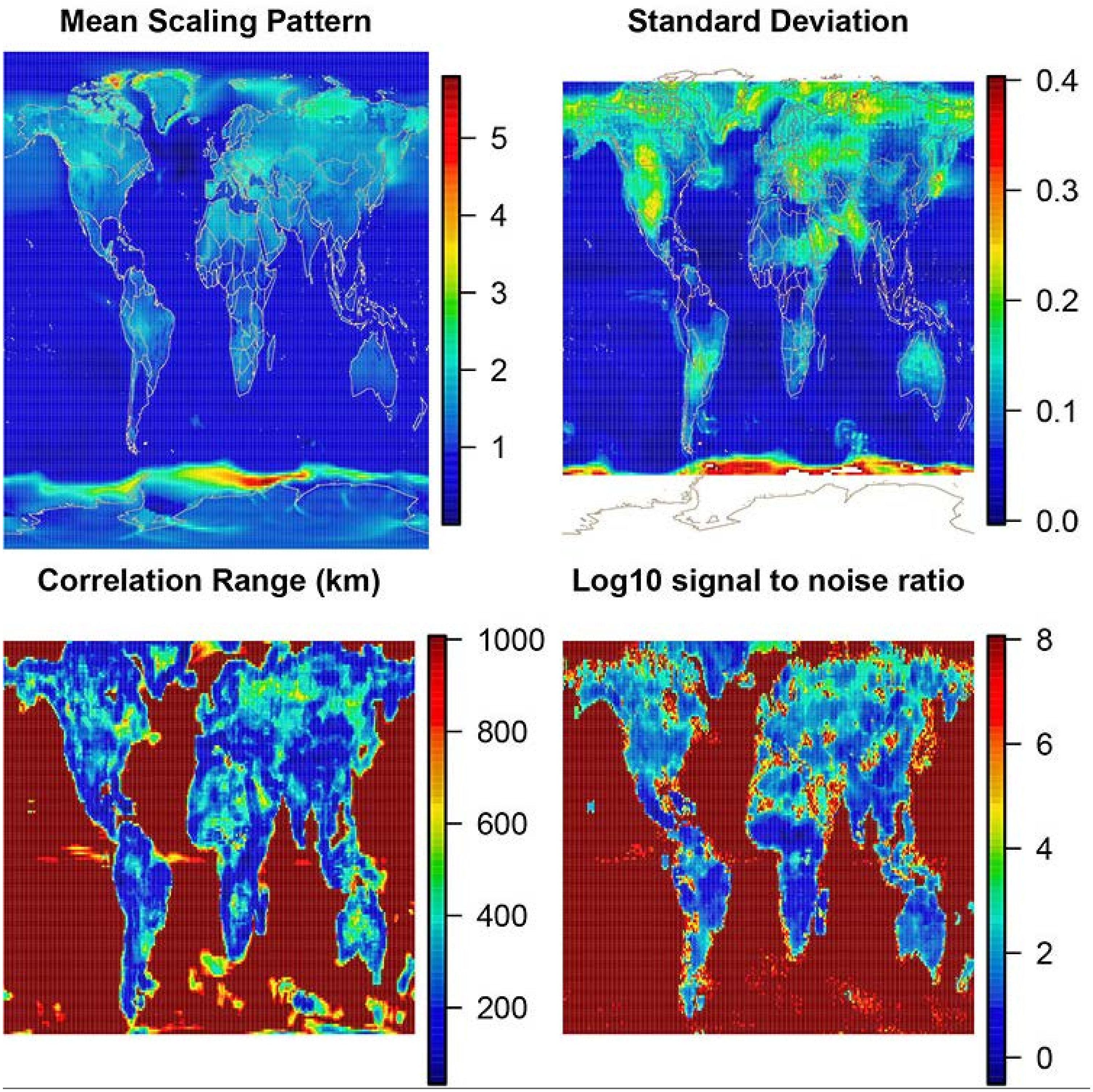
Causal discovery is an area of machine learning that identifies potential cause-effect relationships from data and is used to learn so-called causal signatures from data. It is applied to climate model simulations that indicate interactions between different geophysical variables. During FY2016 this approach was refined for distinguishing among climate model runs and provided a different measure than the usual comparisons based on mean climate fields. These techniques can also quantify the impact of data compression on the causal signatures to determine which type and amount of compression is acceptable.

Statistical methods for large spatial data

Kriging is a well-known method used in geostatistics to estimate how climate varies over a geographic region when the observational data is sparse or the computer model runs are limited. This research has resulted in spatial methods for large sample sizes using both new numerical algorithms that exploit sparse matrix methods (LatticeKrig) as well as approaches that use linear algebra libraries optimized for coprocessors such as GPUs. It also adapts the ideas of a multi-resolution representation to the distributed data constraints. This work produced 10x-100x computational speedups and makes spatial data analysis possible for geoscience problems that would have been intractable using traditional methods. During this period the LatticeKrig package was extended to include a spherical geometry to model spatial data of global extent.

Uncertainty quantification and statistical emulators

Applying data science techniques to the analysis of numerical models is useful where a complex geophysical model is expensive to run under many different inputs, but can be approximated with a statistical emulator. During this period an emulator method was successful in representing a wider range of climate model responses than the parent numerical model ensemble. Specifically, pattern scaling was used to extend surface temperature results of an NCAR/DOE CESM1 large initial-condition ensemble from a high-emissions scenario (RCP8.5) to a lower-emissions scenario (RCP4.5). Significantly, the emulation also reproduces the internal variability in the temperature fields along with uncertainty in the scaling pattern. The uncertainty in the scaling pattern itself is represented by a Gaussian random field where the covariance parameters can be estimated from the ensemble model output.

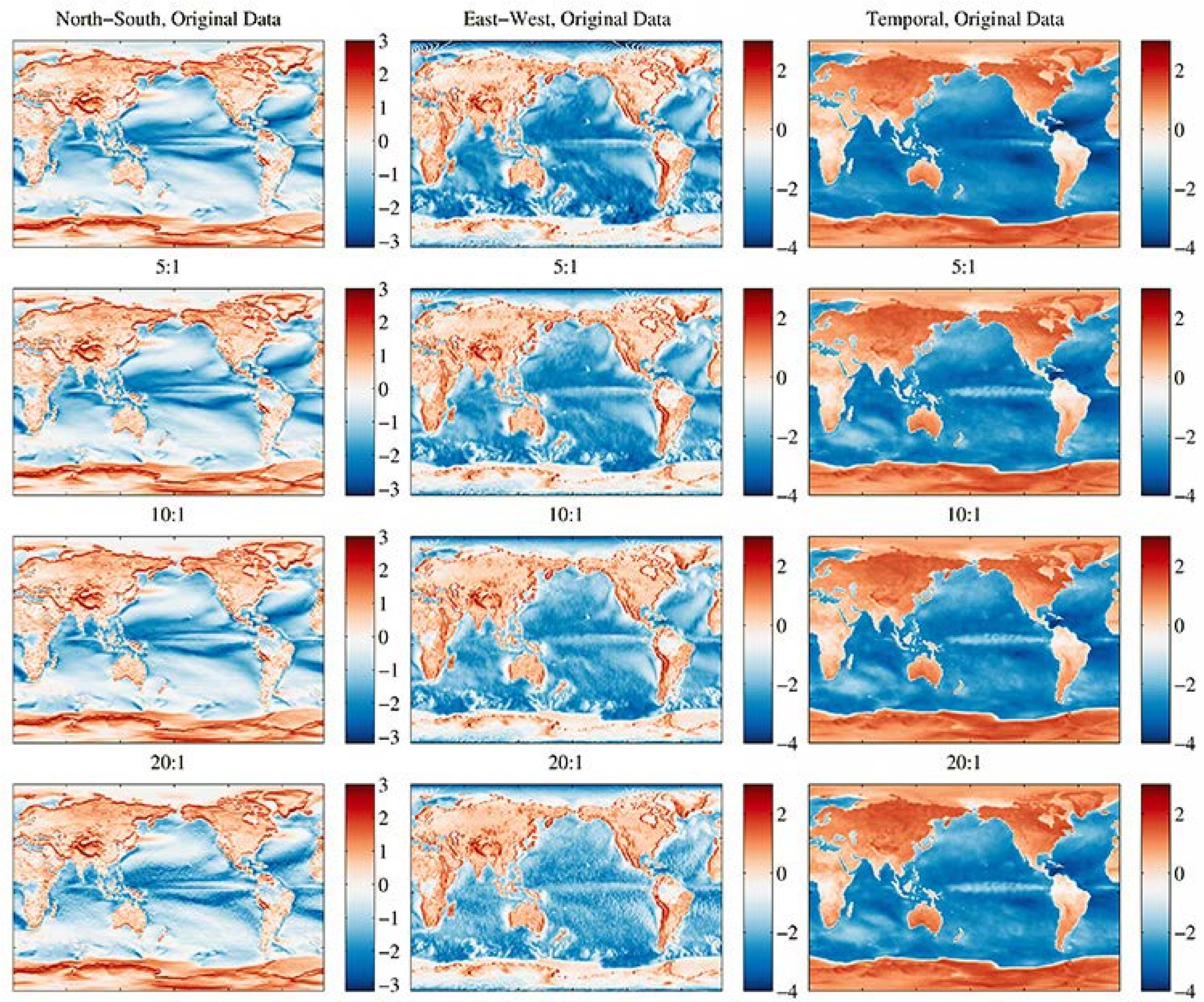


Estimated pattern scaling for surface temperature based on the CESM large ensemble. This panel of plots summarizes the results of estimating the local temperature response to a global temperature change and also quantifies the uncertainty in this estimate using a spatial statistics model (Matern Gaussian Process). This analysis is based on the CESM large ensemble (30 members) for RCP8.5 and at approximately 1 degree spatial resolution. The image plot in the upper left is the change in mean temperature (C) in each model grid box due to a one degree change in global mean temperature. Note that the changes are more over land and also increase for higher latitudes. The plot in the upper right is the expected standard deviation (C) in this pattern and reflects the variability in the mean pattern due to internal variability of the climate system as represented by the ensemble experiment. This variability was found to have some spatial coherence, and the plots in the lower left and right are the result of estimating a local spatial covariance function based on the Matern covariance with smoothness of 1.0. The correlation ranges indicate higher correlation in the pattern over the ocean and less over the land. Moreover the signal-to-noise variance shows that patterns over land also have a larger component that is uncorrelated over space. These distinctions are important in

simulating the variability in the pattern and are valuable for integrated assessment models (IAM). Based on this analysis, a much simpler climate model run could determine the global mean temperature under different scenarios of human activity, then use simulated pattern scaling fields to infer local changes in the mean temperature. This technique is much less costly in computer resources than running CESM for other scenarios and large ensembles.

Statistical compression of climate data

Numerical climate model simulations at high spatial and temporal resolutions generate massive quantities of data. As our computing capabilities continue to increase, storing all of the data is not sustainable, and thus it is important to develop methods for representing the full data sets by smaller, compressed versions. During FY2016 a statistical compression and decompression algorithm was developed based on storing a set of summary statistics as well as a statistical model describing the conditional distribution of the full data set given the summary statistics. This approach is distinct from more deterministic representations of the fields using conventional compression technology. The statistical model can be used to generate realizations representing the full data set, along with characterizations of the uncertainties in the generated data. Considerable attention is paid to accurately modeling the original data set, particularly with regard to the inherent spatial nonstationarity in global fields, and to determining the statistics to be stored, so that the variation in the original data can be closely captured. Moreover, the method allows for fast decompression using parallelization on HPC systems and conditional emulation on modest computers.



Effect of compression on log contrast variances in daily temperature fields. This figure illustrates the compression for daily surface temperature fields from one member of the CESM large ensemble experiment and for (model) year 2081. For each day, adjacent grid or time point values are differenced. The log variance of these differences across the year is reported. This is a stringent test of the compression veracity and measures how well local variability and spatial structure in the fields are preserved by the compression scheme. The first column shows average North-South log contrast variances, the middle column shows east-west log contrast variances, and third column shows one-step temporal contrast variances. The first row is computed from the original data, and the remaining rows represent compressions of 5:1, 10:1, and 20:1 respectively. Based on this metric, the spatial and temporal properties of the compressed data are almost indistinguishable from the original data, especially at the 5:1 level.

Funding

Research in the Geophysical Statistics Project is made possible through NSF Core funding and NSF DMS award 1406536.

‹ Advance data assimilation science | up | Develop data science techniques for regional climate change studies ›

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DEVELOP DATA SCIENCE TECHNIQUES FOR REGIONAL CLIMATE CHANGE STUDIES

A grand challenge for Earth System science is to translate the influence of global processes that affect our climate into specific regional and local impacts. The research in CISL combines knowledge of Earth System models, downscaling methods, scientific workflows for large data sets, statistics, and the needs and constraints of local stakeholders. This effort therefore integrates CISL expertise in data science and impact assessment with the goal of transferring climate science into useful products for decision making in adaptation research and risk analysis.

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, make them widely available to the broader research community, and 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.

RISC also develops and maintains the Weather and Climate Impacts Assessment Science Program (WCIASP) to investigate uncertainty in climate change research, study extreme weather and climate events, and support climate and health impacts workshops.

High-resolution research data for climate change studies

The Regional Integrated Science Collective (RISC) collaborates with public and private laboratories and universities to generate and evaluate regional-scale climate change scenarios using high-resolution regional climate models. Its goals are to:

- Combine global and regional climate models to project regional climate change over North America and analyze resultant uncertainty, particularly focusing on process-level analysis.
- Produce high-resolution, 150-year regional climate model simulations for North America.

CISL tackles the challenges of quantifying the uncertainty in predictions in ways that are useful for decision making and policy. This research supports CISL's strategic goal 2: "Enhance the effective use of current and future computational systems by improving mathematical and computational methods for Earth System models and related observations." It specifically fulfills CISL's strategic imperative 2.1 to advance data-centric research by developing and applying novel data science techniques for regional climate change studies using high-resolution research data sets.

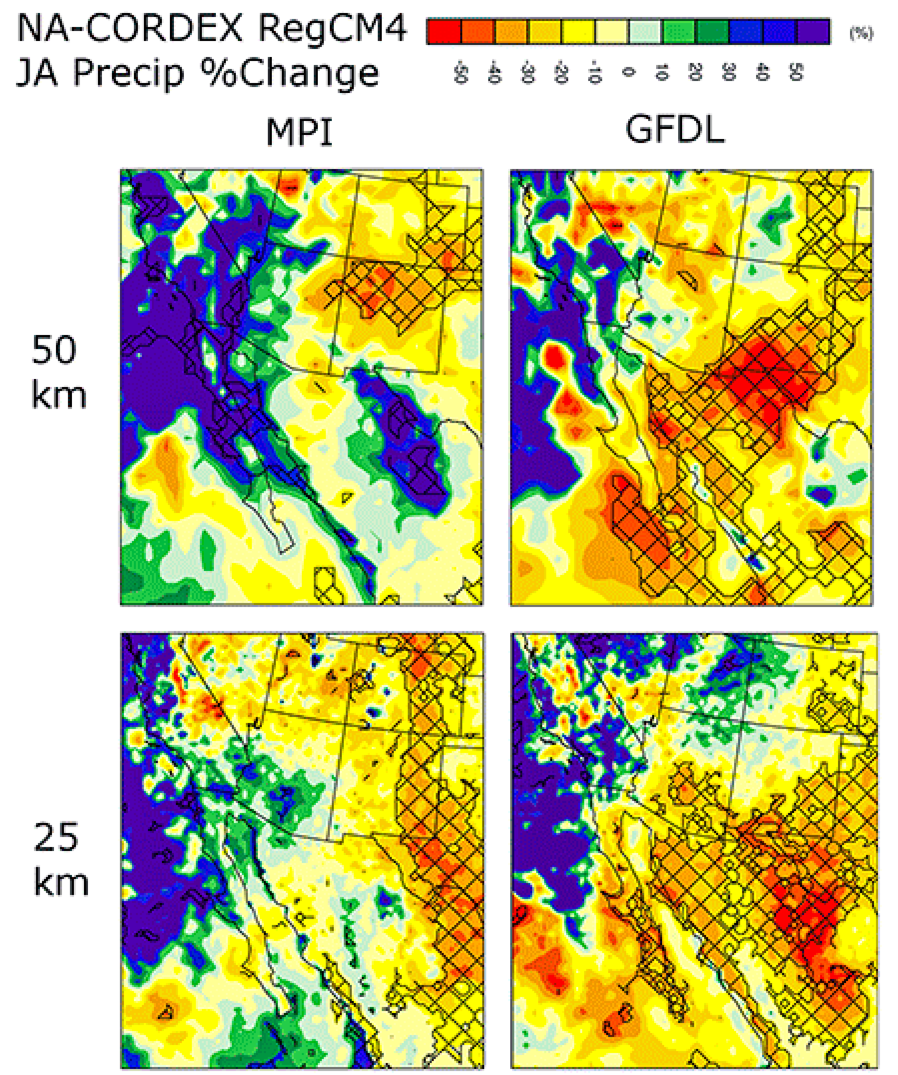
The research in RISC combines knowledge of Earth System models, downscaling methods, statistical techniques, and scientific workflows for large data sets with the needs and constraints of local stakeholders. This effort therefore integrates CISL expertise in data science and impact assessment with the goal of transferring climate science into useful products for decision making in adaptation research and risk analysis. Furthermore, guided by the NCAR strategic plan, CISL research improves predictions of weather and climate and estimations of their impacts.

NARCCAP and data products development for further analyses using NARCCAP: 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 has been 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 structure of the simulations is unique in its balanced design that allows for isolating the influence of individual regional and global models on the resultant climate simulations. The project also includes an evaluation arm whereby the participating RCMs were forced by reanalysis data sets. The resulting regional climate model runs and time slices formed the basis for multiple high-resolution climate scenarios that have been used in climate change impacts assessments in the U.S. and Canada. In

FY2016, work related to NARCCAP has entailed further development of data products, detailed analysis of the simulations, and application of the data to numerous adaptation contexts.

RISC's accomplishments in FY2016 include the development of a number of data products and services to support the users of NARCCAP data. These products 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 section 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.

Development of NA-CORDEX and preliminary analysis: The Co-ordinated Regional Climate Downscaling Experiment (CORDEX) has been ongoing for several years. It may be seen as an expansion of NARCCAP in the context of an international program. Regional models are driven by the more recent CMIP5 GCMS for a 150-year time period (through 2100), and the more recently developed representative concentration pathways (RCP) are used, including RCP8.5 and 4.5 The goal is to combine global and regional climate models to project regional climate change over North America and analyze resultant uncertainty, particularly focusing on process-level analysis.



These plots show the percent change in precipitation, future mid-21st century vs. current (1971-2000) period, from four simulations with the RegCM regional climate model. The upper left panel shows 50-km resolution driven by the MPI global model, the lower left panel shows the 25-km version. The upper right panel shows 50-km resolution driven by the GFDL model, and the lower right shows the 25-km version. Hatching indicates where the changes are statistically significant (at the 0.1 level). This image represents two types of uncertainty in future regional climate projections, based on different driving models and different simulation resolutions. Analyzing and comparing different types of uncertainty is important for more usefully and completely representing uncertainty in future climate.

Simulations continue to be performed even though North American CORDEX has been slow to advance through its schedule of simulations due to lack of sufficient funding from U.S. funding agencies. Linda Mearns of CISL and William Gutowski of Iowa State are NA-CORDEX co-chairs. In collaboration with Iowa State and the University of Arizona, simulations are being performed for a 150-year time period (1950-2100) over most of North America – approximately the same domain as NARCCAP – with two different regional climate models (RegCM4 and WRF), at two different spatial resolutions (50 km and 25 km) using ERA-Interim boundary conditions, and boundary conditions from three different GCMs that span the equilibrium climate sensitivity of the CMIP5 collection of global climate model simulations. An earlier version of RegCM (RegCM2) was NCAR's original regional climate model.

Specifically, in RISC, in addition to the RegCM simulations produced last year at 25 and 50 km using the Max Planck Institute (MPI) global model boundary conditions for the RCP 8.5 concentration pathway, M. Bukovsky has produced similar simulations using WRF driven by the GFDL-ESM2M global model. Preliminary simulations with WRF driven by the

HadGEM GCM have been produced, which will be completed in FY2017. When completed (including driving the RCMs by the HadGEM GCM) in early FY2017, a 2x2x3 matrix of simulations will be produced. Change in precipitation (current vs. mid-21st century) for the North American Monsoon region for the RegCM4 at the two different resolutions driven by the MPI and GFDL global models is presented in the figure above. Note that the different resolutions driven by the same GCM can result in different patterns of change, rather than producing the same pattern with greater detail in the higher-resolution case. The differences in the 50 km simulations driven by the two different global models are as great as the differences between the resolutions when RegCM4 was driven by the MPI global model. Other simulations have been produced by other groups, most notably in Canada using the Canadian regional climate model (CRCM5). The NA-CORDEX website lists all simulations being performed.

Archiving of NA-CORDEX data: Seth McGinnis and student assistant Daniel Korytina have made rapid progress in preparing and archiving subsets of NA-CORDEX data for all simulations completed so far. This includes archiving temperature and precipitation at multiple time scales (sub-daily to seasonal) for the entire NA-CORDEX domain. All data have been published.

Further development of simulation data bias correction for application to NARCCAP and NA-CORDEX data: 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 has broken 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. In FY2016, McGinnis improved on basic KDDM by refining the correction of extremes of daily temperature and precipitation. He evaluated the effect of bias correction using Kernel Density Distribution Mapping (KDDM) on extremes of precipitation and temperature. The KDDM methodology is effective at correcting the extremes of the data, and it produces better results than simply adjusting the mean and variance of the model outputs. In principle, it is possible to make additional small improvements to the correction of the tails using Extreme Value Theory, but in practice, this improvement is much smaller than the uncertainty associated with differences between the models, and does not in general warrant the extra effort involved. McGinnis is also developing an R package that implements the KDDM bias correction methodology. Application of KDDM to NA-CORDEX data will proceed in FY2017.

Process-level analysis of climate model results to determine the credibility of projections

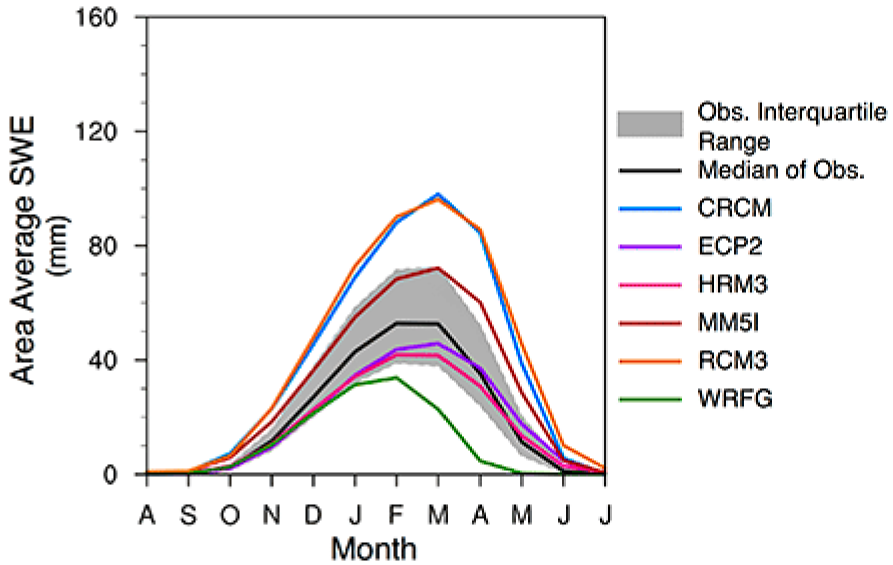
Using the data generated by RISC for RISC scientific projects leads to greater understanding of the strengths and limitations of the data, which can then be communicated to the users so they can refine their investigations. Determining the credibility of climate projections is crucial for properly accounting for uncertainties in the projections.

This research supports CISL's strategic action items to develop and apply novel data science techniques for regional climate change studies using high-resolution research data sets, and to develop statistical methods to interpret geophysical data and improve model experiments.

Analysis of the southern Great Plains: RISC scientists and U. Connecticut colleagues produced a paper in *J. Climate* exploring the uncertainty in the NARCCAP data set for the Southern Great Plains region, and they established detailed

credibility of the different climate change simulations. They determined that for this region there is consistency and credibility in all 12 simulations for changes in spring and summer precipitation. Warm-season precipitation will increase during the early spring wet season, but shift north earlier in the season, intensifying late summer drying. [Bukovsky et al., 2016: A Credible, Poleward Shift in Warm-Season Precipitation Projected for the U.S. Southern Great Plains. *J. Climate* (accepted, pending revision)].

Analysis of snow water equivalent (SWE) in NCEP-driven NARCCAP simulations: Rachel McCrary, Seth McGinnis, and Linda Mearns have produced detailed analyses of the simulations by six different regional climate models. An additional part of this project entailed the development of an extensive set of observational data sets in order to include estimations of uncertainty in the observations to characterize in a more robust manner the biases in the regional models. The figure at right shows SWE aggregated over the full domain on a monthly basis for each model compared to the observations (including uncertainty in the observations). Note that the biases vary greatly from one model to another, for example, both CRCM and RCM greatly overestimate SWE, while WRFG substantially underestimates SWE. The paper describes how the biases in temperature, precipitation, and the nature of the surface package in each model largely explains the biases. [McCrary et al., Evaluation of Snow Water Equivalent in NARCCAP simulations, including measures of observational uncertainty. *J. Hydrometeorology* (submitted).]



Annual cycle of Snow Water Equivalent (SWE) averaged over North America from the six NARCCAP models (colors), the interquartile range of the observational ensemble data set (gray shading), and the median of the ensemble (black line). Units of area averaged SWE are in millimeters. Permanent ice points over Greenland and the northernmost Coast Range have been removed. This figure represents an advance in analyzing the climate model biases by taking into account the uncertainty in the observations, which can be quite large for SWE.

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

In collaboration with university partners, RISC scientists perform complex interdisciplinary research and work with stakeholders on projects relevant to climate change adaptation. This research is valuable in its own right, but it further serves to enrich the scientists' understanding of stakeholder needs in the context of decision making under uncertainty. This understanding then feeds into their research on appropriately quantifying uncertainty in regional climate projections.

This work integrates CISL expertise in data science and impact assessment with the goal of transferring climate science into useful products for decision making in adaptation research and risk analysis. These efforts advance two of CISL's strategic action items: to develop and apply novel data science techniques for regional climate change studies using high-resolution research data sets, and to develop statistical methods to interpret geophysical data and improve model experiments.

At end-FY2016, RISC has largely concluded work reported in FY2015 on three different research projects concerning adaptation to climate change at local and regional scales. In addition, work continued on one of two projects 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 the University of Massachusetts. As part of this project Mearns, McGinnis, and colleagues at U. Massachusetts developed a novel approach to quantifying uncertainty in the climate change projections for the project by formulating priors for the Bayesian probabilistic model (joint PDFs for seasonal and annual temperature and precipitation) based on climate projections from the global climate models used to

drive the NARCCAP models (Mearns et al., Characterization and Quantification of Uncertainty in the NARCCAP Regional Climate Model Ensemble and Application to Impacts on Water Systems, in preparation). When used in the context of a water resources model for the Colorado Springs area, the resulting PDFs (using either informed or uninformed priors) demonstrated that, even at the annual time scale, important differences resulted in the water resource reliability domain covered by the PDFs. Using the informed priors resulted in a smaller percentage of the joint PDF falling in the unreliable portion of the water resources reliability domain.

WCIASP

RISC also maintains and develops the Weather and Climate Impacts Assessment Science Program (WCIASP). The goal of WCIASP is to improve society's ability to manage weather and climate risks by creating and providing research tools and methods at the critical frontiers of impact assessment science. 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. In FY2016 WCIASP funded projects throughout NCAR, particularly in RAL and IMAGe.

This work supports CISL's strategic imperative to advance data-centric research by combining climate data products and impact projections with companion measures of uncertainty. It also supports CISL's imperative to foster research collaborations by drawing scientific, mathematical, and computer science researchers to NCAR and engaging them in CISL's research efforts.

Projects funded in FY2016 included four in RAL and two in IMAGe/RISC: development and maintenance of the Extremes Toolkit, uncertainty in vulnerability assessments, integrated uncertainty in water resource assessments, planning for the climate and health workshop, NA-CORDEX regional climate model simulations and data archiving, and analysis of snow in the NCEP-driven NARCCAP models.

Funding sources

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, and the U.S. Department of Defense Strategic Environmental Research and Development Program (SERDP).

‹ Develop statistical methods to interpret data and improve models   up   Exploit high performance computing for data analysis ›

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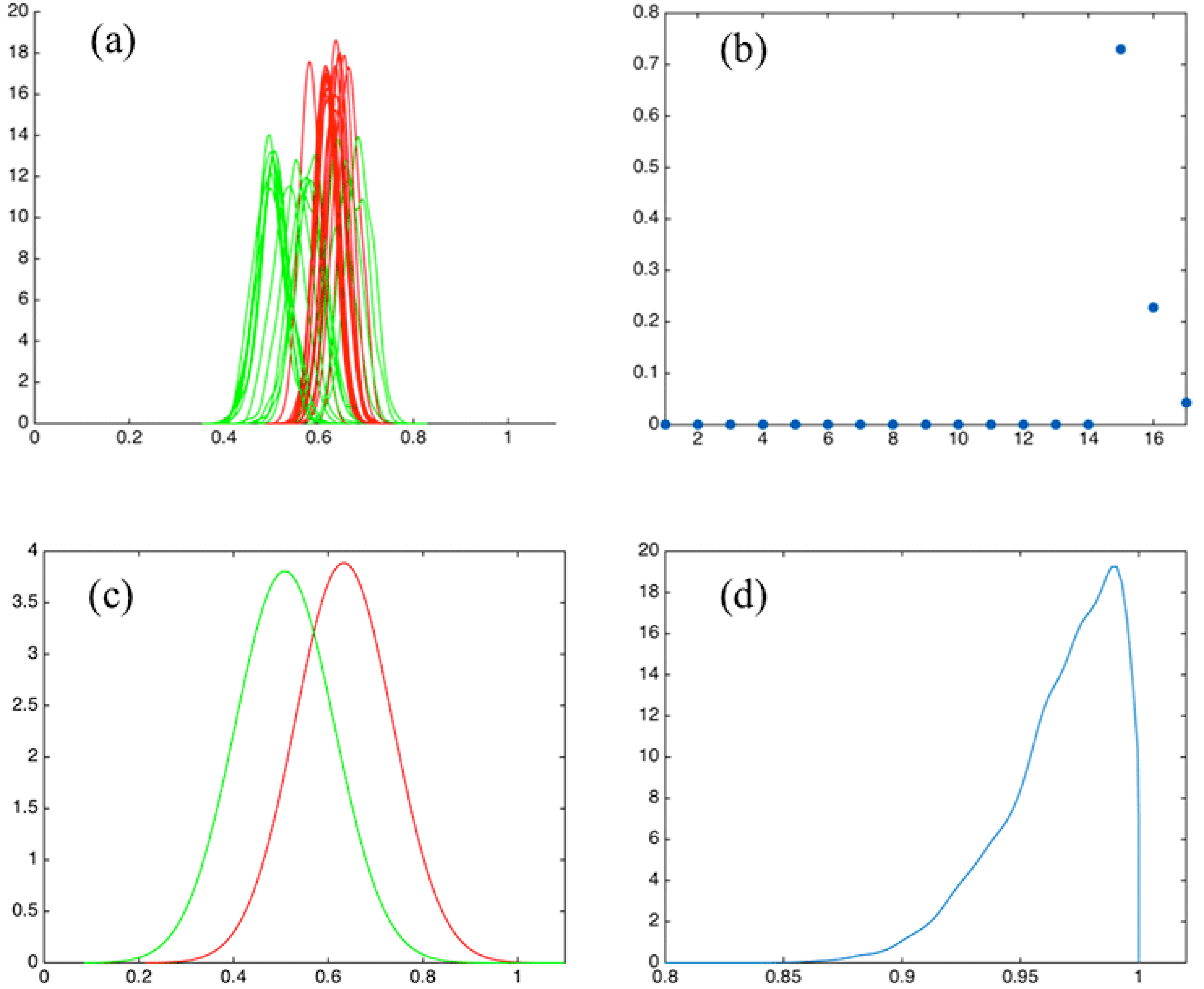
EXPLOIT HIGH PERFORMANCE COMPUTING FOR DATA ANALYSIS

We are exploring the use of HPC systems for statistical analysis in the climate and atmospheric sciences for a variety of topics. The goal is to enable types of analyses that were previously computationally not feasible or would have taken too much time to be of practical use. One example is a Bayesian model for climate change detection and attribution that we developed recently in collaboration with academic researchers. Detection and attribution is a commonly used multivariate regression methodology to identify if changes in observational trends can be detected beyond natural variability, and if so, if they can be attributed to human actions. One of the issues in current detection and attribution methods is that certain

quantities are used in an *ad hoc* way, e.g., the choice of truncating the empirical orthogonal functions (EOFs), and the uncertainty associated with their estimation is not incorporated properly. The Bayesian framework address these issues.



Results for a tropospheric temperature data analysis. (a) Posterior distributions of the coefficients' anthropogenic forcing in red and natural forcing in green for each EOF truncation. (b) Posterior probabilities for all values of the EOF truncation. (c) Marginal posterior distributions of the coefficients obtained by Bayesian model averaging. (d) Posterior distribution of p-values for the residual consistency test.

In the spirit of developing statistical methods that rely on the effective use of modern computational infrastructure, we have developed a computationally efficient, parallelizable Bayesian detection and attribution model and created a corresponding software implementation. We have submitted a journal article describing the method and presenting an example application. The newly developed method does not require a specific EOF truncation, but rather evaluates all truncation options and then performs Bayesian model averaging to combine them.

This research is made possible through NSF Core funding.

‹ Develop data science techniques for regional climate change studies up Develop numerical methods for modeling through collaborations ›

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DEVELOP NUMERICAL METHODS FOR MODELING THROUGH COLLABORATIONS

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. Numerical models are the basis for assessing, understanding, and forecasting the complex interactions among geophysical processes and human activities. CISL focuses on the numerical algorithms and computational science that will accelerate the simulation rate of Earth System models by crafting scalable numerical algorithms that can take advantage of large numbers of processors and coprocessors.

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 the massively parallel hardware that makes up today's high performance computing environments.

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 community models.

This work is supported by NSF Core funding.

‹ Exploit high performance computing for data analysis | up | Extend HOMME to non-hydrostatic scales ›

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STRATEGIC PLANS

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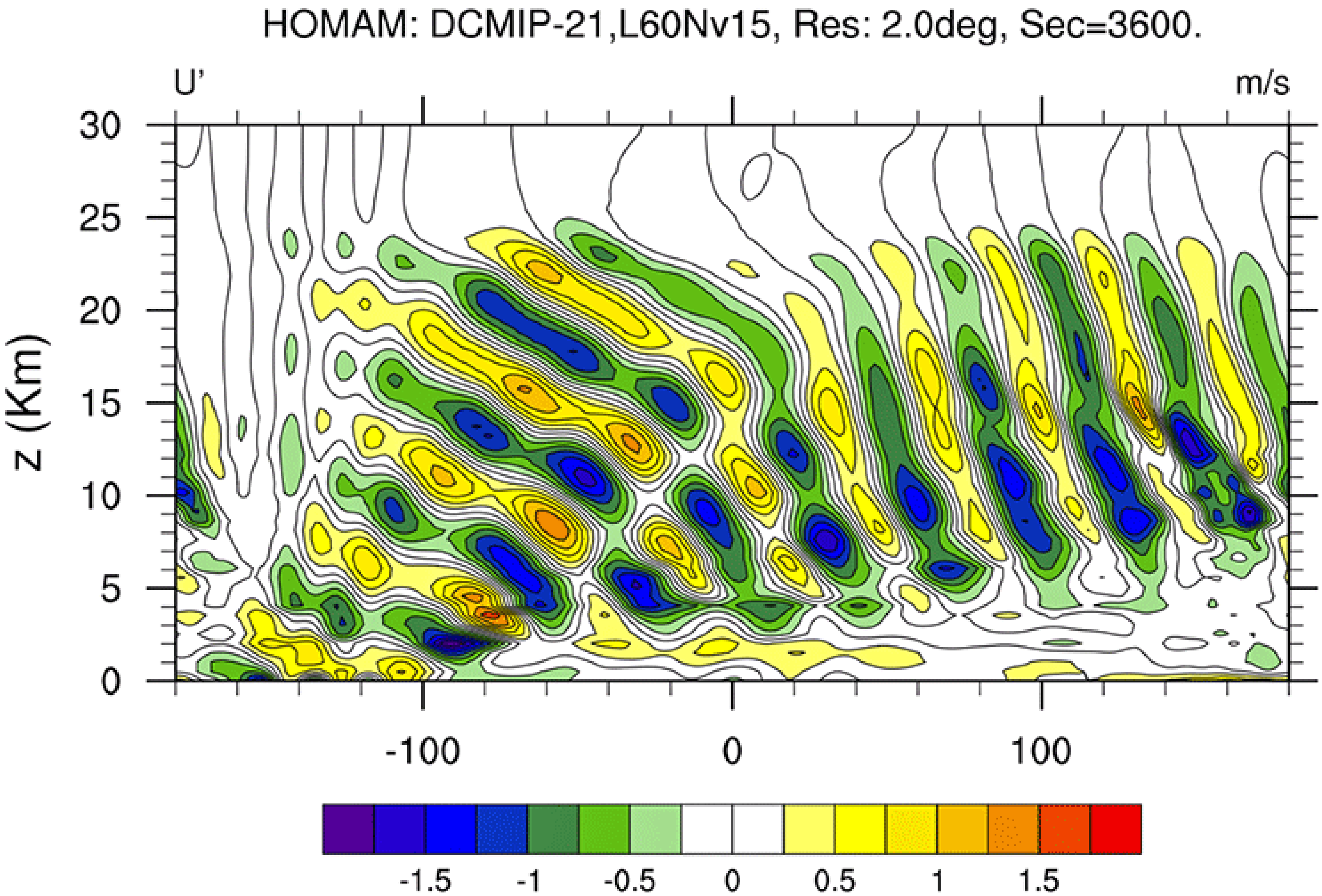
EXTEND HOMME TO NON-HYDROSTATIC SCALES

The High-Order Method Modeling Environment (HOMME) is a framework to develop global atmospheric models (dynamical cores) based on high-order accurate and conservative element-based Galerkin methods. HOMME employs the continuous Galerkin or Spectral Element (SE) and the Discontinuous Galerkin (DG) methods, on a cubed-sphere tiled with quadrilateral elements. The element-based Galerkin method possesses computationally desirable properties such as local and global conservation, geometric flexibility, high on-processor operations, and minimal communication footprints. The cubed-sphere geometry provides quasi-uniform rectangular elements on the sphere without polar singularities and suitable for SE or DG discretization schemes. HOMME can be configured to solve the hydrostatic primitive equations on a uniform or variable-resolution cubed-sphere grid with explicit time stepping. In addition, the HOMME framework facilitates multi-tracer transport modeling based on finite-volume approaches. Currently the SE version of HOMME is the default dynamical core for NCAR's Community Atmosphere Model (CAM), and HOMME-SE can efficiently scale to hundreds of thousands processors on a supercomputer.

The objective of this project is to extend HOMME to a framework capable of providing the CAM and the Community Earth System Model (CESM) with high-resolution and parallel efficient global dynamical cores at non-hydrostatic (NH) scales. The

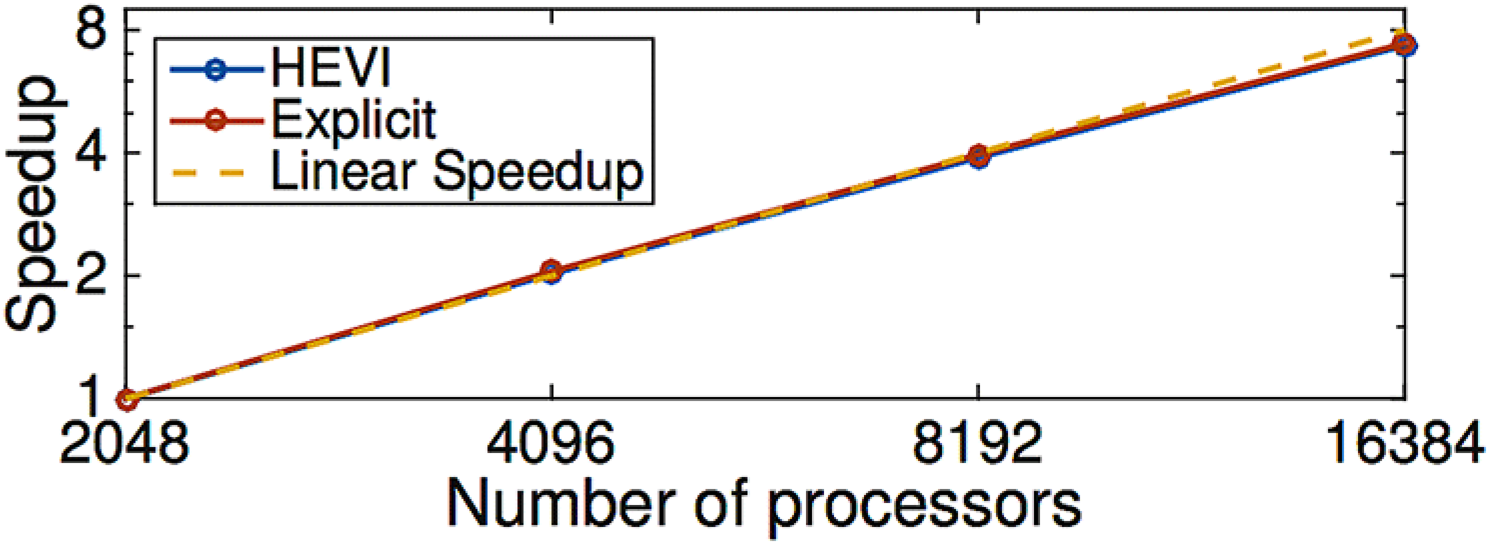
next-generation atmospheric climate models will depend on numerical methods that scale to large numbers of processors, and element-based Galerkin methods provide one route to meet the need for high-resolution dynamical cores. Numerical development within HOMME is strategic because it is not only a robust numerical test bed, but it is also a framework to transfer numerical methods to the CESM. CISL's strategic goal includes enhancing the effective use of current and future computational systems by improving mathematical and computational methods for Earth System models, and HOMME development plays a major role in this aspect. 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.

In FY2016, the HOMME framework has been further extended to a non-hydrostatic dynamical core named the "High-Order Multiscale Atmospheric Model (HOMAM)," and which is based on prior research. The horizontal aspects of the HOMAM discretization remain the same as that of the current HOMME cubed-sphere grid system, with the DG spatial discretization method. The vertical discretization relies on terrain-following height-based z-coordinates. 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. To examine the ability for the solver to represent non-hydrostatic effects, we conduct the mountain waves test over a non-smooth idealized 3D mountain. The main purpose of this test is to study the impact of orography on an atmosphere at rest, and it is particularly interesting for models with terrain-following height-based vertical coordinates that invariably introduce numerous metric terms. The model correctly captures the mountain-induced gravity wave propagation as shown in the figure below, and results are comparable with that of the reference results presented in DCMIP tests (Nair et al. 2016, DOI:10.2514/6.2016-3888).



Simulated results for non-hydrostatic mountain waves over a 3D idealized mountain (DCMIP test) with HOMAM. The figure shows the mountain-induced gravity wave propagation for the vertical slice of the horizontal wind perturbation (u' m/s) along the equator, after 3,600 seconds of simulation.

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 (horizontally explicit and vertically implicit) scheme does it precisely. A major research effort in FY2016 was to test the accuracy and scalability of the HEVI scheme in the HOMME framework. The time-stepping scheme HEVI has been implemented in HOMAM, and its performance has been compared with a fully explicit Runge-Kutta (RK) method. The figure below shows the scaling results with HEVI and the standard RK method, which are close to ideal scaling (dotted line). Moreover, the HEVI scheme does not impede the parallel scalability of the HOMME framework.



The strong scaling results with the HEVI and explicit RK time stepping methods for the HOMAM non-hydrostatic dynamical core. The HEVI scheme does not affect the scalability of the model.

Primary support for HOMME is provided by NSF Core funding.

‹ Develop numerical methods for modeling through collaborations | up | Explore meshless numerical methods for modeling ›

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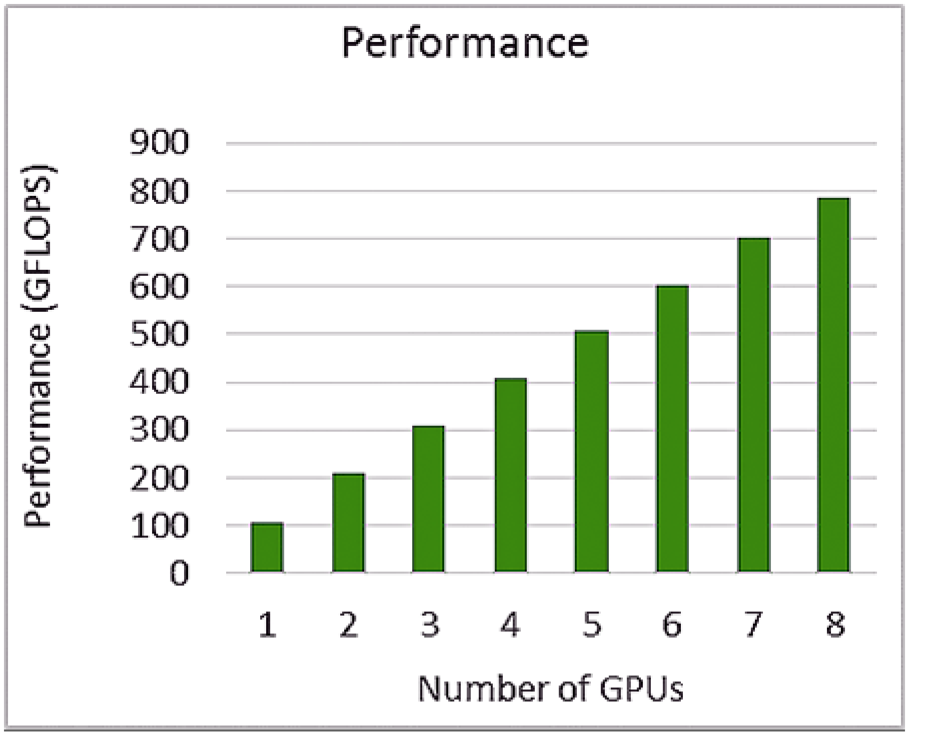
EXPLORE MESHLESS NUMERICAL METHODS FOR MODELING

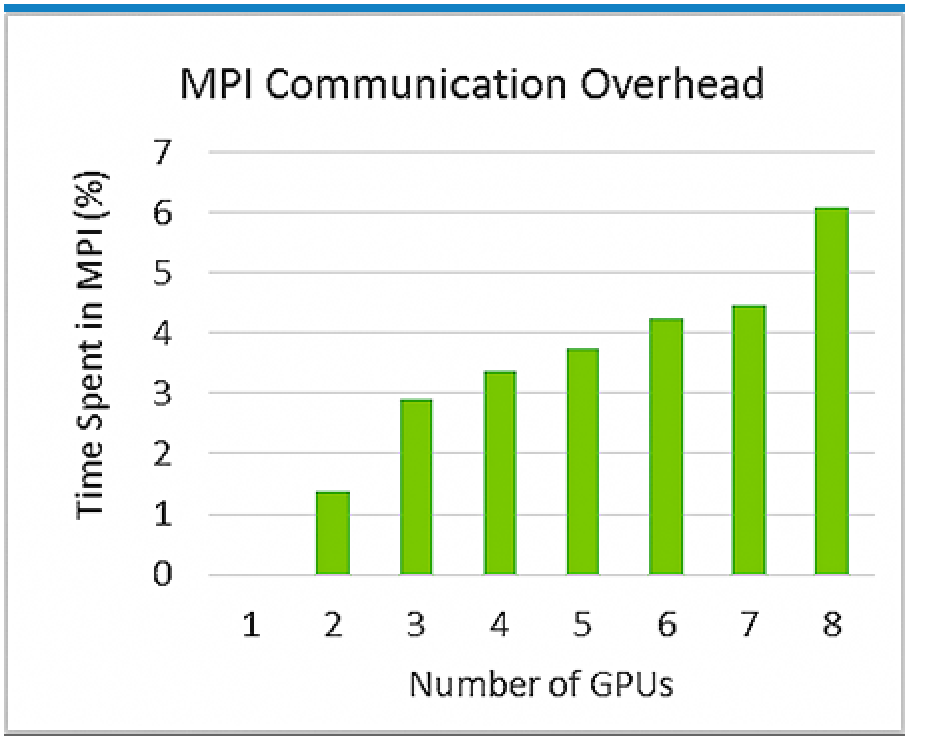
Radial basis functions (RBFs) offer a novel numerical approach for solving partial differential equations to high accuracy. Being a meshless method, RBFs excel in solving problems that require geometric flexibility and local refinement for small features. Further, RBFs require very little increase in programming complexity when problems are 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.



Performance of the RBF-FD shallow water equation (SWD) solver, measured in GFLOPS, as a function of the eight Nvidia K40 GPUs connected over a PCIe bus in a Cirrascale GX-8 system.



MPI communication overhead of the RBF-FD SWE solver using the same Cirrascale GX-8 multi-GPU system with eight Nvidia K40 GPUs. The solver demonstrates excellent scaling with less than 7% of the time spent in MPI communication and getting close to 1 TFLOPS of performance on a single multi-GPU system.

- 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.

Development in FY2016 focused on parallelization for computer architectures using hardware accelerators. Scalability, performance, and portability are essential when developing HPC algorithms. Many of the current standard atmospheric models lack particularly in the aspect of portability. In developing the RBF-FD solver for the shallow water equations (SWE) on the sphere, RBF development targeted today's three dominant HPC architectures: Intel Multicore, Intel Manycore, and Nvidia GPUs. To tackle portability of the solver on all three architectures, the directive-based OpenACC and OpenMP languages for simple shared memory parallelization were used. MPI was used for distributed-memory parallelization to address the scalability of the solver. This allowed for a single-source implementation requiring only a simple recompilation to run on practically any HPC system today.

Excellent performance was demonstrated on the Intel Multicore and Manycore systems. However, with regard to MPI implementation, optimizing GPU systems presented the most challenging task. The figures above show the high performance – close to 1 TFLOPS – and the minimal MPI communication overhead – less than 7% – of the RBF-FD SWE solver on a eight-GPU system.

This work advances CISL's scientific efforts to develop scalable algorithms for atmospheric modeling on massively parallel and accelerator-based computer architectures. Development of numerical algorithms based on meshless methods for atmospheric modeling at NCAR is supported by NSF Core funds.

‹ Extend HOMME to non-hydrostatic scales up Advance applied computational science research ›

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ADVANCE APPLIED COMPUTATIONAL SCIENCE RESEARCH

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.

Advancing applied computational science research enhances the effective use of current and future computational systems by improving mathematical and computational methods for Earth System models and related observations.

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 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 lengths than previously required. The target here is emerging many-core architectures such as Intel's Xeon Phi and NVIDIA's Tesla GPU architectures. In addition to reducing the overall computational cost of the Community Atmosphere Model by 15%, this effort has also further reduced the cost of the dynamical core used within high-resolution configurations of the Community Atmosphere Model (CAM).

Second, CISL continues to evaluate the impact that data compression may have on the fidelity of climate simulation data. This evaluation involved both investigating the accuracy of a wavelet-based compression algorithm from the University of Oregon as well as the completion of a study that challenged the climate modeling community to test whether compression of model output degrades its scientific content.

Third, CISL has focused on accelerating the end-to-end workflow for climate modeling. In the past, optimization efforts were focused on reducing the computational cost of the simulation models. However, as computational science has become more data-centric, attention is now being given to reducing the execution time for the analysis and post processing. Several new parallel Python tools have been developed that reduce the post-processing time of climate simulation data by a factor of 10 to 100.

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 by using fewer cyber-resources. One example of this work is the development of a transport scheme 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.

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

‹ Explore meshless numerical methods for modeling | up | Explore many-core and accelerator-based architectures ›

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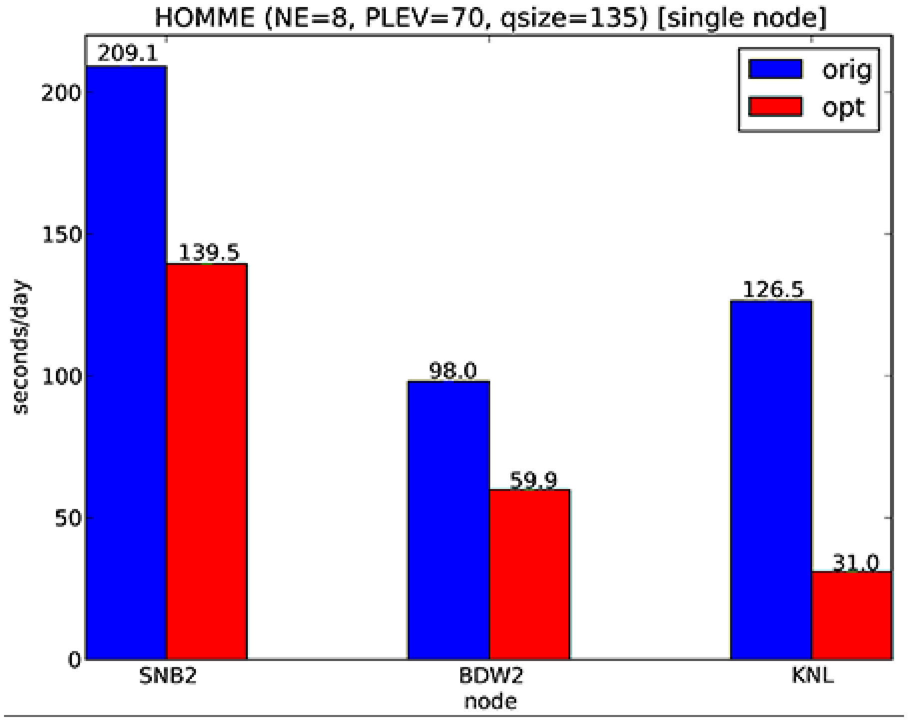
EXPLORE MANY-CORE AND ACCELERATOR-BASED ARCHITECTURES

CISL collaborates with NCAR’s science laboratories to provide new tools for exploiting many-core architectures such as general-purpose graphics processing units (GPGPUs). This allows us to increase model performance on advanced many-core architectures, such as those in NCAR’s next supercomputer. CISL also plans to give our users access to advanced systems by acquiring a many-core cluster.

Using codes developed under this initiative, our scientific users will gain experience with production systems composed



This chart shows the execution times for the High Order Method Modeling Environment (HOMME), which is a dynamical core that is used by the Community Atmosphere Model (CAM) using the Intel compiler on several different Intel processors (SNB2 = 2-socket Sandy Bridge node, BDW2 = 2-socket Broadwell node; KNL 1-socket Knights Landing node). Note that while optimizations have reduced execution time on all three architectures, a factor of four reduction in execution time is achieved on KNL. Depending on the particular scientific configuration, the HOMME dynamical core consumes 23% of CAM and 81% of the Whole Atmosphere Chemistry (WACCM) model. Reducing the cost of the HOMME dynamical core will increase the amount of science that can be performed on our existing and future supercomputers.

of these emerging technologies. 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.

In FY2016, CISL's Application Scalability and Performance (ASAP) group 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.

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.

CISL has made significant progress optimizing several sections of CESM and MPAS that reduced their computational costs. Also, the execution time of multiple physics modules including those within CAM was shortened, and this reduced the total cost of CAM by 15%. Moreover, the HOMME dynamical core used within CAM received additional optimizations that reduced the total cost of HOMME from 23 to 75%, depending on the scientific configuration. Work was also done to address the problematic data structures and computationally intensive subroutines within MPAS that were inhibiting compiler optimizations. Addressing these data structure issues enabled a speedup on the entire MPAS dynamical core by a factor of two on Yellowstone.

Work will continue with the science and model development teams at NCAR to both optimize existing application codes and provide guidance for future code development.

The IPCC-WACS project is funded by a donation from Intel Corporation. Additional optimization efforts within ASAP are

supported by NSF Core funds.

‹ Advance applied computational science research up Evaluate data compression for scientific data ›

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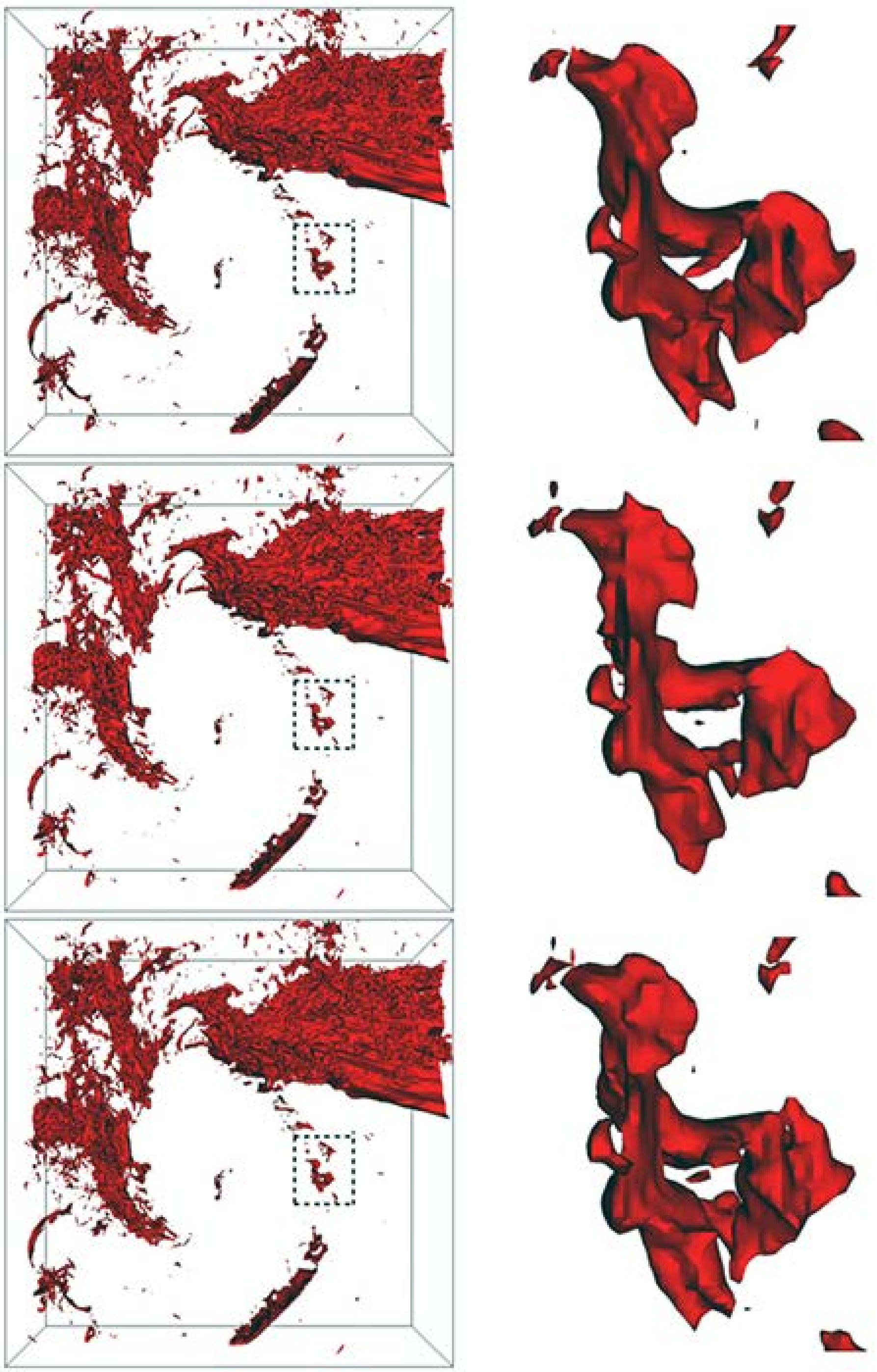
EVALUATE DATA COMPRESSION FOR SCIENTIFIC DATA

Due to a combination of factors that include both diverging rates of technological advancement and cost, our ability to compute data has outstripped our ability to effectively store, manage, and analyze it. This trend is expected to continue for the foreseeable future as evidenced, for example, by specifications for exascale computing platforms that are anticipated to arrive near the end of the decade. Computational scientists, such as those studying climate, whose research depends on ever-increasing model resolution and complexity for improved understanding are facing



Renderings of isosurfaces of the z-component of velocity from a numerically simulated tornado. The left figures are of the entire data set, while the right figures are enlargements of one feature. Dashed lines in the left figures indicate the enlarged region. The top row of figures are from the original (raw) data; the middle row is from 128:1 compressed data using spatial domain compression only; and the bottom row is from 128:1 compressed data using both spatial and temporal compression.

daunting challenges posed by both limited storage capacity and I/O bandwidth. In response to these issues, CISL is exploring a variety of novel hardware- and software-based solutions.

Two related research areas with a high-impact potential are lossy data compression and progressive data access. Lossy compression, unlike lossless compression, fails to exactly reproduce original data, but is capable of far greater reduction than lossless techniques when applied to floating-point data. Though not able to exactly reproduce the original data, the reconstructed results may be indistinguishable from the original by many salient metrics. Progressive data access, on the other hand, offers progressive reconstruction of original data in a manner that enables an investigator to make speed-quality tradeoffs that can be subsequently validated, as needed, with lossless reconstruction. The goals of this work are to:

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

This work is aimed at ensuring that NCAR's substantial investments in HPC resources produce significant returns. The work directly supports CISL's strategic plans in advanced applied computational science research calling for "pursuing novel, aggressive data compression techniques that have the potential to substantially reduce the storage and bandwidth needed for numerical experiments." The work also aligns well with strategic plan goals for providing the NCAR user community with Big Data services aimed at analyzing a variety of data sets, and goals in the area of advancing data-centric research by exploring and developing visualization approaches that can handle the very large volumes of data that are

increasingly common in the geosciences.

In FY2016 CISL researchers continued earlier efforts to investigate applying lossy data compression to CESM output. In particular, this work builds on a 2014 paper by Baker et al., that introduces a methodology for evaluating the impact of compression on climate simulation data and examines a number of lossy compression techniques within this framework. The key idea in quantifying the impact of compression is that, to preserve the integrity of the climate simulation data, the effects of lossy data compression on the original data should, at a minimum, not be statistically distinguishable from the natural variability of the climate system. The preliminary work with data from CESM in Baker et al., 2014 indicates that this goal is attainable.

Therefore, our path forward has included both providing climate scientists with direct experience with climate data that has undergone lossy compression and extending the suite of previously explored compression strategies to include state-of-the-art wavelet encoders. In the former case, we conducted a blind experiment that engaged the wider climate community to evaluate the impact of lossy data compression on publicly available climate data from the CESM Large Ensemble Community Project. Climate scientists examined features of the data relevant to their interests and attempted to identify which of the ensemble members have been compressed and reconstructed. Overall, we found that while detecting distinguishing features is certainly possible, the compression effects noticeable in these features are often unimportant or disappear in post-processing analyses. While the original goal of this study was to convince climate scientists that using lossy data compression is both acceptable in terms of effects on scientific results and advantageous in terms of data reduction, the feedback that we received was invaluable in terms of informing future compression error metrics. A paper detailing this work has been accepted for publication in *Geoscientific Model Development*.

In the area of wavelet-based encoders, preliminary results suggest that these encoders compare favorably with the best compression techniques investigated previously. However, the story is complicated: different compression techniques appear to work better for different data variables. Therefore, this ongoing work involves expanding our original analysis of lossy compression in CESM to better understand the strengths and weaknesses of different varieties of compression algorithms (e.g., transform vs. predictive), and plans call for a follow-up paper to Baker et al., 2014 later this year. Ultimately the goal is to determine the most effective compression approach for each variable based on measurable properties of that variable.

CISL researchers also explored spatio-temporal compression of scientific data using wavelets. This research exploits the coherence that exists in both the spatial and temporal domains of many numerical simulations. The results of this work, conducted in collaboration with the University of Oregon, led to a manuscript that has been submitted for review to *IEEE Transactions on Visualization and Computer Graphics*.

CISL also completed work funded by an NSF SI2 grant – the Wavelet enabled Storage Access Protocol (WASP) – to develop a scientific file format, based on NetCDF, capable of supporting both lossy compression and progressive data access. The new WASP file format is the cornerstone of the VAPOR Data Collection, Version 3, and has also been adopted by the University of California at San Diego for their bio-imaging analysis platform, QUEST.

CISL's scientific data compression research is supported by NSF Core funds. Development of the WASP API was funded via a subaward from the University of California at San Diego, NSF grant 54067252.

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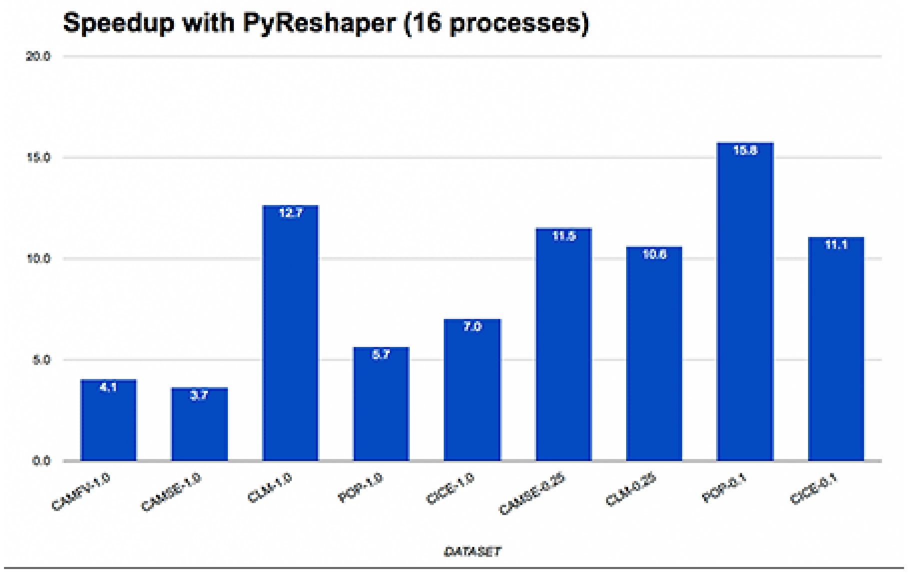
DEVELOP EFFICIENT PARALLEL DATA PROCESSING CAPABILITIES

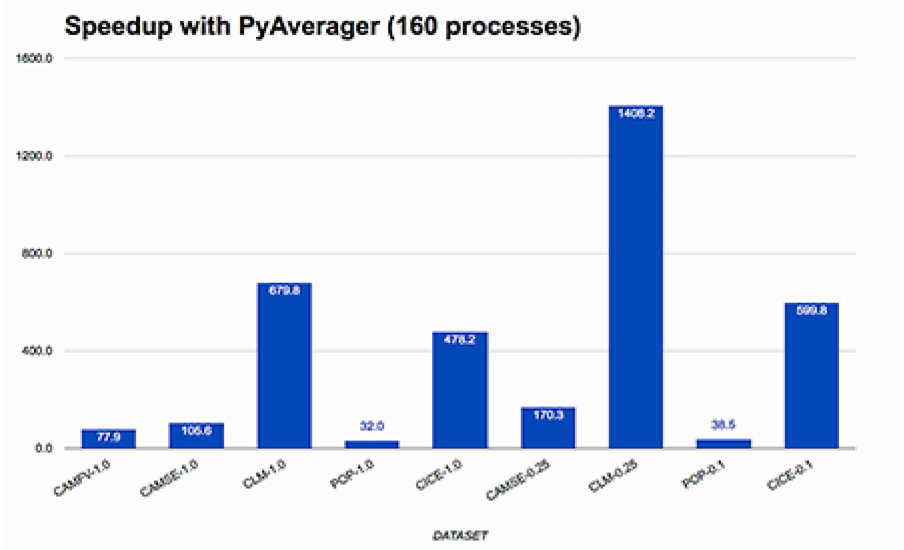
Efforts to meet the grand challenge of simulating the Earth System require ever-increasing model resolutions and model complexity. The supercomputing systems capable of tackling these challenges produce output data volumes that exceed the capacities of previous generations of data-processing utilities. Because the serial tools formerly used for processing model data will restrict the increasing pace of scientific discovery, researchers require new and efficient tools and techniques for processing today’s and tomorrow’s data flows. Simulations of the Earth System now consider data processing

as an integral part of the workflow necessary to produce results in a reasonable amount of time. CISL's work to parallelize steps in data processing workflows includes the development of new, lightweight Python utilities. Through parallelization, the bottlenecks in each phase of the data processing workflow are being eliminated.



This plot shows the speedup with PyReshaper (using 16 MPI processes) over the old NCO (serial) utility when transforming time-slice data into time-series format. The different datasets range in size from 8 GB (1-degree CICE) to 3 TB (0.1-degree POP), and the speedups range from 3x to 16x.

CISL's parallel Python data processing project has produced several new parallel utilities to handle the Community Earth System Model's (CESM) current and future data volumes. These parallel utilities are critical to meeting NCAR's obligations as a member of Phase 6 of the Coupled Model Intercomparison Project (CMIP6). This work – to develop more efficient approaches for data processing and compression – is specified as an action item in CISL's new strategic plan.



This plot shows the speedup with PyAverager (using 160 MPI processes) over the old NCO (serial) utility when computing climatological temporal averages from time-series data. The different datasets range in size from 8 GB (1-degree CICE) to 3 TB (0.1-degree POP), and the speedups range from 32x to 1400x.

In FY2016, members of the Application Scalability and Performance (ASAP) Group collaborated with NCAR's Climate and Global Dynamics (CGD) Laboratory to continue improving two parallel Python utilities that were released in FY2015: the PyReshaper and the PyAverager. Each tool relieves congestion at a significant bottleneck in the CESM post-processing workflow. The PyReshaper tool transforms CESM data from synoptic (history or time-slice) format to single-field (time-series) format in parallel. The PyAverager computes climatologically important temporal averages in parallel. Both utilities use the Message Passing Interface (MPI) for parallelism and utilize PyNIO (the Python NCL I/O library) for NetCDF file access.

In FY2016, CISL staff added new features and other improvements to the PyReshaper and the PyAverager, and both tools were made available publicly though GitHub. Also in FY2016, CISL developed a third parallel Python utility, code-named PyConform, to perform the "data standardization" step of the post-processing workflow for CMIP6. This is the last step in the workflow before the CESM data are published. PyConform is currently in the testing phase and its first release is scheduled for early 2017.

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

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FOSTER RESEARCH AND TECHNICAL COLLABORATIONS

CISL has a robust set of ongoing partnerships and collaborations that are focused on the effective use of current and future high performance architectures for NCAR applications. These collaborations take the form of membership in a regional HPC consortium, on-going R&D projects that include vendor partners, annual workshops, symposia, hackathons, training events focused on emerging technologies and techniques, as well as regularly scheduled teleconferences on code optimization with various vendor partners.

Rocky Mountain Advanced Computing Consortium

CISL's participation in the Rocky Mountain Advanced Computing Consortium (RMACC) not only supports the development of regional high-performance CI but also broadens and informs CISL's knowledge of various computing options. For instance, seeking to replace the aging Janus supercomputer, the University of Colorado at Boulder and Colorado State University led, in partnership with RMACC, a successful NSF Major Research Instrumentation grant proposal to bring a 450-teraflops PowerEdge C Series system from Dell to the Front Range. Named Summit, this heterogeneous computing system includes Intel Xeon, Xeon Phi, and NVIDIA GPU components, along with the newly introduced 100 gigabit-per-second Intel Omnipath (OPA) Interconnect. CISL contributed to this successful proposal as an RMACC partner, and is therefore entitled to access to the system for benchmarking and evaluation purposes. This access to Summit's novel heterogeneous architecture provides CISL an important avenue to gain vital technical information about the performance and production

readiness of both OPA and Xeon Phi.

In FY2016, the planned refurbishment of the Mesa Laboratory Computing Facility required the de-installation of the Colorado School of Mines (CSM) IBM supercomputer named “BlueM.” In accordance with the contractual arrangement associated with the colocation agreement, CSM was given ample advanced notice, and CISL and CSM subsequently worked together to develop a mutually agreeable plan by which BlueM was relocated to a new computing facility located at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. The deinstallation also ended the joint computational science research project related to this novel hybrid computing system that combined IBM’s iDataPlex and Blue Gene/Q platforms. This relationship afforded CISL the opportunity to gain further experience with both highly parallel BlueGene-style computers and heterogeneous systems.

UCAR Indirect funds supported the operating costs of the colocated BlueM computer system. The minimal costs of CISL’s participation in RMACC education and outreach activities are entirely supported by NSF Core funds.

Vendor partnerships

CISL maintains a wide spectrum of vendor research and development partnership activities. These include active collaborations with Intel (IPCC-WACS), NVIDIA (WACA), SGI (JCoE), and Cirrascale (GX8). CISL uses the HPC Futures Lab facility and support from CISL's Supercomputing Services Group to enable the gear required to perform these R&D efforts.

IPCC-WACS: In 2016, CISL and the University of Colorado at Boulder (CU) continued their Intel-funded collaboration as 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 back into key weather and climate community models. IPCC-WACS also has a student education and training component being led by CU.

The Intel gift has enabled CISL to develop the Kernel Generator (KGEN), a labor- and resource-saving tool for automatically extracting part of a large modeling code base and creating a kernel or unit test around it for optimization and subsequent verification. The KGEN tool is also being used and evaluated by engineers and scientists at other research institutions, including ETH and GFDL, thus providing significant broader impacts to the atmospheric science community. The value of these impacts was recognized by Intel, who provided additional funding in early 2016 after reviewing the progress and accomplishments of the IPCC-WACS team.

IPCC-WACS supported optimization work focused on the spectral element dynamical core in CESM, called HOMME, as well as key, expensive portions of the CAM physics packages such as cloud microphysics, convection, and radiation physics. Many of these optimizations were incorporated into the source code base for CESM.

The NCAR/CISL portion of the IPCC-WACS project is funded by Intel Corporation through the mechanism of a corporate gift.

WACA: In FY 2016, CISL also initiated a new partnership with NVIDIA Corporation and the GPU Research Center (GRC) at the University of Wyoming. This partnership is called the Weather And Climate Alliance (WACA). CISL’s initial objective in WACA is to work with the partners to port the Model for Prediction Across Scales (MPAS) dry dynamical core to multiple GPUs using the OpenACC directive-based paradigm. By using OpenACC, the new version of the MPAS code will be able to use both conventional microprocessors and GPUs. WACA will enable students at the University of Wyoming to gain valuable hands-on experience with HPC application software and optimization techniques. As an inaugural WACA activity, NVIDIA

and CISL staff hosted an OpenACC Hackathon in June 2016 that provided hand-on experience with application porting using Portland Group OpenACC directives. The Hackathon was attended by a dozen students and NCAR staff.

WACA is partially funded by NVIDIA Corporation and partially by NSF Core funds.

Cirrascale GX8: A fundamental question in computational science at extreme scale is “How will we program an exascale system?” With each passing year, the design for the exascale computational building block is gradually becoming clearer. Because of the size and complexity of atmospheric and Earth System science applications, it is necessary to begin evaluating these designs far in advance. So in FY 2016, CISL completed a careful review of existing proxies for an “exascale computational building block” that might be purchased with the objective of informing application design. CISL acquired the Cirrascale GX8 dense-GPU solution that puts O(10) teraflops in a 4U chassis with a scalable PCI-switch interconnect. Starting in summer 2016, this GX8 system has formed the basis of three different research projects focusing on different 2D atmospheric PDE solvers: MPAS Finite Volume approach, the Discontinuous Galerkin method, and Radial Basis Function Finite Difference (RBF-FD) methods. Using the RBF-FD method, the GX8 system delivered 0.8 teraflops sustained across eight, K40 NVIDIA Tesla GPUs, a throughput that is equivalent to the performance of about 40 Yellowstone nodes.

Funding for the Cirrascale GX8 comes via NSF Core funds, jointly supplied by CISL’s Technology Development Division and Operations and Services Division.

NCAR-SGI Joint Center of Excellence: Silicon Graphics’ successful proposal response to the NWSC-2 RFP included the suggestion to create a “Joint Center of Excellence” (JCoE) between NCAR and SGI. After creating an MOU for the JCoE, regular monthly meetings have begun to develop joint R&D activities and to provide a forum for identifying and discussing strategically important issues of mutual concern.

One significant project immediately emerged around the area of workflow acceleration using the SGI UV 300 platform. The UV-300 is a large shared-memory architecture designed to handle large-scale, data-intensive analytics workflows. CISL’s Application Scalability and Performance Group worked with SGI engineers to evaluate climate workflow benchmarks on UV 300 systems containing NAND-based SSD storage. The use of SSD storage as a high-speed cache enabled these climate data post-processing workflows to speed up by factors of two to five at both high and low resolutions. A subsequent loaner system was embedded in the “Laramie” test system at NWSC and confirmed the results of the tests performed by SGI in Chippewa Falls. This type of collaboration fostered by the JCoE partnership helps NCAR in designing future analysis systems that can process large data sets more efficiently. In turn this data helps SGI evaluate future system design concepts for the wider HPC marketplace. Working through the JCoE has thus enabled mutually beneficial outcomes for NCAR and SGI.

The JCoE is based on cosponsored staff time, which is provided on NCAR’s side from NSF Core funds.

HPC Futures Lab

CISL’s HPC Futures Lab (HPCFL) and CISL's Supercomputing Services Group play a critical role in supporting technology evaluation activities required by computational science research and development. For example, the Cirrascale GX8 evaluation activity cited here is entirely enabled by support received through the HPCFL and SSG teams.

Funding for HPCFL comes via NSF Core funds, jointly supplied by CISL’s Technology Development Division and Operations and Services Division.

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PURSUE A VIGOROUS VISITOR PROGRAM

The CISL Visitor Program (CVP) was overhauled and redesigned for 2016 and beyond. The main purpose of this reorganization was to provide a more formal approach for allocating visitor resource funds over a broader spectrum of CISL's program activities in IMAGe, OSD, and TDD. In doing so, CVP fosters collaborative projects with academia as well as the public and private sectors of the national economy that are of strategic value to NCAR and in alignment with CISL's mission in research, education, and service.

IMAGe visitor Phillipe Naveau (right) led a summer course titled "Statistics of Extremes," with topics that included introductions to univariate and multivariate extreme value theory in climate sciences, and detection and attribution for extremes. Philippe is visiting from

The CVP promotes scientific and professional visits to enhance the productivity of CISL staff, visiting researchers, and other professionals. Further, it enriches the training of students, post-doctoral researchers, and early-career scientists and engineers. With the redesign of the program, collaborative projects are encouraged in a much broader range of fields than was supported by CISL's previous visitor program. These

Laboratoire des Sciences du Climat et l'Environnement in France. In this photo he is interacting with another scientist during a reception at NCAR.

include, but are not limited to, climate variability and impacts, optimizing supercomputing applications, computational mathematics, geostatistics, data assimilation, data curation, data science, facility engineering and management, computer networking, scientific visualization, cybersecurity, and many more.

The CISL Visitor Program (CVP) brings university faculty, researchers, and students to NCAR to foster collaborations with CISL staff by providing travel and living expenses for stays of up to three months. These extended visits establish strong relationships that can lead to long-term collaborations. For many visitors, CVP represents a unique opportunity to interact with NCAR scientists. It focuses on two-week to 12-week visits. Applications are accepted between January and March, then they are formally reviewed for alignment with CISL's strategic goals. Funding is capped based on budgetary constraints.

In FY2016, 20 applications to the CVP were received, and 10 were funded. CISL staff from all three divisions, IMAGe, OSD, and TDD was involved in hosting visitors from three main research communities: academia, industry, and government labs. Visitors also included foreign nationals from the United Kingdom and South Korea. In the coming years, CVP plans to increase the number of applications by vigorously pursuing various advertising venues such as UCAR's *Staff News*, connections with UCAR visitor programs, career fairs, and ads in scientific society newsletters.

The CVP is supported by NSF Core funds, with supplemental funding from other sources if available.

‹ Foster research and technical collaborations | up | Reach out to new generations of scientists through education ›

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REACH OUT TO NEW GENERATIONS OF SCIENTISTS THROUGH EDUCATION

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CISL integrates research and education to teach the skills that students and faculty need to use advanced cyberinfrastructure effectively. These programs also promote diversity, enhance CISL's culture of teaching and mentorship, and stimulate collaborations with the university community, all in support of NCAR's strategic imperative to educate and entrain a talented and diverse group of students and early-career professionals. This support for young people seeking careers in science, technology, engineering, and mathematics will provide NCAR, NSF, and the nation with a skilled and capable future workforce.

CISL accomplishes these educational objectives through internships and externships, as well as visitor, workshop, and training programs that supplement education efforts throughout UCAR and at other institutions. A collaboration with NCAR's Director of Diversity, Education, and Outreach will follow up with the Summer Internships in Parallel Computational Science (SIParCS) interns and produce a formal assessment of their research as one evaluation of CISL's education activities.

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.

‹ Pursue a vigorous visitor program up Integrate research and education ›

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INTEGRATE RESEARCH AND EDUCATION

As a supercomputing laboratory embedded in a national center focused on the atmospheric and related sciences, CISL serves community needs by integrating research and education in the computational Earth System sciences. CISL provides resources for this highly effective approach to developing an effective research workforce. An interdisciplinary focus enables CISL to complement and supplement related programs within NCAR, UCAR, and 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.

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.

‹ Reach out to new generations of scientists through education | up | Provide internships and externships that support CISL research ›

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PROVIDE INTERNSHIPS AND EXTERNSHIPS THAT SUPPORT CISL RESEARCH

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. CISL's goal is to support 12 or more internships each summer to create a critical of mass of intern peers and to increase the program's visibility outside NCAR.

The SIParCS class of 2016 included 13 interns. Pictured here are, (back row) Tao Zhao, Vinay Ramakrishnaiah, Andre Nunes Guerrero, Negin Sobhani, Sisi Liu, Delilah Feng, Samm Elliott, Francois Hebert, Pulong Ma, Pranay Reddy Kommera, and Ramesh Baral, (front row) Marjani Peterson, Xiaoying Pu, and Nihanth Cherukuru . SIParCS is an 11-week summer program run by CISL that provides undergraduate and graduate students with an opportunity to work on research projects in the computational sciences that span computer science, applied mathematics, statistics, visualization, and software engineering.

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 2016 class of the SIParCS program was an accomplished and diverse group, with two interns from Minority-Serving Institutions (MSIs), four female interns, and four interns from 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 one undergraduate and two graduate 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 using parallel computation to accelerate statistical analysis. Others worked on the implementation and design of parallel atmospheric PDE solvers on many-core CPUs and GPUs, extending the 2D MPI parallel implementation of DG-NH to GPUs, while others focused on enhancing the performance of climate models and climate data analysis workflows. Still others focused on writing an application to automate Fortran-C interoperability, and creating an augmented reality application to display data sets in an engaging manner. During the summer, SIParCS students had an opportunity for enrichment activities such as a resume-writing seminar, workshop on creating and presenting a scientific talk, workshop on diversity in

the workplace, 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 at a symposium in NCAR's main seminar room.

The FY2016 SIParCS program was made possible by NSF Core funding.

‹ Integrate research and education up Engage mathematicians and computer scientists through education ›

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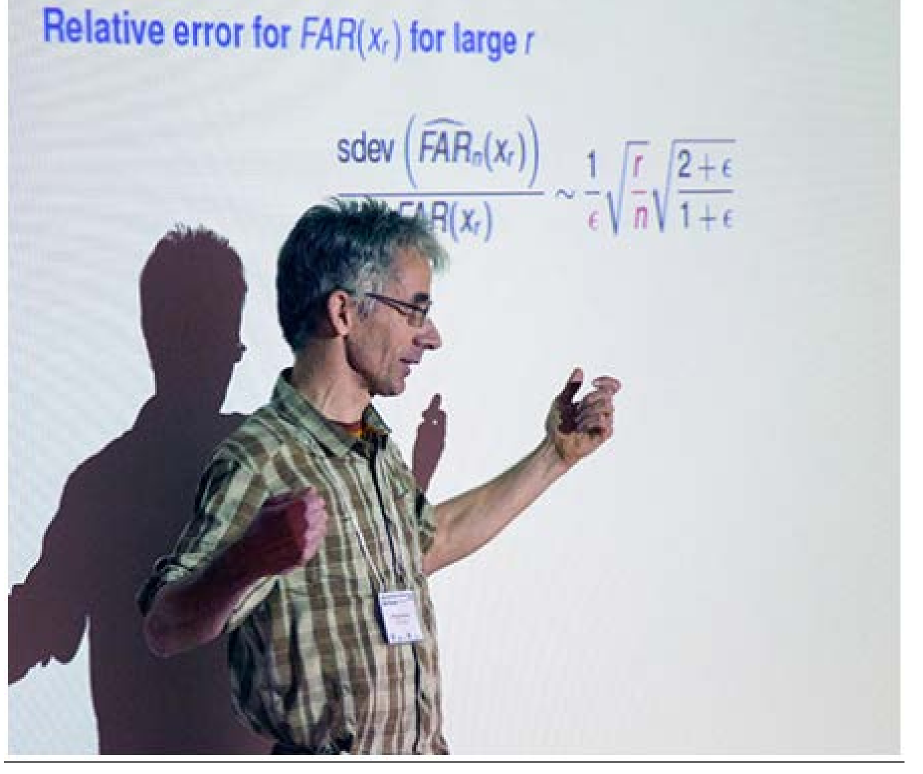
ENGAGE MATHEMATICIANS AND COMPUTER SCIENTISTS THROUGH EDUCATION

Numerous workshops, seminars, and summer schools have brought a steady stream of mathematical and computer scientists to NCAR – often for the first time – and these have led to collaborations, influence on graduate student research, and a broader awareness of research that can be applied to the geosciences.

An important part of CISL's educational portfolio is the Theme-of-the-Year (TOY), a year-long focus on an aspect of applied mathematics for the geosciences designed to advance research and education between the mathematics and the geosciences communities. Typically the TOY sponsors a series

During the Climate Informatics Workshop poster session, Imme Ebert-Uphoff (center) talks with Xaiowei Jia (right) and Vipin Kumar (left). Jia and Kumar are computer scientists from the University of Minnesota who use remotely sensed image data to map vegetation changes, surface water, and other features of human activity that are useful for climate studies.



Philippe Naveau (Laboratoire des Sciences du Climat et l'Environnement, Centre Nationnal de la Recherche Scientifique) teaches part of a course at NCAR on statistical methods for extremes.

of workshops or schools along with a visitor program that coordinates with NCAR science groups and partners with other mathematics institutes. CISL has supported 10 separate TOYs with the most recent being Extremes in Climate Sciences: a Statistical, Dynamical, and Machine Learning Inquiry.

The theme for FY2016 focuses on extremes in climate sciences, and is being organized by visiting scientist Philippe Naveau, a leading expert in the field. Extreme value theory has long been an active area of mathematical statistics, but it is only recently that approaches have been devised to handle the practical problems for large climate data sets. One goal of this TOY is encourage a process of technology transfer between the data science and the work at NCAR. Besides a focused workshop on the statistics of extremes held in May 2016, this TOY also ran an informal seminar series during the year and also partnered in two other international meetings: International Detection and Attribution Group, NCAR, February 2016, and Uncertainty Modeling in the Analysis of Weather, Climate, and Hydrological Extremes, Banff International Research Station, June 2016.

Emerging from the TOY were new collaborations and the potential for more deliberate interaction between researchers at Centre National de Recherche Scientifique in France and NCAR. From a scientific point of view, what has emerged from the TOY is a plan for data analysis that can seamlessly move from characterizing the center of a distribution to that of the tails. In this way extremes can be incorporated into a single complete analysis of the climatological distribution.

The International Workshops on Climate Informatics are held annually to build collaborations between climate scientists and researchers from statistics, machine learning, and data mining. This year marked the sixth annual event (NCAR has hosted and cosponsored all except for the first workshop). The purpose of this workshop series is to build interdisciplinary

partnerships between these researchers.

The format for this year focused on several plenary talks on statistical methods for large spatial data, the role of risk, and insurance in climate change, paleoclimate, and observational data for the polar regions. Interspersed were micro-presentations of selected posters and much discussion. The 2016 workshop hosted more than 80 participants from more than 50 institutions and corporations.

The day preceding the workshop featured an all-day hackathon where the researchers collaborated on solving a big-data problem. Although such events are common in computer science forums, they are still new to NCAR and much of the geosciences. For this hackathon, the students were tasked to predict the monthly sea ice extent based on historical atmospheric variables that were derived from one of NCAR's models. The students collectively worked toward their predictions by using the platform RAMP (Rapid Analytics and Model Prototyping), which allows modelers to share pieces of their code with others. Balazs Kégl, a hackathon organizer, said the hackathon provided valuable experience for the students because “the [hackathon] pipeline is what you do in reality.”

IMAGe's Theme of the Year activities are supported by NSF Core funding. Climate Informatics is supported by NSF Core funds with contributions from Nvidia corporation and the following NSF awards to external institutions: 1345052 (George Washington University, Monteleoni) and 1106862 (University of Washington, Guttorp).

A short walk by participants during the Climate Informatics workshop. Among the many activities for informal interaction, discussion, and research networking is a popular walk from the Mesa Lab during the second afternoon.

‹ Provide internships and externships that support CISL research up Train the scientific computing community ›

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TRAIN THE SCIENTIFIC COMPUTING COMMUNITY

CISL provides training opportunities for researchers in the atmospheric and related sciences to improve their understanding and usage of NCAR's petascale computing and data resources. CISL delivers content synchronously through conferences, workshops, tutorials, webinars, and training classes, and asynchronously through web-based content such as online documentation and recorded lectures.

CISL also leverages the training and student professional development opportunities provided by regional and national HPC consortia such as the Rocky Mountain Advanced Computing Consortia (RMACC) and the eXtreme Science and Engineering Discovery Environment (XSEDE).

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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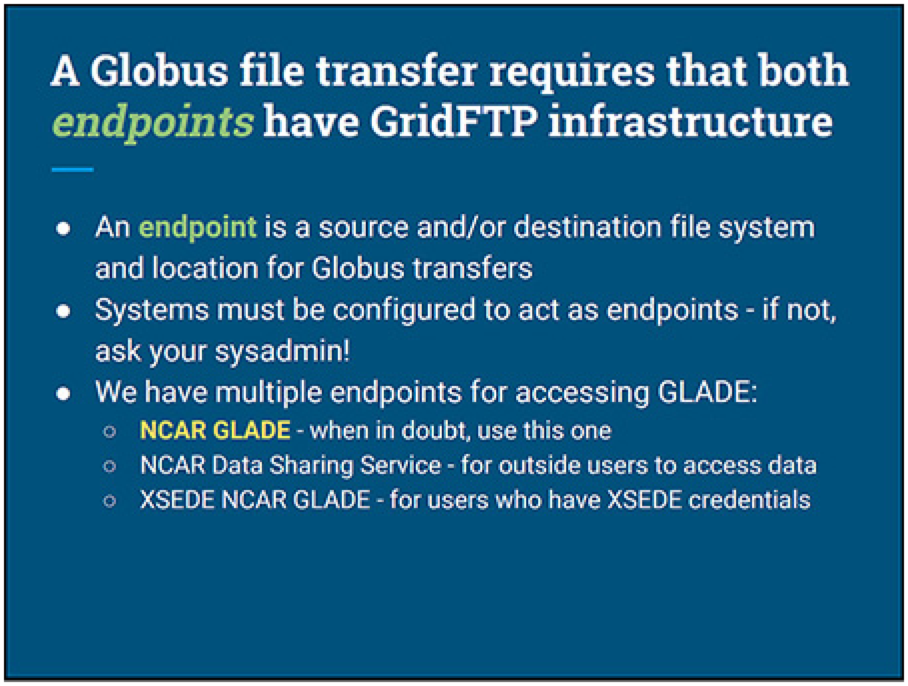
TRAIN USERS AND INTERNS IN COMPUTING AT NCAR

Through a combination of face-to-face and online training efforts, CISL helps prepare students, postdocs, early-career scientists, and more experienced users to investigate questions in the Earth System sciences using its high-performance computing systems and cyberinfrastructure. CISL delivers this content synchronously through workshops, webcasts, and training classes, and asynchronously through its website.

CISL uses these learning opportunities to reach out and inspire new generations of computational geoscientists and



This slide from the training course "Large File Transfers with Globus" focuses on a key aspect of the widely used Globus system for managing and sharing large amounts of scientific data. 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.

enhance the skills of atmospheric researchers in support of its strategic imperative to train the scientific community. By teaching students and faculty to use advanced cyberinfrastructure effectively, CISL facilitates and speeds users' achievement of their scientific objectives, making production of scientific results more efficient. CISL's community development and training efforts also focus on outreach to potential users, particularly those from underrepresented groups.

CISL instructors provided training classes in high-performance computing to approximately 400 local and national HPC users. CSG and other USS staff presented the following courses and seminars in FY2016: Large File Transfers with Globus; Introduction to Yellowstone; Introduction to Cheyenne; Reading and Writing Large Files in Parallel; Git Training (three days); and Modern Fortran (two multi-day classes). USS staff also organized training events taught by outside experts, including Intel Parallel Studio and Allinea Performance Tools Overview. USS also provided 233 Yellowstone authentication tokens for participants in colloquia, tutorials, and classes at NCAR and the University of Colorado in Boulder; NOAA in College Park, Maryland; the University of California, Davis; and Northland College, Ashland, Wisconsin.

In addition to presenting and supporting training classes, CSG staff coordinated the 2016 UCAR Software Engineering Assembly conference. This event included five days of talks and tutorials on big data for the atmospheric sciences; tools, techniques, software frameworks, and platforms for data exploration, analysis, and visualization; batch vs real-time data analysis; cyberinfrastructure for big data in scientific fields; data science workflows; and reproducibility for data science. USS staff also supported NCAR training events that were delivered by other groups and labs, including the CMIP Analysis Platform Tutorial; Community Earth System Model (CESM) Tutorial; and the Community Land Model (CLM) Tutorial. The NCAR Command Language (NCL) team taught two NCL workshops in Boulder, one at the University of Montana, and one at ResCLIM/CHESS in Bergen, Norway, with a total of 60 students. The NCL team also provided Python training in an AMS short course, in a UCAR Software Engineering Assembly tutorial using RDA data, and at a WRF Users Event that trained approximately 90 students.

CISL also hosted and presented a special XSEDE training webcast titled "F5 Tornado Visualizations with VAPOR." 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 has also served as a satellite site for select events in the XSEDE HPC Monthly Workshop Series.

CISL's education imperative for workforce training and development is supported by NSF Core funding.

‹ Train the scientific computing community up Provide training in data analysis and visualization ›

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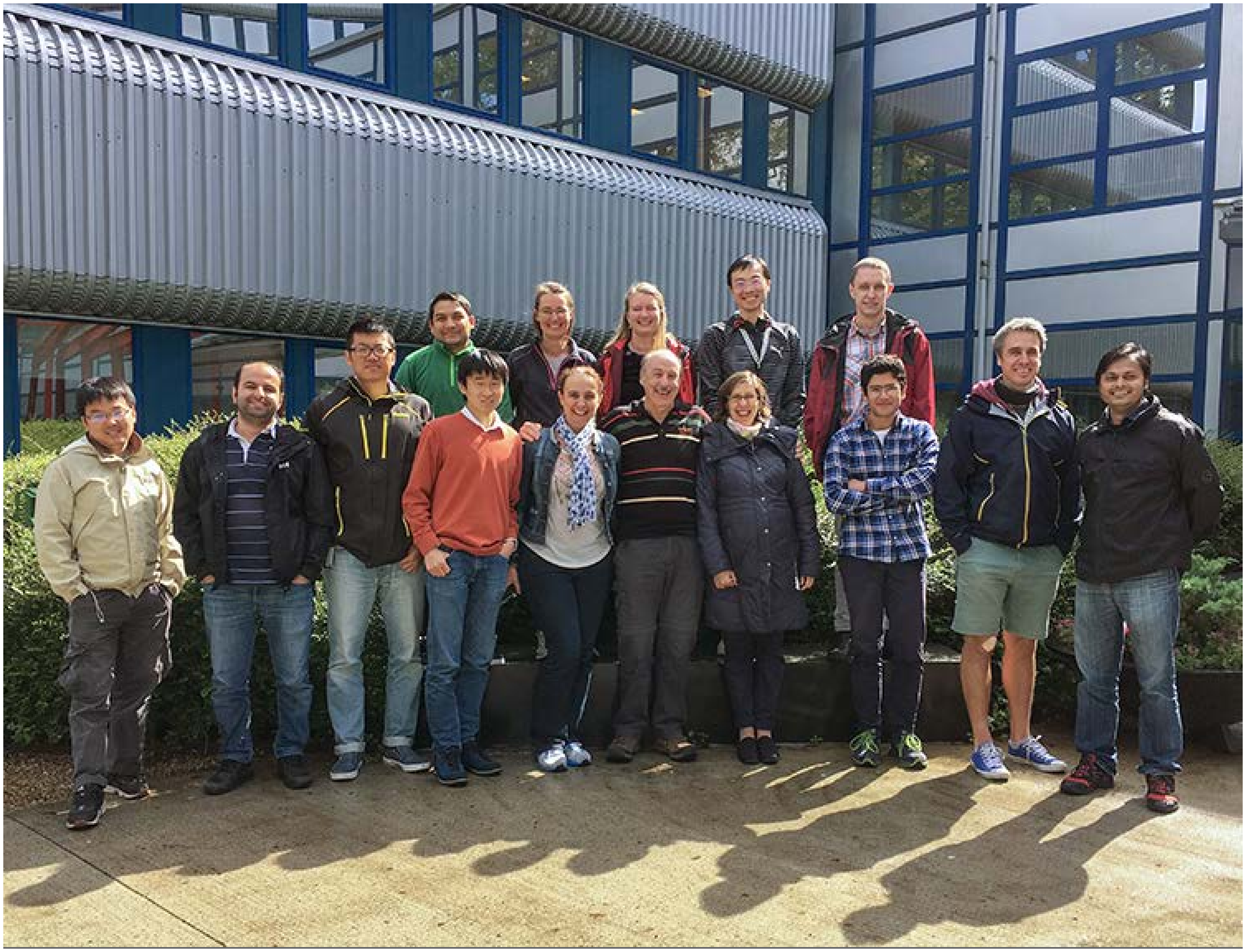
PROVIDE TRAINING IN DATA ANALYSIS AND VISUALIZATION

Effective analysis and visualization of the vast data produced by CISL resources and the geosciences community at large requires thoughtful outreach and immersive training activities. CISL collaborates with the Climate and Global Dynamics division at NCAR to offer three to five training workshops annually for the NCAR Command Language (NCL) – a free, interpreted language designed specifically for geoscientific data analysis and visualization. Multiple-day NCL workshops combine lectures on data formats, visualizations, and data analysis, with intensive hands-on labs. CISL staff also provides hands-on training for related Python tools and the VAPOR package.



ResCLIM / CHESS hosted an NCL Workshop at the University of Bergen in Norway, August 2016. Students in this workshop worked with data from many climate and weather models, including the CESM, NorESM, and WRF.

CISL integrates research and education to prepare current and future generations of scientists to tackle the challenges of 21st-century computational geoscience research. The NCL and VAPOR training programs 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. CISL proactively reaches 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 programs also promote diversity, enhance CISL's culture of teaching and mentorship, and stimulate collaborations with the university community.

VAPOR tutorials were provided at these events:

- WRF Tutorial, July 2016, Boulder, Colorado (~30 attendees)
- XSEDE webinar, June 2016, (~90 attendees)
- WRF Users Conference, January 2016, Boulder (~35 attendees)
- Korean Supercomputing Conference, October 2015, Seoul, Korea (~20 attendees)

Four NCL Workshops were presented in FY2016:

- University of Montana, September 2016, Missoula, Montana (9 attendees)
- University of Bergen / ResCLIM, August 2016, Bergen, Norway (16 attendees)
- NCAR, June 2016, Boulder (16 attendees)
- NCAR, February 2016, Boulder (19 attendees)

NCL and Python training was also offered at these events:

- WRF Users Event, July 2016, Boulder (~30 attendees)
- SEA Tutorial, April 2016, Boulder (~40 attendees)
- AMS PyNIO short course, January 2016, New Orleans, Louisiana (~20 attendees)

The University of Montana workshop was fully funded by CISL. Partial travel funds were provided for 10 EPSCoR students to attend the NCL workshops. The VAPOR tutorial at the Korean Supercomputing Conference was funded by the Korea Institute for Science and Information Technology. All other VAPOR tutorials were supported by NSF Core funds. The NCL workshop at the University of Bergen was funded by ResCLIM/CHESS, while all the other NCL Workshops and related Python training were supported by NSF Core funds.

‹ Train users and interns in computing at NCAR up Support community workshops, tutorials, and summer schools ›

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SUPPORT COMMUNITY WORKSHOPS, TUTORIALS, AND SUMMER SCHOOLS

NCAR plays an important role in helping scientific communities focus on the grand challenge problems of the Earth System. Targeted workshops with flexible formats that adapt to the audience and topics are particularly useful in highlighting areas where more research is needed. These events expose data scientists and computational scientists to the unique problems of climate and Earth System science. They also make NCAR scientists aware of new advances in computer hardware, computational science, and data science that can advance NCAR's scientific mission and improve its facilities.

NCAR Multi-core 6 Workshop

A group of 42 computational experts familiar with creating and optimizing weather and climate applications, along with representatives from industry, gathered at the NCAR Mesa Lab on 13-14 September 2016 to attend the sixth Heterogeneous Multi-core Workshop. Their objective was to share and discuss the latest findings in programming for emerging disruptive computing technologies. This workshop is part of CISL's ongoing processor technology tracking

activity. It is focused on an emerging class of processors, now increasingly in the mainstream, with the common design feature that they trade off lower clock speed for a greatly increased CPU count, and typically offer a large amount of peak floating-point computing power in the form of many SIMD/vector processing elements. The result is a system design that is potentially much faster and more efficient in terms of energy per floating point calculation, but also one that can be much more difficult to program. By persisting year to year, the workshop helps to build a sense of community, create continuity, and foster a clearer understanding of the progress being made in both applications and architectures.

The Multi-Core 6 workshop is held annually at NCAR and focuses on tracking the community's progress in exploiting emerging microprocessors with very high levels of parallelism. The 42 participants came from South Korea, Germany, the United Kingdom, and the U.S. Key vendors in this tech sector and researchers from multiple U.S. government laboratories and agencies were also represented.

The NCAR workshop provided a forum for experts to share experiences and have open discussions that lead to an improved collective understanding of how these new technologies can be most useful to atmospheric science. The workshop specifically focused on the algorithms, programming models, design strategies, and tools that will be needed to create a new generation of applications to exploit these architectures. The workshop also enables this community of developers to participate in a forum where they can collectively provide technical feedback to vendors, develop and share necessary software tools, techniques, and standards, and further develop a new generation of applications for the benefit of Earth System science.

Three themes emerged from this year's conference. First, multi-core system designs are beginning to appear with limited amounts of high-bandwidth memory (HBM). HBM provides O(1) terabyte per second to a new generation of many-core processors, such as Intel's Knights Landing (KNL) and NVIDIA's P100 "Pascal" system. As the latter are just becoming available, many presenters focused on KNL results and the intricacies of using HBM effectively. Second, the Multi-core 6 Workshop had multiple presenters reporting on the status of software tools, programming paradigms, and frameworks designed to ease the difficulty of programming and optimizing atmospheric applications on these systems. Finally, presentation of performance results for specific models and the intercomparison of processors and vendors continued to be a strong focus of the workshop.

Third Annual Graduate workshop on Environmental Data Analytics

Held 25-29 July 2016, this workshop is part of series designed to prepare the next generation of researchers and practitioners to work within, and contribute to, the data-rich era. Each workshop will bring together graduate students and senior scientists in environmental statistics and related fields to explore contemporary topics in applied environmental data modeling. This event hosted 27 graduate students in either statistics or ecology and guided them through hands-on computing and modeling tutorials.

This workshop also offered them an opportunity to share research findings and explore open questions within and at the interface of environmental, ecological, climatic, and statistical sciences. Finally, the workshop also included a visit to the National Ecological Observatory Network (NEON) headquarters to learn about NSF plans for the systematic monitoring, instrumentation, and data collection at the scale of the North American continent. The popularity and impact of this event is evidenced by an applicant pool of more than 50 students. Moreover, the lectures were given by prominent researchers in Bayesian methods and showcased state-of-the-art R packages for computation.

Funding

The Multi-core 6 Workshop is supported by NCAR Core and discretionary funds. The Third Annual Graduate workshop on Environmental Data Analytics was supported by NCAR Core funding plus an NSF CAREER Award 1253225 (Andrew Finley).

‹ Provide training in data analysis and visualization up Perform community outreach ›

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2016 LAB ANNUAL REPORTS

- Atmospheric Chemistry Observations & Modeling
- 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

STRATEGIC PLANS

- CISL Strategic Plan
- NCAR Strategic Plan

PREVIOUS CISL REPORTS

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PERFORM COMMUNITY OUTREACH

Outreach is a conduit through which other goals are reached. Examples include integrating education and research, broadening participation, and developing the future workforce. Enhancing outreach activities increases NCAR’s connection with our university community, students, interns, 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.

On January 15, 2016 23 teachers and administrators from the Wyoming Department of Education visited for a tour of the NWSC.

Students and the public were educated and inspired by the NWSC facilities, computers, and science. In FY2016, 16 school groups with more than 350 students visited the NWSC. In addition, the center has received 27 non-school groups, with a total of nearly 300 members. The NWSC hosted 1,311 total visitors in FY2016, for a total of 8,069 since opening in 2012. In FY 2016, the Pi in The Sky (PinTS) program inspired two summer events in Wyoming: “Robotics, Applied Mathematics, Physics and Engineering Design” (RAMPED) and “Engineering Summer Program for Teachers” (ESP4T). Adding the University of Wyoming as a PinTS partner proved very productive, resulting in over 80 K-12 teachers from around the state learning how to incorporate Raspberry Pis in their school curriculum. CISL honored five students with awards and scholarships at the Wyoming State Science Fair.

These efforts are supported by NSF Core funds, with supplemental funding supplied by other sources as appropriate.

‹ Support community workshops, tutorials, and summer schools   up   Communicate NCAR science using visualizations ›

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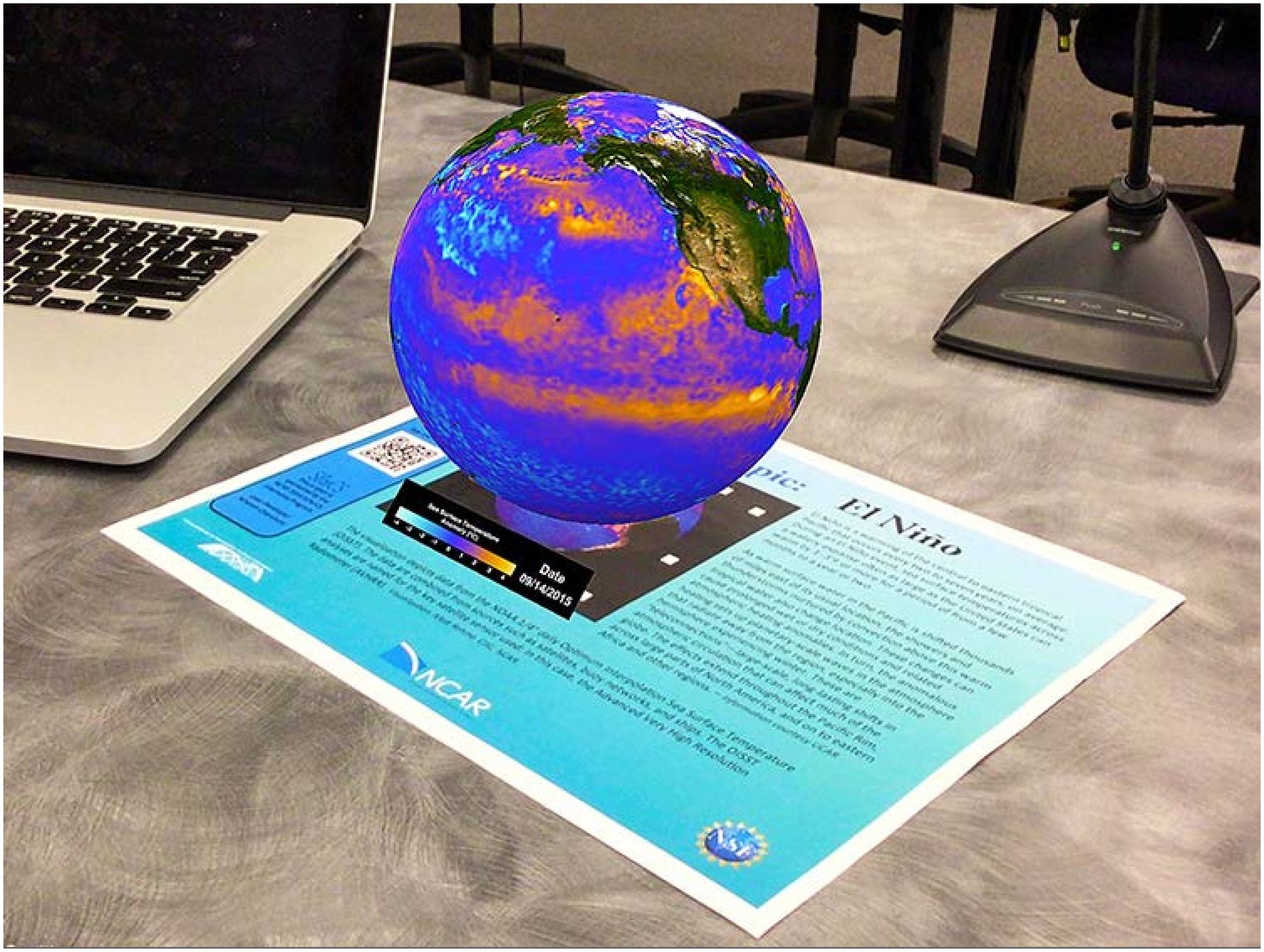
COMMUNICATE NCAR SCIENCE USING VISUALIZATIONS

CISL's Scientific Visualization Services Group (SVSG) operates the VisLab, a center for visual computing, educational activities, and remote collaboration efforts. It serves as a virtual window on NCAR science to communicate NCAR's scientific achievements – and CISL's role in supporting them – through the use of visualizations in a theater-style, high-resolution, 3D presentation format. The VisLab also explores novel visualization techniques and tools, and collaborates with NCAR researchers to create engaging digital media for publication and to help foster the transfer of knowledge and interest in the atmospheric and related sciences. Additionally, its advanced collaboration environment fosters geographically distributed research and communication while minimizing the need for travel by teams collaborating on cross-institutional projects.



This is an iPad screenshot from an augmented reality (AR) project showing El Niño data mapped onto a 3D globe. Nihanth Cherukuru (Arizona State University) worked with SVSG staff to develop an AR mobile app as part of his summer SIParCS internship in CISL. Augmented reality technology enables an interactive environment for overlaying computer-generated imagery on top of real-world video, and it provides new and engaging tools for education and outreach.

The VisLab is a key CISL education, outreach, and training resource that supports CISL's plans and mission to reach out and inspire new generations of computational geoscientists. It provides demonstrations of NCAR science to a wide variety of users including university, government, corporate, and scientific visitors, and by partnering with UCAR's science education program (UCSE) it provides demonstrations to K-12 audiences that help educate and inspire young people about Earth System sciences, scientific research, and High Performance Computing (HPC). The VisLab provides mentoring resources to the CISL SIParCS internship program, which serves university students who are interested in pursuing careers in the computational geosciences. Also, the VisLab collaborates with NCAR scientists to create visualizations of current research that are used in publications, presentations, broadcast news, and posted for community outreach on social media to enhance public understanding of NCAR science and HPC.

In FY2016 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, HPC, and environmental issues. The Scientific Visualization Services Group (SVSG) supported approximately 160

meetings and demos in the CISL VisLab to over 2,050 users including Congressional staffers, NSF officials, NOAA analysts, corporate and research representatives, university students, and international visitors from Germany, China, and Korea, to name a few. Collaborative technologies and tools for video, web, and telephone conferences were used to host over 50 HPC and VAPOR training classes and webinars, connect remote participants at NCAR campuses and other collaborating institutions, and to provide audio-visual and editing support for online access to class recordings. 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 created this fiscal year have been used to educate and to inform about climate change, geoengineering, El Niño, hurricanes, and sonification research. Additionally, SVSG sponsored an intern project with the SIParCS program that resulted in the development of mobile apps for education and outreach through the implementation of virtual and augmented reality technologies.

This project is supported by NSF Core funds.

‹ Perform community outreach | up | Maximize NWSC impact as a teaching and outreach tool ›

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MAXIMIZE NWSC IMPACT AS A TEACHING AND OUTREACH TOOL

The NWSC visitor center is located inside the NWSC facility in Cheyenne, Wyoming and offers a high-quality educational experience that includes windows for viewing the computer room, videos, animated films, touchscreen interactive games, kinesthetic interactive elements, question-and-answer displays, and vivid “story-telling” narratives and imagery. NWSC visitors have included members of professional engineering and technical organizations, K-12 school groups,

Boys and Girls Clubs of America, summer camps of at-risk youth, and the general public. Student groups visiting the NWSC generally engage in supplemental education activities during their visit and explore careers in STEM disciplines. Since January 2013, the visitor center has averaged 2-3 school groups per month in sizes ranging from 12 to 226. The NWSC plays an important role in supporting the computational needs of the scientific community, and its visitor center helps NCAR present its science and mission to educators, students, the public, Wyoming officials, and professional groups.

Students explore the infrastructure required for the NWSC's supercomputer on an interactive display. The NWSC offers hands-on opportunities for visitors to discover and engage in STEM disciplines. The visitor center is a valuable resource for exposing K-16 students to real-world STEM-related career possibilities.

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. 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 goals of the exhibit were to explain how the NWSC's research and science mission benefit people and society, to introduce concepts of computational science and parallel computing, and to provide visitors with a fun and memorable experience. In October 2012, the NWSC opened its doors to the public, and inaugurated its Educational Visitor Center.

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.

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, we updated some of the video content and are preparing for a major update in FY2017, concurrent with the deployment of the NWSC's newest

supercomputer, named Cheyenne.

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.
- Illustrate and explain how the NWSC's research and science mission benefit people and society while providing visitors with a fun and memorable experience.

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. 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 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 8,069 visitors, which is about 13% of the population of Cheyenne, Wyoming, where the NWSC is located. The NWSC hosted 1,311 total visitors in FY2016, including 16 school groups with more than 350 students. In addition, the center received 27 non-school groups totaling nearly 300 members. These numbers represent a decline from previous years which we are addressing through a more robust outreach initiative with a part-time docent and by updating the content and the exhibits, as they have not had significant upgrades since the center opened four years ago.

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.

‹ Communicate NCAR science using visualizations up Perform outreach at regional, national, and

international levels ›

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PERFORM OUTREACH AT REGIONAL, NATIONAL, AND INTERNATIONAL LEVELS

CISL provides exhibits at scientific, technical, and diversity-oriented conferences (e.g., the yearly Supercomputing conference sponsored by the Institute of Electrical and Electronics Engineers (IEEE)), 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.

Richard Tapia (center) with CISL Diversity, Education, and Outreach Specialist AJ Lauer and UCAR Senior Recruiter Tom Cordova at the Richard Tapia Celebration of Diversity in Computing Conference.

CISL's outreach program supports CISL's education imperative for outreach by actively attracting 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's outreach activities at the 2015 IEEE SuperComputing (SC15) conference in Austin included a series of presentations, a stop on the Intel technology tour, and supporting a scavenger hunt for students attending the international supercomputing conference. The presentations in CISL's booth were given by SIParCS interns. Topics ranged from "Performance Analysis and Optimization of the WRF on Intel Multicore and Manycore Architectures" (Samm Elliott, University of Colorado) to "Estimating the Accuracy of User Surveys for Assessing the Impact of HPC Systems" (Melissa Rishel, University of Northern Colorado). We also had guest speakers from Colorado State University. Susmit Shannigrahi and Christos Papadopolous spoke about their "Named Data Networking" architecture. Another key part of SC activities is the technical conversations and private meetings with vendors, some requiring specific non-disclosure agreements, that provide information about future high performance computing developments. These meetings allow CISL staff to preview the future technology landscape, and they 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 SC15 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, the Richard Tapia Celebration of Diversity in Computing, the Rocky Mountain Celebration of Women in Computing, and the Rocky Mountain Advanced 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 2016 Wyoming State Science Fair at the University of Wyoming in Laramie. CISL, UCAR Science Education, and NCAR's Climate and Global Dynamics Laboratory supplied five volunteers as judges, presented five awards for top junior and senior computational and Earth System science projects, and presented atmospheric science demonstrations. 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.

These efforts are supported by NSF Core funds, with supplemental funding supplied by other sources as appropriate.

‹ Maximize NWSC impact as a teaching and outreach tool | up | Communicate via social media ›

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COMMUNICATE VIA SOCIAL MEDIA

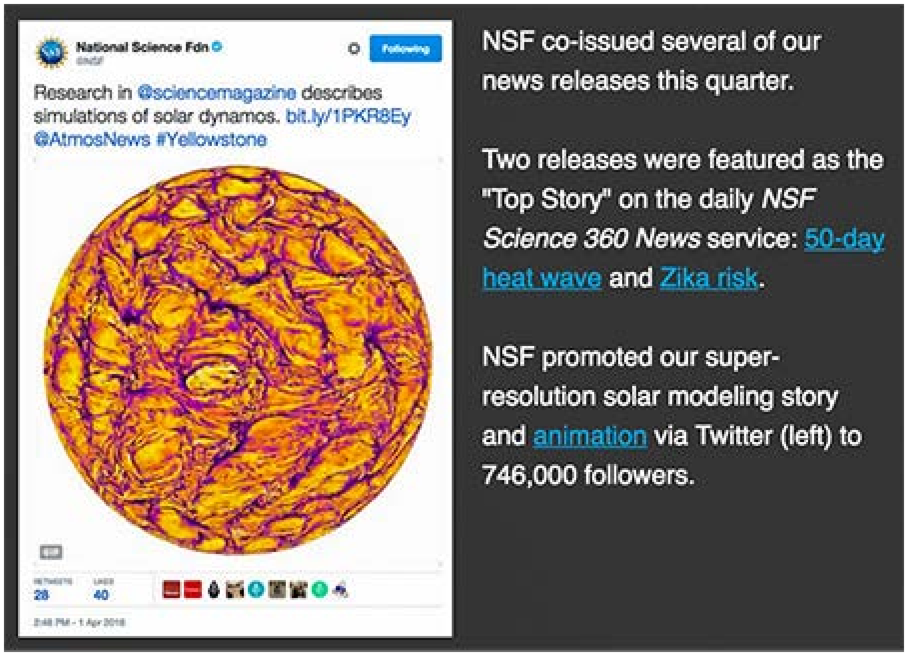
In today’s rapidly changing and increasingly socially networked media landscape, it is important for CISL to identify opportunities and to engage with the public in areas where they are active. To this end, it is becoming more important to use social media strategically. CISL has been working to identify ways to increase its followers and deliver more content via its Facebook pages and Twitter feeds.

CISL uses traditional and social media to communicate the technical and scientific accomplishments of CISL staff, the users of CISL resources, and the visitors and interns who engage in collaborative and professional development activities with our laboratory. Promoting and sharing CISL's work via social media gives greater visibility to the supercomputing resources and their value not only to advancing science, but also how that science serves society.

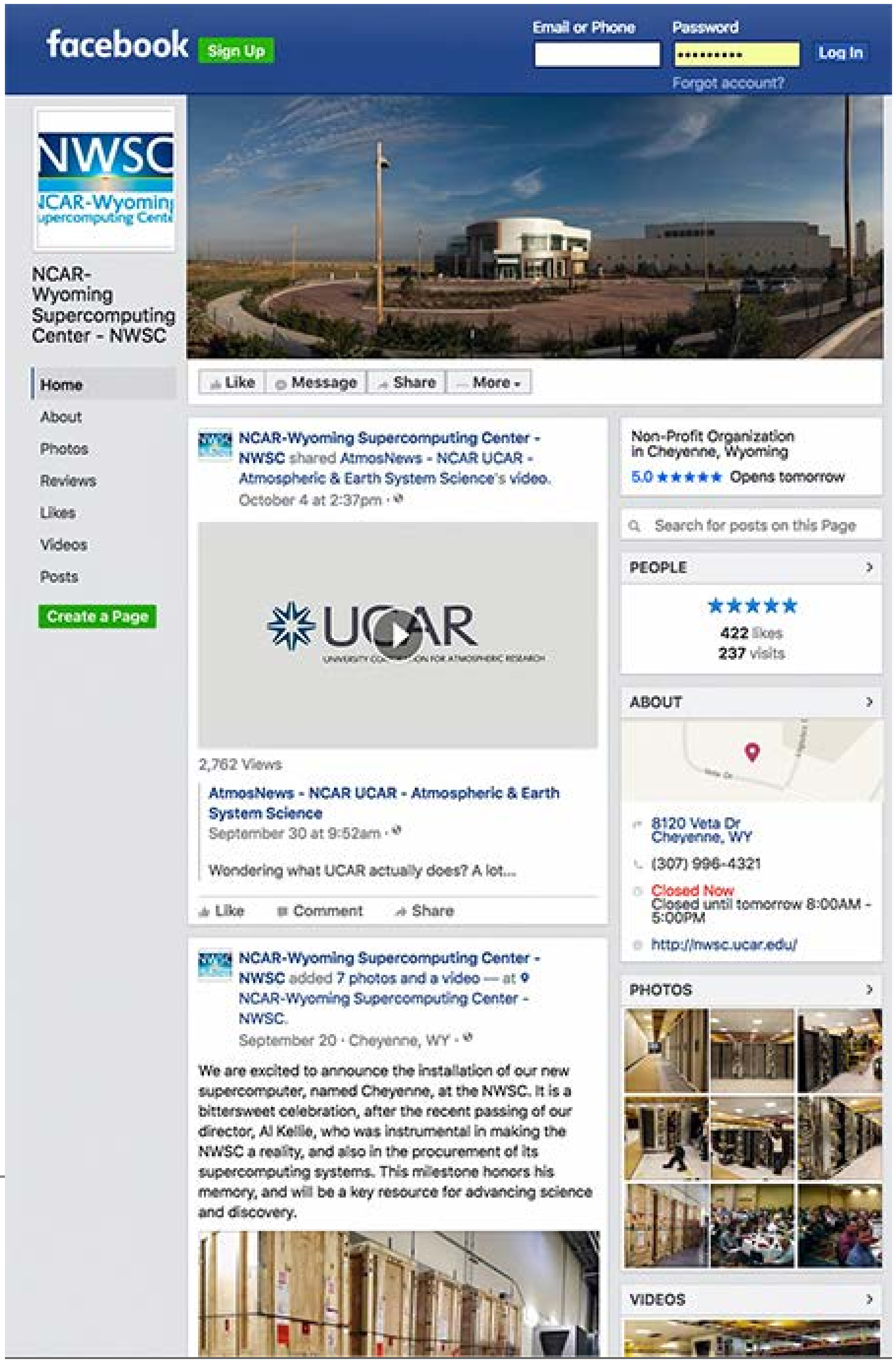
In FY2016 we worked with NCAR/UCAR and NSF to promote a story on solar research by NCAR scientist Matthias Rempel that was published in the journal *Science*. By joining social media forces with NSF on Twitter, the story reached nearly 750,000 people in addition to thousands of followers of *AtmosNews*, NCAR's social media channel. Given this success, we plan to diversify and expand our Twitter engagement as part of developing a coherent and more active social media strategy.

In addition to showcasing NCAR science, social media can also increase community interest and engagement. For example, CISL recently shared a story and photos about the arrival and installation of its newest supercomputer named Cheyenne. This use of social media reached key members of the Wyoming community and created some "buzz" around its official unveiling and other upcoming community activities planned for the spring of 2017.

CISL is also in the process of restructuring and enhancing its video content on YouTube in an effort to better integrate it with other NCAR/UCAR materials, make it easier to find, and improve the quality of our channel. This is an ongoing project in collaboration with other labs and UCAR multimedia services, UCAR Connect, and UCAR Communications. In FY2016 we developed and began to implement new guidelines to ensure consistency and rigorous compliance with copyright and other requirements.



Results of CISL's collaboration with NSF on a social media push about recently published solar research. Within hours, the story reached nearly 750,000 people who follow NSF, in addition to several thousand who follow the NCAR/UCAR *AtmosNews* channel.



The Facebook page for the NCAR-Wyoming Supercomputing Center has several hundred followers, including key partners and collaborators in the Wyoming community. Our updates and stories quickly reach those key stakeholders, and are often re-shared with their constituencies, elevating the profile of our facility and the science it enables.

This work is supported by NSF Core funding.

‹ Perform outreach at regional, national, and international levels
up
Broaden the diversity of education, outreach, and training activities ›

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BROADEN THE DIVERSITY OF EDUCATION, OUTREACH, AND TRAINING ACTIVITIES

Many of NCAR’s outreach efforts are aimed at increasing diversity. In the areas of computational and data science, CISL conducts outreach at conferences that focus on the overlap of diversity and computer science by attending events like the Rocky Mountain Celebration of Women in Computing, the Richard Tapia Celebration of Diversity in Computing, or the ADMI Symposium on Computing at Minority Institutions. NCAR advertises internship and employment opportunities at the IEEE Supercomputing Conference Job Fair and at conferences such as AMS and AGU, as well as on email lists, professional society sites, and university career centers that serve underrepresented groups. NCAR and UCAR internship programs collaborate in outreach activities and have established a reciprocal arrangement for distributing each other’s brochures at events. Diversity outreach and engagement activities in the computational and data sciences are designed to foster strategic diversity-enhancing


CISL Diversity, Education, and Outreach Specialist, AJ Lauer, with Yegeta Zeleke, the CISL-sponsored student travel scholarship recipient at the Richard Tapia Celebration of Diversity in Computing.

conversations and collaborations in mutually beneficial areas in general and at NCAR specifically.

CISL programs enhance the quality and diversity of CISL interns, apprentices, and job applicants, and increase awareness of opportunities for students, faculty, and collaborators among target institutions, underrepresented communities, and EPSCoR states. These programs also promote diversity, enhance CISL's culture of teaching and mentorship, and stimulate collaborations with the university community, all in support of NCAR's strategic imperative to educate and entrain a talented and diverse group of students and early-career professionals.

For the fourth 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 in Winston-Salem, North Carolina from 31 March through 2 April, 2016. 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 2016 ADMI Symposium highlighted undergraduate and graduate research with particular interest in data science. 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. 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. About 20 student attendees signed up for the SIParCS information email listserv. CISL staff also judged ADMI's student poster competition. A CISL collaboration with Intel brought Todd Singleton, VP of Sales at Mashery, as a keynote speaker. Mr. Singleton gave a well-received talk that tied his life experiences to a powerful technology message.

In FY2016 CISL provided funding to support the biennial Rocky Mountain Celebration of Women in Computing. CISL sponsored travel for two female staff members and one female SIParCS intern to attend the conference. One hundred sixty college-age women attended the conference, as well as some high school students and early-career professionals. The CISL attendees provided mentoring to younger women at the conference and staffed a job fair booth where they provided information about the SIParCS program and other internship opportunities through NCAR and UCAR. About 30 of these attendees signed up for the SIParCS information email listserv.

CISL also provided funding to support travel for one student to attend the Richard Tapia Celebration of Diversity in Computing. The Tapia Conference was held in Austin, Texas on 14-17 September and had about 900 attendees. Travel scholarship recipient Yegeta Zeleke is a Ph.D. student studying Sensor Networks and Autonomous systems at the University of California at Santa Cruz. CISL's Diversity, Education, and Outreach Specialist attended the conference accompanied by the UCAR Senior Recruiter to staff a booth at the Job Fair. About 30 students signed up for the SIParCS information email listserv, and several students were identified as candidates who may be interested in participating in the CISL Visitor Program.

These and other diversity-enriching activities were funded by NSF Core travel funds.

‹ Communicate via social media up Expand diversity-tailored education and training opportunities ›

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EXPAND DIVERSITY-TAILORED EDUCATION AND TRAINING OPPORTUNITIES

CISL 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, workshops, and conferences, and offering diversity-focused internships and externships. Diversity outreach and engagement activities in the computational and data sciences are designed to foster strategic diversity-enhancing conversations and collaborations in mutually beneficial areas in general and at NCAR specifically.

In FY2016, NETS manager Marla Meehl served as Principal Investigator of the Women in IT Networking at SC (WINS) program, which funded five women to attend and participate in SCinet and SC15. Aimed at increasing diversity in the national network engineering field, the WINS program leverages the annual SCinet activity to help train and mentor women faculty and staff from institutions across the U.S. in the use of advanced technologies and the national scientific infrastructure. Meehl received a three-year grant to continue the WINS project, which has awarded eight women to attend and participate in SCinet at SC16, which will be held in early FY2017.

Marla Meehl and Jason Zurawski (on left) and Mary Hester (far right) were instrumental in making the WINS program possible. Here, they visit the new NCAR booth at SC15 with the five WINS recipients: (from left) Sana Bellamine, Kathy West, Amy Liebowitz, Debbie Fligor, and Megan Sorensen.

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 provided funding for 13 students to attend the UCAR Software Engineering Assembly (SEA) conference on 4-8 April 2016 that focused on data science. Selected students demonstrated engagement with data science and a desire to learn the skills being taught in the sessions. Funded attendees were from Minority Serving Institutions and received a full travel grant including airfare, hotel, meals, and conference registration. Three future SIParCS interns were among the awardees. MSIs represented included Florida International University, Claflin University, Grambling State University, and New Mexico State University. In addition to attending the conference, awardees attended a luncheon with NCAR and UCAR scientists to learn about careers at NCAR.

Travel scholarship awardees had the opportunity to meet with several NCAR and UCAR scientists during lunch at the SEA Conference in April 2016.

NSF Core funds and grant funding support the SEA conference travel and WINS programs, respectively. The Internet2 Gender Diversity Initiative is funded by Internet2.

‹ Broaden the diversity of education, outreach, and training activities   up

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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) 2016. 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 2016, EOL deployed instrumentation to two NSF-approved field campaigns, one of which fell into the small/simple category (VERTEX), and one that was considered a complex/large project (ORCAS). EOL also supported one cost recovery project for NASA (OLYMPEX), two cost recovery projects for NOAA (SHOUT and MITTS), and two NSF-approved instrumentation tests on the NSF/NCAR aircraft (ARISTO 2016, SOCRATES Test). These campaigns ranged from a few days to several months long, and put to use a variety of the NSF Lower Atmosphere Observing Facilities LAOF that EOL manages to support critical scientific work. EOL's work on these campaigns entailed direct support of more than 25 principal investigators from 40 institutions. Students – undergraduate, graduate and postdoctoral – were directly involved in these field campaigns as well. With the ORCAS campaign, this year again EOL was in the co-leadership of the science team that is focused on biogeochemical cycles over

the Southern Ocean and on challenging predictions of the Earth System global model with observations collected during the campaign.

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. In FY 2016, EOL has continued with efforts to assign Digital Object Identifiers (DOIs) to our archived datasets and to date we have issued over 1,300 DOIs. This year we have also undertaken efforts to collect metrics on publications that have resulted from field campaigns supported by the LAOF. Through our efforts we have identified more than 1,200 publications resulting from the field campaigns in the 10-year time period (2005-2015). The observational science is highly collaborative as reflected in nearly eight authors per publication on average. It is also highly cited with 23 citations per publication, nearly a factor of two higher than the average number of citations per publication for atmospheric sciences according to Thomson Reuters.

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 2016, EOL supported three educational deployments - UIDOW 3 (University of Illinois), MEDOW (Millersville University), and WWCC (Western Wyoming Community College). We also engaged the public and media during the ORCAS field campaign and have been developing educational modules for the Synergistic Environments in Graduate and Undergraduate Education (SEGUE) project to be used to help students understand the complexities and nuances of instrumentation and measurements, a field in which EOL staff holds considerable expertise.

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 2016 we have continued our work on the APAR Master Project Management Plan (MP2). In addition to APAR, teams of EOL scientists and engineers have continued to advance 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®), which is now trademark EOL technology.

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 2016.

Vanda

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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) 2016 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 2016, EOL deployed instrumentation to two NSF-approved field campaigns, one of which fell into the small/simple category (VERTEX), and one that was considered a complex/large project (ORCAS). EOL also supported one cost recovery project for NASA (OLYMPEX), two cost recovery projects for NOAA (SHOUT and MITTS), and two NSF-approved instrumentation tests on the NSF/NCAR aircraft (ARISTO 2016, SOCRATES Test). These campaigns ranged from a few days to several 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 25 principal investigators from 40 institutions. Students –undergraduate, graduate and postdoctoral – were directly involved in these field campaigns as well. EOL’s deployments of the NSF LAOF in FY 2016 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 2016 EOL conducted work on several high priority developments: CentNet, the mobile 449 MHz modular wind profiler, the Water Vapor Differential Absorption Lidar (WV DIAL), and the Airborne Phased Array Radar (APAR).

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 2016, EOL addressed some of our Frontiers by making progress on APAR; planning for a network of WV DIALs; installing a new environmental chamber for instrumentation calibration; and furthering CentNet's reach.

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 increased data stewardship activities; and collaboration with NCAR’s Computational Information Systems Laboratory (CISL) for improved data access; work to help ensure the discoverability of legacy data; new software tools for instrumentation; and furtherance of EarthCube initiatives.

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 2016, EOL conducted education and outreach activities for ORCAS, and continued two internship programs: the Summer Undergraduate Program for Engineering Research (SUPER), and our Technical Internship Program (TIP II). EOL was also in the co-leadership of the science team for ORCAS, which focused on biogeochemical cycles over

the Southern Ocean and on challenging predictions of the Earth System global model with observations collected during the campaign.

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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 2016.

IS-BAO Stage III Audit Results

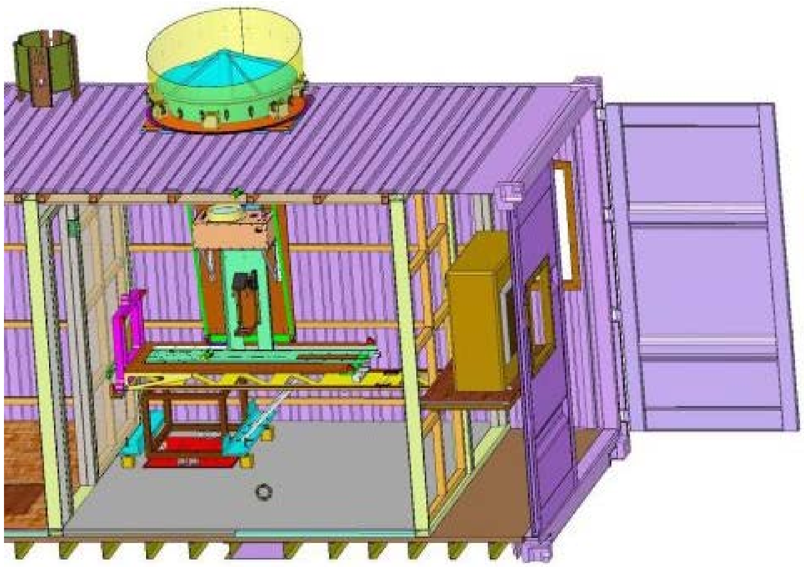
A Stage III International Standard for Business Aircraft Operations (IS-BAO) Stage 3 Audit took place at RAF in April 2016. The IS-BAO audit process is designed to help flight facilities achieve high levels of safety and professionalism. The last stage in the IS-BAO audit process is meant to prove that the audited facility is not only following the rules of the IS-BAO manuals but also working with a self-improvement mentality. Auditors inspected RAF's

operations, maintenance, and safety, and the results were outstanding. Exactly zero violations or “findings” were reported, meaning that RAF is a “top one percenter” facility, according to the inspectors’ outbrief. RAF’s culture of safety and the backing of EOL and NCAR top-level management helped ensure the success of the audit. For more information on what a Stage 3 audit entails, please see here.

National Transportation Safety Board (NTSB) course

EOL and UCAR Communications organized a full-day National Transportation Safety Board training course titled “Managing Communications Following a Major Aviation Accident or Incident”. The June 2016 training highlighted the importance of communications in the event of a major accident. The impact of social media during such an event and the value in coordinating online posts with press briefings were especially discussed and apparent.

Expanding HCR’s Capabilities to Include Ground-based Operations

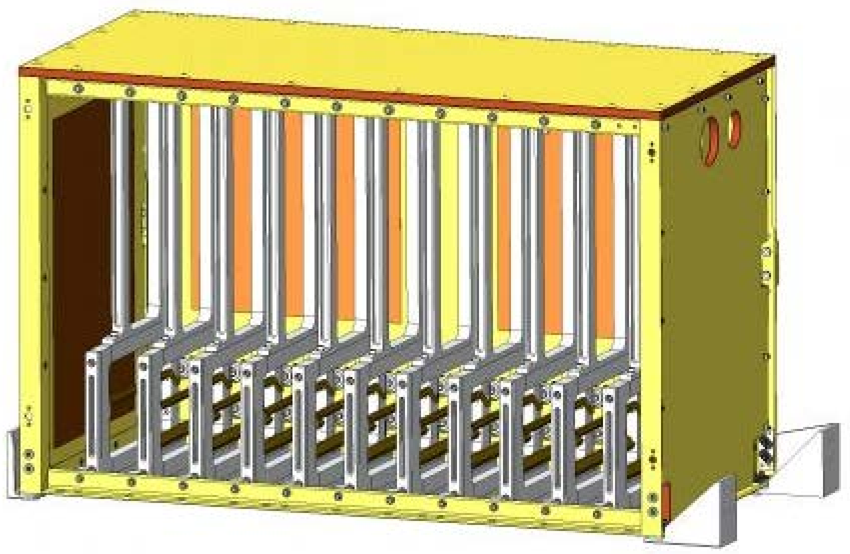


The HIAPER Cloud Radar (HCR) underwent significant improvements to its ground-based home. Besides some initial prototyping, the HCR has always been an airborne instrument with storage between projects taking place in a seatainer alongside the High Spectral Resolution Lidar (HSRL). The HCR’s side of the seatainer was upgraded by DFS with a larger 36-inch Cassegrain antenna, vibration isolators, and a new bench for much easier installation and transport. The new bench features rollers for sliding the radar into the seatainer and a lifting mechanism for positioning the radar into its upright, operational position. Since the radar must be transported in a horizontal position, the vibration isolators will prevent damage. These new upgrades give the HCR more versatility, allowing for deployment as a ground-based system.

S-Pol at Marshall

Through our partnership with the NOAA Radar Operation Center, the S-Pol radar has been set up at the Marshall Field Site. This includes completing the inter-container wiring, lightning protection, fall protection, air conditioner setup, the placement of the SCC and Tech containers, and a fiber network connection, among other work. Work will continue in FY 2017 on finishing waveguide installation, testing of various subsystems, radar calibration, and various smaller tasks. This move ensures that S-Pol can be maintained for use by the community for field campaigns, if requested.

Dropsonde Updates and Improvements



EOL's Design and Fabrication Services (DFS) Facility completed work in 2016 to develop and apply mechanical updates to the automatic dropsonde system for use on the NASA Global Hawk aircraft. This included updating the dropsonde storage release system to the same design as the NSF/NCAR GV system for releasing dropsondes from the storage compartment. The new design and the GV system use a spring return rather than a mass-balance system for the dropsonde release from the storage container. In addition, the rail spacing between compartments holding all the dropsondes was widened to allow for tolerances in dropsonde diameter, as there were variations from sonde to sonde, which caused the dropsondes to catch during the release process. DFS also designed and fabricated a test fixture to easily verify dropsonde diameter to insure uniform dropsonde tube shapes. The In Situ Sensing Facility (ISF) updated the launcher firmware for improved fault detection in the system if issues do occur. ISF and DFS worked very closely together on this project, as all the wiring had to be completely disassembled and reassembled along with full system testing for these modifications. During the rewiring process by ISF, changes were made such that the total sonde capacity has been increased from 88 to 90 dropsondes for each flight.

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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:

- VERTEX(small)
- ORCAS (large)
- OLYMPEX (small, NASA-funded)
- SHOUT (large, NOAA-funded)
- MITTS (small, NOAA-funded)
- ARISTO 2016 (instrumentation test)
- SOCRATES-Test (instrumentation test)

In FY 2016, 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.

ORCAS

The O_2/N_2 Ratio and CO_2 Airborne Southern Ocean Project (ORCAS) campaign took place from 15 January – 29 February 2016, operating from Punta Arenas, Chile. The goal of ORCAS was to advance the understanding of the physical and biological controls on air-sea exchange of O_2 and CO_2 in the Southern Ocean. ORCAS conducted intensive airborne surveys of atmospheric O_2, CO_2, related gases, and ocean surface properties over diverse biogeochemical regions adjacent to the southern tip of South America and the Antarctic Peninsula on 19 flights in January and February 2016. The NSF/NCAR GV aircraft flew with a suite of high-precision in situ and remote sensing instruments combined with whole-air samplers. The project also included hyperspectral remote sensing of the ocean surface, characterization of the emissions of biogenic reactive gases over the Southern Ocean, and measurements of cloud and aerosol properties. ORCAS observations were guided by and will be used to test ocean biogeochemistry models to improve our understanding of key processes and feedbacks in an undersampled yet climatically important part of the world.

Preliminary results show that, among several other findings, ORCAS was successful in characterizing the large-scale abundance of O_2 and CO_2 over the Southern Ocean and its evolution over six weeks, which will provide precise estimates of O_2 and CO_2 exchange over much of the Southern Ocean in the preceding months and during the campaign.

Airborne Research Instrumentation Testing Opportunity (ARISTO) 2016

ARISTO 2016 was conducted in August 2016, and its payload included instruments from JPL, IMK, Colorado State Univ., Univ. of Washington, Univ. of Colorado, Univ. of Wyoming, and NCAR. The instrument installations required the fabrication of infrastructure for the aircraft, and DFS and RAF worked together to ensure the successful integration of the scientific payload.

A total of 14 instruments flew during ARISTO 2016 and six flights were carried out, providing crucial engineering and science data for the participants. The fourth flight was particularly productive with all the instruments on the payload working well, and the C-130 flight crew was able to locate and penetrate local biomass burning smoke plumes. As a result, most of the air atmospheric chemistry objectives were accomplished. The last flight targeted the West Coast to support maritime cloud sampling and dropsonde deployment.

HCR Test 2016

The HCR Test 2016 program ran from September 19 to October 10, 2016, operating from RAF. Four flights were executed to test and evaluate several aspects of HCR operation, including a new INS that would hopefully improve angle accuracy as compared to the current unit. The flights were successful in that all potential issues related to the aircraft and GPS feed were illuminated, but unforeseen problems were discovered with the angle information from the new INS unit. EOL staff began work with the vendor on firmware updates in hopes of correcting the isolated INS dynamics issues. Further testing and correction will continue in FY 2017.

VERTEX

The Vertical Enhanced Mixing research project was led by Cristina Archer at the University of Delaware to study the effect of the wake of a wind turbine on the atmosphere-surface exchange of momentum, sensible heat, and water vapor. Fifteen ISFS stations collected data from 1 September through 31 October 2016 in a challenging wetlands environment. EOL staff showed their ingenuity and talent in their unique capability to deploy in just about any environment - the project is situated in a marsh where boats are required for all project operations. The project setup was so reliable that all of the sites survived the remnants of Hurricane Hermine, and the scientific data obtained will be analyzed by the PI in FY 2017.

VERTEX instrumentation after Hurricane Hermine.

SHOUT

EOL supported the third field campaign of the Sensing Hazards with Operational Unmanned Technology (SHOUT) NOAA project with the automated AVAPS system on the NASA/NOAA Global Hawk, which was based at NASA Wallops flight facility in Virginia and the NASA Armstrong Research Center in California. The field campaign took place for ten weeks from 1 August to 10 October 2016.

Flights took place into Hurricane Gaston, Hurricane Hermine, Tropical Storm Karl, and Hurricane Mathew. Flight RF03 released 90 dropsondes, which is a new record for the most sondes released during a single flight of any dropsonde system. In all, 647 sondes were deployed in 213 flight hours during the SHOUT campaign. The SHOUT team was on call for 10 consecutive weeks, including an extension during Hurricane Matthew, without missing a scheduled flight. The SHOUT Hurricane Rapid Reponse (HRR) Management Team wrote an encouraging letter touting the outstanding interagency work on the project. “This effort results in the most comprehensive set of observations to date from an unmanned aircraft in a tropical storm environment,” said Project Manager Philip Kenul.

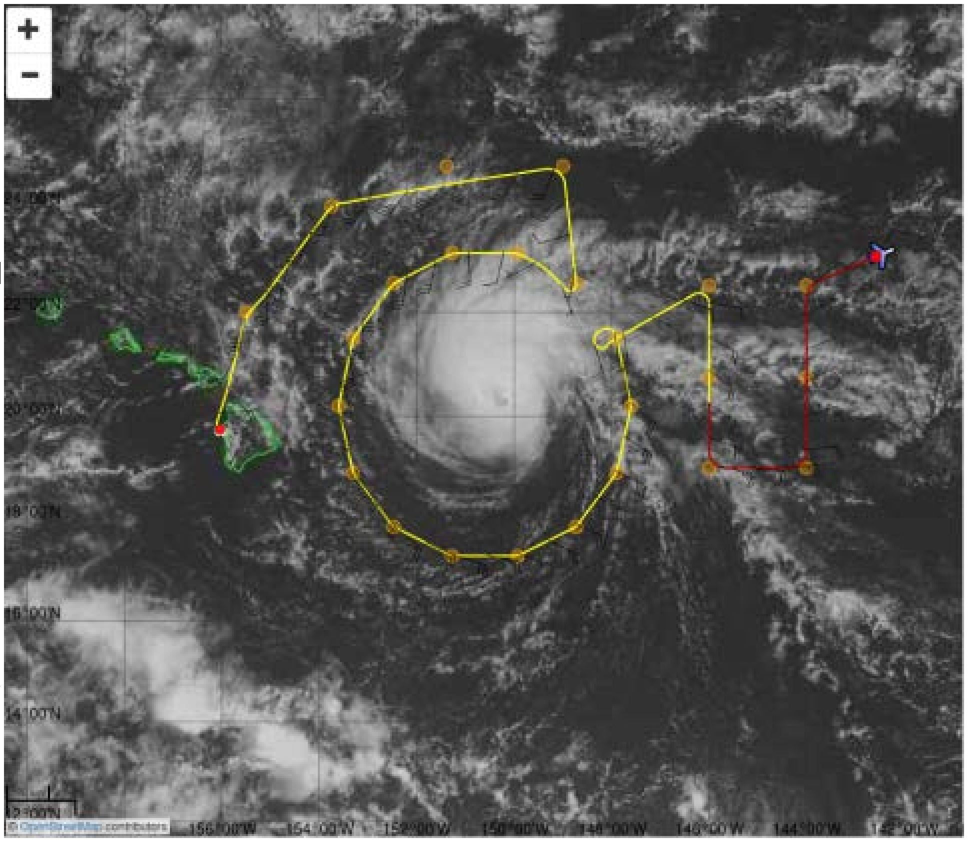
EOL also supported the NOAA Global Hawk’s participation in the ENSO Rapid Response Mission, which is part of SHOUT, by installing and supporting the dropsonde system on the GH for flights during spring

2016. The dropsonde system was an integral part of this three-week mission, which was based out of Edwards AFB at NASA Armstrong in California.

MITTS

The Monitoring the Intensification and Track of Tropical Storms (MITTS) project's purpose was to support NOAA operational hurricane tracking and observations while their G-IV was undergoing repairs. The NSF/NCAR GV was outfitted with AVAPS to take observations of developing and mature tropical systems in the tropics when needed. Collected data supported operational forecasters and models to help provide better forecasts of tropical storm strength and track.

On 23 August 2016, RAF received a request to deploy the GV, and a group leads decided such a deployment was feasible. Maintenance on the GV was finished 25 August, and AVAPS was installed onto the plane. Tampa, FL was the initial target, but on 29 August, the MITTS team was informed they were going to Hawaii. Between 23 August and 30 August, important maintenance items were finished; AVAPS, display racks, and seats were installed; the aircraft was certified for flight; aircraft and ground products were configured; and logistics were planned without knowing exactly where the GV would be sent. On 30 August, the GV began testing dropsondes off the coast of California in preparation for a Pacific deployment. On Wednesday, 31 August, the GV flew around Hurricane Lester, deploying 22 dropsondes and recovering to Honolulu. The GV flight track around Lester is shown below.



The GV returned from Hawaii the evening of September 3rd after its last surveillance flight around Hurricane Lester. In the three days that the GV flew around Lester, 87 total sondes were dropped, sending valuable information to the National Centers for Environmental Prediction Environmental Modeling Center (NCEP/EMC) in real time for modeling the track of the storm.

NOAA was very impressed with EOL's efficiency, professionalism, and commitment to safety. The work on MITTS was noticed at high levels within NOAA and NSF and will only serve to boost EOL's reputation. NOAA Rear Admiral Anita Lopez wrote a letter praising "the outstanding support provided by the NSF/NCAR Gulfstream V." Lopez said that the data collected by the GV improved forecasts by 15% for the storms that impacted Hawaii.

See the MITTS project page for more information on MITTS and 9News, NSF's media site, and the Daily Camera for media coverage on the project.

Olympic Mountains Experiment (OLYMPEX)

The NASA Olympic Mountains Experiment (OLYMPEX) occurred in November - December 2016. One of the NSF science goals of the project is to test hypotheses regarding orographic precipitation in conjunction with frontal passages over

mountain ranges. Those on the project plan to release AVAPS Dropsondes over the Pacific Ocean.

This joint project between NASA and the University of Washington's Department of Atmospheric Sciences, OLYMPEX wrapped up with a successful Global Precipitation Measurement (GPM) satellite underpass over post-frontal oceanic precipitation. ISF supported OLYMPEX with dropsondes on the NASA DC-8, which carried out 19 science flights for a total of 93.3 flight hours. The DC-8 was used to help assess the accuracy of a new generation of weather satellites and to precisely calculate how much water is in a storm in the form of rain, snow, or ice. In addition to the DC-8, the project involved two other aircraft and a variety of ground-based instruments including the CSWR DOWs.

‹ Imperative I | up | Imperative III ›

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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).

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.

Our development efforts in FY 2016 included continued work on expanding CentNet; improvements to the 449 MHz wind profiler system, including development of a mobile version; further development of the Water Vapor Differential Absorption Lidar; work on the Airborne Phased Array Radar; and the Lidar Radar Open Software Environment (LROSE). We also expanded our expertise in project management practices and held an R&D Summit to hear about emerging development ideas from EOL staff.

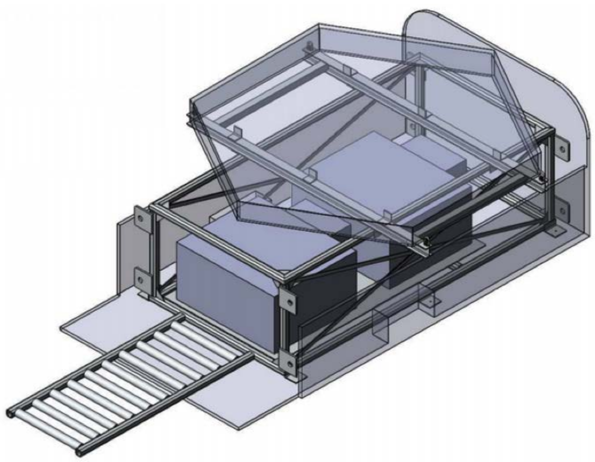
CentNet

A new Data System Module (DSM) for CentNet

In FY 2016, CentNet's capabilities were significantly enhanced through the replacement of hygrometers, the addition of sonic anemometers, building new TRH sensors, building 60 new Data System Modules (DSMs) based on inexpensive and efficient Raspberry Pi, the addition of 60 more motes to connect radiation and soil sensors, adding more solar panels and tower mounts, purchasing new optical disdrometers, and embedding a new microprocessor into new integrated net radiometers. EOL also used our newly installed altitude/temperature calibration chamber to calibrate all of the in-situ sensors necessary to support of the VERTEX (FY 2016 – 2017) and Perdigão (FY 2017) deployments and to achieve high quality data sets for these field programs.

Mobile 449 Profiler

The motivation for this development is to take advantage of EOL's expertise in 449-MHz wind profiler technology to replace and enhance the current LAOF Mobile Integrated Sounding System (MISS), which uses an older 915-MHz profiler. The 449-MHz profiler is advantageous in that it takes measurements at higher frequencies (every few minutes) and is more flexible than the 915-MHz profiler. DFS and ISF are bringing together design plans for the Mobile 449-MHz Wind Profiler, which is designed to fit into the bed of a pickup truck or onto a trailer with design elements including vibration isolates, a leveling system, and air conditioners on the electronics boxes. A design with the profiler inside the bed of a pickup is pictured to the right. The Mobile 449-MHz Wind Profiler is set for completion in early 2017.



Truck Bed Install (Antenna & Truck Bed Transparent)

APAR

The second official meeting of the APAR Advisory Panel (AAP) occurred in December 2015 and included four panel members, 15 EOL APAR Team members, and other EOL staff. The meeting covered a number of topics including the expanded project management activities, updates on technical aspects and testing of the transmitter/receiver (T/R) module printed circuit board (PCB), the antenna aperture design, and C-130 APAR feasibility analysis. The Panel offered comments on these developments and provided suggestions for content in the Request for Information to be released in the first part of this year.

Based on the AAP's recommendations, APAR's technical team produced a comprehensive Technical Requirements Document

(TRD) for APAR. The TRD includes the scientific rationale for the radar; technical requirements (AESA hardware); system calibration; aircraft structural, electrical, and environmental considerations; radar maintenance; concept of operations; and an overview of risk and project management. The document was finalized on 29 April and distributed to the EOL Management Council and AAP for comments.

In general, the APAR effort is moving along. A full assessment of the LRU transmitter/receiver printed circuit board has been completed, and a redesign of the board is underway. An airflow study was conducted to assess how two different APAR external antenna configurations would fare on the C-130; the computational fluid dynamics study found that either configuration can be flown on the aircraft. A Request for Information (RFI) was sent to industry sources to assess the technical viability of our approach and to better estimate the cost to develop and fabricate the Active Electronically Scanned Array (AESA). Evaluation of those responses began in late FY 2016.

LROSE

The Lidar Radar Open Software Environment (LROSE) development continued in FY 2016 with the awarding of funding for continued work between NCAR and University partners. The goal of the work is to apply a collaborative open source approach to help to address the “big data” problem faced by users in the radar and lidar research community and to provide solutions that are readily accessible to the average user. The plan involves:

- packaging LROSE so that it can be run on a virtual machine, either locally or in the cloud;
- collaborating with other developers of open-source radar software who have adopted a similar approach;
- developing standard algorithm modules for those typical processing steps that are well understood and documented in the available literature; and
- involving the user community in the development of new research modules that address the specific needs of the latest scientific research.

This project will build on existing prototypes and available software elements, while facilitating community development of new techniques and algorithms.

LROSE work in FY 2016 included improving data infrastructure and using S-Pol data from PECAN to develop improved algorithms for data quality and assessing the calibration accuracy of the radar. This work lays the framework for the planned steps outlined above.

R&D Summit

EOL held a two-phased Research and Development Summit in fall 2016. The Summit provided a unique opportunity for any member of EOL to present new and creative ideas for sensors, instrumentation, software tools, or other capabilities, as well as new and novel approaches to the challenges and opportunities in EOL and for the communities we support. EOL management then underwent an evaluation process that led to seed funding for two of the proposed activities. One will allow EOL to further its progress towards an airborne microwave radiometer for water vapor and liquid water by delivering a concept for a new or enhanced microwave radiometer. Such measurements are critical for cloud and environment characterization and for understanding the impact the earth’s water cycle. The other project will make major strides for EOL towards low-cost, low-maintenance, quantitative measurements of aerosol and improved measurements of water vapor above the boundary layer and at cloud boundaries, as well as providing us better understanding of a perhaps alternative path to thermodynamic profiling.

Project Management Professionals

Fifteen EOL staff participated in a nine-month course for Project Management Professional (PMP) certification and 8 of them have taken and passed the exam required by the Project Management Institute (PMI) to become certified. According to PMI, those who complete the course are “expected to be able to lead and direct cross-functional teams to deliver projects within the constraints of schedule, budget, and resources and to demonstrate sufficient knowledge and experience to appropriately apply a methodology to projects that have reasonably well-defined project requirements and deliverables.” These new skills in EOL will be extremely helpful as we undertake developments and other complicated projects.

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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 and Publication Stewardship Project (DPS)

The Data and Publications Stewardship Project (DPS) began in late 2015 with the goal of identifying, locating, managing,

and then assigning Digital Object Identifiers (DOIs) for all datasets collected from EOL instrumentation between 2005 to 2015. By managing these datasets within the EMDAC data system, we now allow for easy access and metrics tracking for the data and metadata. Significant progress has been made on metadata cleanup, field project web page development, dataset addition to EMDAC, and DOI assignment, and as of the end of FY 2016, 90% of all datasets from that timeframe have been assigned DOIs.

The DPS project also included work on identifying publications resulting from EOL-maintained instrumentation and datasets and metrics collection. Over 6,000 publications are now included in the EMDAC database, including the 1,200 added for the years 2005 through 2015, and EOL began work in 2016 to verify that all publications included are indeed associated with EOL-supported field campaigns.

Mission Coordinator and Catalog Maps for Aircraft

A new software tool aimed at scientists has being installed on EOL aircraft. This tool merges the Mission Coordinator Display with the Catalog Maps GIS Tool and allows airborne and ground-based scientists to overlay relevant information (e.g., satellite imagery, radar data, lightning, vertical profiles) and flight imagery with the locations, tracks, and plans of project aircraft in real time. Previously, the Catalog Maps GIS Tool (shown above) only worked on the ground. As part of this upgrade in 2016, its capabilities are now available in the air. Merging these tools provides a more coherent set of displays to scientists and flight personnel and improves the flow of supporting products between the ground and the plane. The new software will also provide a streamlined pathway for upgrading features and services both on the ground and in the air and will offer the ability to playback products during a mission using the tool - a feature that was not available with the Mission Coordinator Display. The new Catalog Maps tool was demonstrated onboard the NSF/NCAR GV during the ORCAS campaign (see here).

Backup and Online Access of EOL's HPSS Holdings

EOL currently has about 350 terabytes (TB) of data composed of 4.3 million files spanning the past 35 years on NCAR/CISL's High Performance Storage System (HPSS). In FY 2016, EOL undertook work to create a consolidated version of EOL's HPSS holdings that would fit on roughly 45 cartridges, as opposed to the 6,600 tape cartridges on which the data currently reside. This dataset would be held at the NWSC and facilitate migration of EOL observational data for any future HPSS upgrades. We also began work to create an offsite disaster recovery file set, which would be stored at the NCAR Mesa Lab, and to build an online copy of EOL data that can be integrated into EMDAC. This implementation will allow for very quick access to EOL data by the user community, allow for building more advanced data services on top of the archive, and will address issues of speed and disaster recovery.

CHORDS

In FY 2016, EOL's Cloud-Hosted Real-time Data Services (CHORDS) proved vital in its implementation on a few projects. Funded by the EarthCube Initiative, CHORDS allows scientists to easily provide Internet access to real-time streaming data, with the goal of lowering the barrier for instrument teams in putting their real-time data online and in standard formats. Scientists and engineers from the Joint Numerical Testbed Program (JNTP) in NCAR/RAL and the UCAR/JOSS program developed a way to three-dimensionally print automated weather stations (3D PAWS), and CHORDS was in turn

implemented into the 3D PAWS project to retrieve the data from the weather stations, allowing it to be viewed and distributed online.

CHORDS was also tested in FY 2016 as a method to provide access to EOL field data in real time during ORCAS, for the purpose of improving data quality for that experiment, and is being used with atmospheric, hydrological, and solid earth sensors. Please see the EarthCube website for more information.

‹ Imperative III up Imperative V ›

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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.

ORCAS outreach activities

ORCAS outreach activities included two graduate students helping with flight planning and participating in a flight, and a Google Hangout for several undergraduate classes. The Chilean Minister for the Environment also visited with others involved in setting Chilean climate policy.

SUPER

EOL hosted four Summer Undergraduate Program for Engineering Research (SUPER) interns in FY 2016. While at EOL, these interns helped develop new instrumentation and software and improve EOL's existing suite of NSF/NCAR LAOF. **Matthew Daily** worked with Stuart Beaton in RAF to create an object-oriented and networked software framework for command and control operation of the Giant Nuclei Impactor (GNI) Analyzer imaging and analysis instrument. **Nicholas DeCicco** worked with Janine Aquino in RAF on developing software to convert legacy data to modern formats. **Joseph Ronsivalle** worked with John Sobtzak in ISF to test, verify and document performance of electronic components for the Mobile 449 MHz profiler system. **Julian Claudio** worked with Jim Ranson in DFS to document, redesign and create engineering drawings of the NCAR balloon borne replicator instrument for use in fabricating such instruments.

TIP

Two Technical Internship Program (TIP) mechanic interns, **Tyler Weyrich** and **Steven Blackman**, work at RAF during FY 2016. They received hands-on experience from RAF's Flight Operations group on a variety of aircraft maintenance tasks, learning how aviation can be used as part of a larger science objective.

SEGUE

In FY 2016, the Synergistic Environments in Graduate and Undergraduate Education (SEGUE) in Atmospheric Instrumentation and Measurement Training proposal was recommended for funding. This collaborative proposal with UCAR/COMET and Millersville University aims to design, develop, and openly distribute a series of interactive, multimedia, and online modules. These modules are intended to be easily and effectively integrated into courses on instrumentation, measurement, and observing systems to supplement traditional teaching methods and enhance blended instruction.

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FRONTIER I

Improve observing capabilities for weather and climate phenomena with high socio-economic impact

Airborne Phased Array Radar (APAR)

The APAR team made steady progress on developing the APAR Master Project Management Plan (MP2) in FY 2016. Since January, the APAR Technical Team has participated in several multi-hour sessions to comprehensively identify the technical and operational requirements needed to document APAR specifications, assumptions, risks, and issues. All in all, the MP2 Project Leads reviewed and vetted 177 requirements in the areas of radar development, operations, lifecycle management, airborne testing, data management, and aircraft modifications. Many of these requirements also translated directly in to the Request for Information (RFI) that was sent to industry in summer 2016. Evaluations of the responses began in FY 2016 and are continuing in FY 2017.

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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.

A proposal for a micro-pulse DIAL (MPD) testbed for sensing lower tropospheric water vapor profiles was recommended in FY 2016 for funding by the NSF Major Research Instrumentation (MRI). Reviewers of the proposal nearly uniformly acknowledged the system’s benefits to society through the advancement of our knowledge of water vapor distributions, which would ultimately result from the MPD system. The project aims to develop and make available to the science community a testbed of five DIAL instruments for measuring the spatial and temporal distribution of water vapor in the lower atmosphere.

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FRONTIER III

Develop new capabilities that focus on processes at interfaces in the atmosphere

CentNet

EOL has been developing a large network of ground-based sensors to help address scientific challenges and to facilitate research in the biogeosciences, hydrology, and urban meteorology, in addition to the mesoscale meteorological research traditionally supported by tower networks. This 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 and will 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. 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 2016, CentNet's capabilities were significantly enhanced through the replacement of hygrometers, the addition of sonic anemometers, building new TRH sensors, building 60 new Data System Modules (DSMs) based on inexpensive and efficient Raspberry Pi, the addition of 60 more motes to connect radiation and soil sensors, adding more solar panels and tower mounts, purchasing new optical disdrometers, and embedding a new microprocessor into new integrated net radiometers. EOL also used our newly installed altitude/temperature calibration chamber to calibrate all of the in-situ sensors necessary to support of the VERTEX (FY 2016 – 2017) and Perdigão (FY 2017) deployments and to achieve high quality data sets for these field programs.

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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

New Cal lab chamber

This year EOL welcomed a new altitude/temperature environmental test chamber to its Calibration Laboratory. The combination of altitude and temperature available with the chamber provides a simulation of real-life conditions and will allow for testing of instrumentation on the ground, verses an aircraft, in a controlled environment. The chamber has an altitude range of seal level to 30,480 m (100,000 ft) and temperature range of -73°C to 177°C. EOL put the new chamber to the test in summer 2016 by testing dropsonde sensors and the Global Hawk launcher in preparation for the SHOUT campaign. The launcher sits in an unpressurized compartment on the NASA Global Hawk where the typical flight altitude is 60,000 feet and extremely cold. This testing was valuable to verify proper operation of the system in real flight conditions without having to fly a plane.

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HAO DIRECTOR'S REPORT–2016

It is with great pleasure that we present the 2016 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.

Director Scott McIntosh

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.

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.

In a year of NCAR-wide scientific and management reviews conducted by the NSF, we had to pause on the implementation of our new strategic plan. In the final quarter of the year we pushed forward with the reorganization of the Lab to deliver

on that plan. A major part of that effort lay in the constitution of eight strategic working groups; six with scientific and two with community focus. We formulated scientific working groups that push forward HAO’s contemporary core scientific programs, like CoSMO, WACCM-X and CSAC while creating pathways for future community modeling efforts for the coupled Geospace environment and for the solar interior. The community-focused working groups help to consolidate our efforts in education, outreach, mentoring, data stewardship and partnerships. All staff have been involved in the construction of these groups and been freely able to associate with them. As the groups complete their charters, goals, and milestones they will be made available on our web page. In due course we desire to have extensive community partnership within these working groups—developing those partnerships will form a large part of the focus in the next year.

The past year saw a massive confluence of scientific and political will towards understanding the relentless coupling between the Sun, solar wind and terrestrial environment through the space weather enterprise. This unparalleled level of interest in our science at national level creates great opportunity for NCAR, HAO and the broader solar-terrestrial physics community - our strategic plan, and working groups, are geared towards pushing forward in several key areas that we hope will not only advance our understanding, but also funding levels to the entire community.

Over the reporting year, several colleagues have gained promotions. Mausumi Dikpati was promoted to Senior Scientist, Mike Galloy was reclassified to Software Engineer III, and Rob Graves to Technician II. It was also a year off loss for the HAO family. In August, we lost Vic Tisone who had recently retired. This left many of us in shock, but in his name the drive to move on is focused.

Beyond the development of our strategic implementation plan and participating in NCAR reviews, you will see that 2016 was a busy year scientifically and, in the following highlights, you’ll see that we made significant progress in key areas of our program.

In the coming year one event will likely dominate proceedings, the once-in-a-generation, total solar eclipse that will transit the continental US on August 21, 2017. In addition to participating in a major citizen-science project, “the Eclipse Megamovie”, HAO will coordinate a first—a community field campaign exploiting airborne and ground-based assets to study the corona of the eclipse in the deep infrared. Our hope is that a successful airborne element to the 2017 eclipse field campaign opens the NCAR Gulfstream 5 aircraft to the our community for future eclipse observations. Complementing the scientific experiments, our staff will be participating in public education and participation events during the eclipse, spanning the path of totality from Oregon to the Carolinas.

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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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 2016.

‹ HAO Director's Report–2016 | up | Super-Resolution Solar Model Achieves Order Out of Chaos ›

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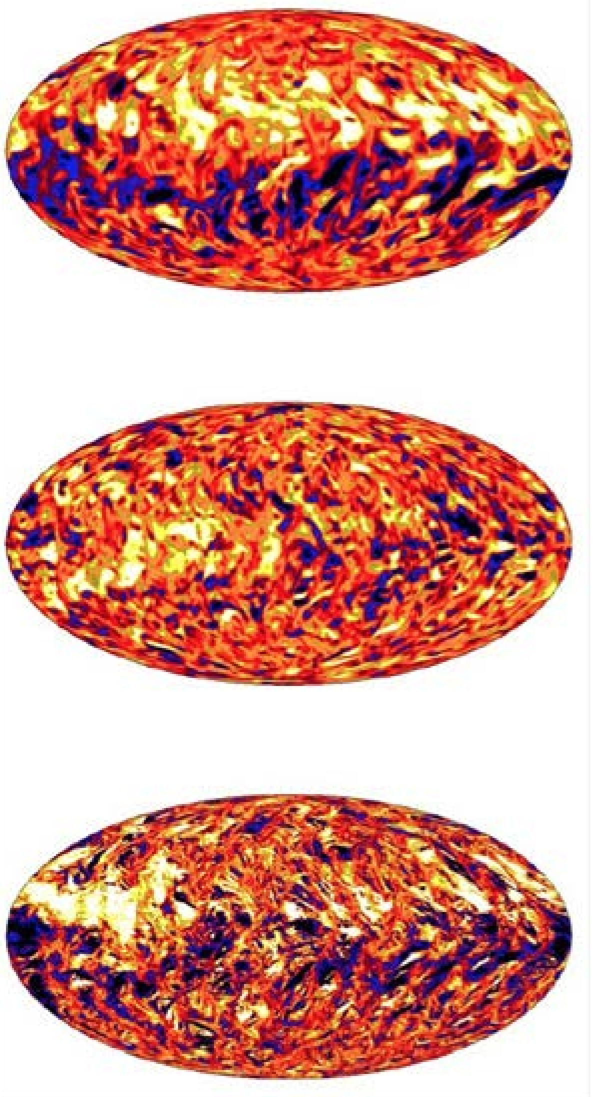
SUPER-RESOLUTION SOLAR MODEL ACHIEVES ORDER OUT OF CHAOS

Credit to HAO and UCAR communications | Over the past few decades, computer models of the Sun's interior have matured, showing that turbulent flows of plasma create a chaotic magnetic tangle. And after observing the Sun's surface for hundreds of years, scientists know that order emerges from that tangle in the form of the solar cycle.

When run at relatively low resolution, three-dimensional models of the Sun have been able to capture the solar cycle, which includes a predictable flip-flopping of the Sun's magnetic field about every 11 years. But something puzzling would happen when researchers increased model resolution in an effort to explore smaller-scale magnetic processes: the large-scale patterns associated with the solar cycle could no longer be seen.

A new study published in the journal *Science*, shows that, for the first time, the Sun's large-scale patterns can re-emerge when a model's resolution is pushed even further, to a scale finer than any ever attempted. To perform the pioneering experiment, the research team—led by Hideyuki Hotta, of Chiba University in Japan, and including Matthias Rempel, of the National Center for Atmospheric Research (NCAR), and Takaaki Yokoyama, of the University of Tokyo—harnessed two of the world's most powerful supercomputers: NCAR's Yellowstone and the K computer at Japan's RIKEN Advanced Institute for Computational Science.

The experimental results give scientists important insight into how the Sun's magnetic fields, both tiny and massive, can co-exist and interact without destroying the solar cycle.



The images show simulations of the Sun's longitudinal magnetic field at the base of the convective zone at low resolution (top), medium resolution (middle), and high resolution (bottom).

"It's like our model has to travel through this valley to get to the other side," said Rempel, a senior scientist at NCAR's High Altitude Observatory and a co-author of the paper. "Many other models of the same type are still on their way into the valley."

The existence of this conceptual valley is likely related to the fact that solar dynamos—the process by which the energy of turbulent flows of plasma is converted into magnetism—occur on both large and small scales inside the Sun. The large-scale solar dynamo is thought to be responsible for the solar cycle. But small-scale solar dynamos also exist, though their effects on the global scale are not well understood.

"There is a lot of small-scale turbulence on the Sun. The smallest eddies, or magnetic whirlpools, you find can be just meters, or even centimeters, in size," Rempel said. "The question is, when you have both large-scale and small-scale dynamos operating at the same time, how do they influence each other?"

Scientists have tried to answer this question by increasing the resolution of their solar models so that the large-scale and small-scale processes could be "seen" at the same time. But in these earlier simulations, the small-scale turbulence appeared to interfere with the large-scale dynamo, and the solar cycle pattern dissipated.

In the new study, the researchers attacked the problem by pushing the model resolution even further. The result was that the model established connections between the small and large magnetic fields, allowing the solar cycle pattern to re-emerge.

Essentially, the models used in previous attempts could see the small-scale phenomena, but it may be that they couldn't see them well enough.

"In the past, the resolution was not high enough to really grow the small-scale component and see its full impact," Rempel said.

Viscosity and computing power

Rempel thinks the key to building the large-scale patterns may be found in how models of differing resolution represent the apparent viscosity of the Sun's plasma. At low resolution, models assume that the plasma is more viscous—flowing more like honey than water—which allows order to emerge in the model system.

But as the resolution increases, the equations that govern the model actively lower the plasma's viscosity. This allows small-scale interactions to begin to play out, but makes it more difficult for large-scale patterns to form.

When the model was pushed to much higher resolution for the new study—about four times higher than previous attempts—the model's viscosity was dropped further still. But because the small-scale dynamos were able to fully evolve in the simulation, the model was able to let new magnetic fields form and grow, something that didn't happen before. The result was that the snarl of new magnetic fields created a level of magnetic stress that caused the plasma to act as if it was more viscous, even though it wasn’t.

While some innovative modeling code allowed the scientists to go to a higher resolution using fewer computing resources than would normally be required, the effort still demanded a lot of computing power. The sheer amount of computing resources needed—and the scarcity and expense of those resources—mean that, practically speaking, many solar physicists may not be able to run their models at a resolution high enough to maintain the Sun's large-scale pattern.

The results of the new study offer at least a stop-gap solution for scientists trying to better understand the complicated interplay of the Sun's dynamos. The study suggests that researchers who can't go to an extremely high resolution may be able to get similar results by artificially increasing the model's viscosity.

More important, the new study offers a look at why increasing the viscosity would work.

"The Sun is magnetic on all scales," Rempel said. "We have shown that it's really important to understand this and account for how those magnetic fields interact."

Supercomputing for super resolution

To complete the study, Rempel and Hotta used 15 million core hours on the NCAR-Wyoming Supercomputing Center's Yellowstone system. Their system allocations were awarded through the competitive NCAR Strategic Capability program, which facilitates large-scale, shorter-term supercomputing projects.

“Yellowstone provided the resources required to carry out a large number of high-resolution calculations, which we used to determine the detailed setting of an ultra-high resolution calculation,” Hotta said. “Since the data analysis system at NCAR's Computational and Information Systems Laboratory shares storage with Yellowstone (unlike Japanese supercomputers), we were able to see the detailed results of our calculations quickly, without transferring huge amounts of data."

‹ Scientific Discovery and Innovation | up | Untangling the Coronal Magnetic Field ›

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UNTANGLING THE CORONAL MAGNETIC FIELD

Society is increasingly dependent on technologies that are vulnerable to the variable output of radiation, energetic particles and magnetized plasma from the Sun. These outputs can drive radical disturbances in the Earth's environment known as "space weather". Space weather has become a national priority, driving a requirement for advanced observation-based modeling throughout the Sun-Earth system.

The Data-Optimized Coronal Field Model (DOCFM) project is a collaboration between NCAR (HAO and CISL) and the Harvard/Smithsonian Center for Astrophysics (CfA), with funding from the Air Force Office of Scientific Research (AFOSR). Its goal is to develop a new methodology for assimilating solar coronal observations into boundary-driven magnetic

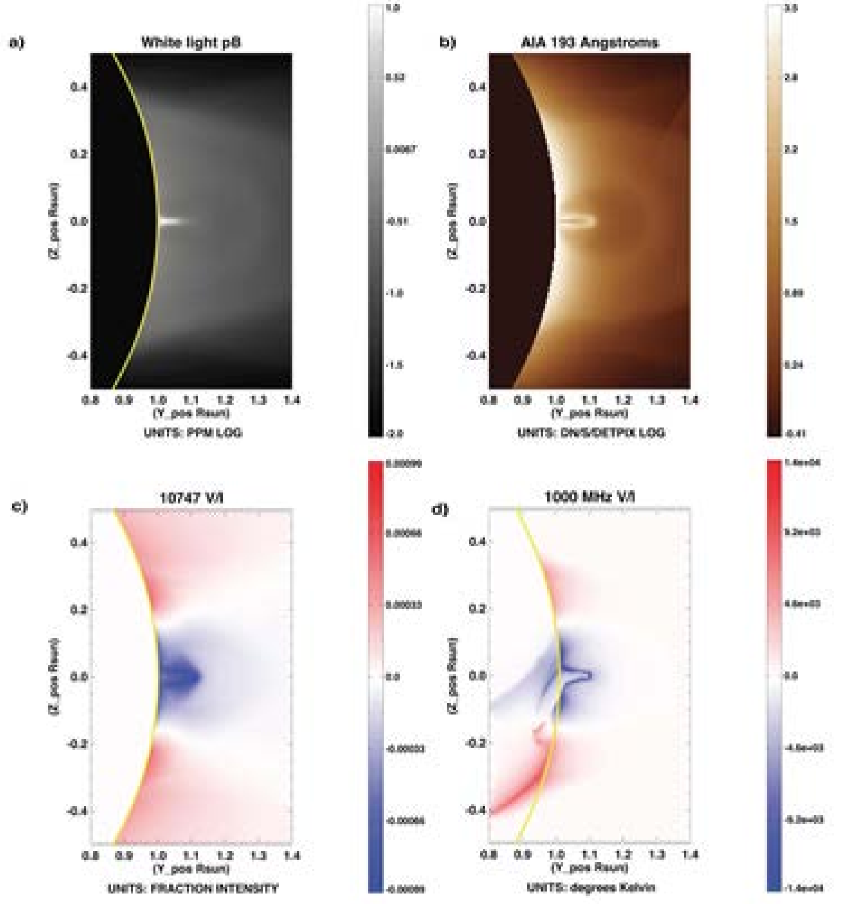

Figure 1: FORWARD-generated synthetic data including a) visible and b) extreme ultraviolet intensity, and c) infrared and d) radio circular polarization, generated for simulated prominence-cavity system based on a model of a confined magnetic flux rope (from Gibson et al., 2016).

models in order to establish not only the magnetic structure of the source region of solar eruptions, but also the global field into which they erupt. Such comprehensively data-constrained models of pre-eruption solar magnetic configurations can then be used as initial conditions for ensemble modeling of space weather events.

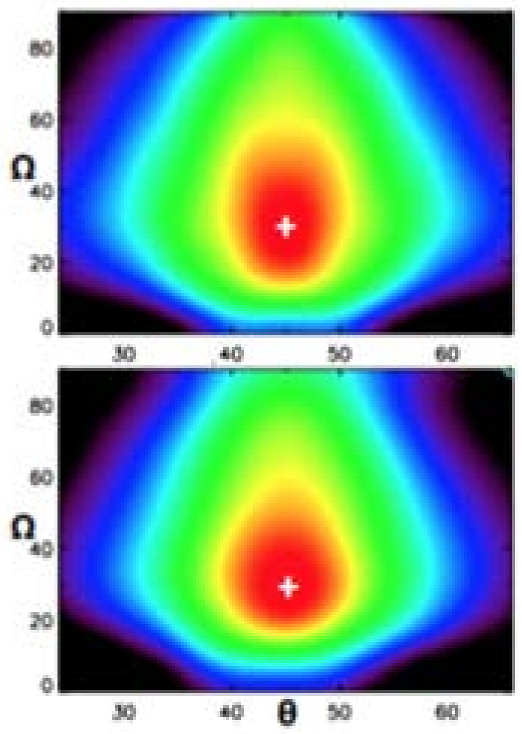

Figure 2: Establishing efficient methods for a full grid search of parameter space represents a challenge to data science. Shown here are maps of goodness of fit, or likelihood (log) in parameter space (tilt angle vs. latitude), determined from comparison of forward-modeled flux rope vs “ground-truth” synthetic data. Top plot shows full map evaluated at regular grid. Bottom plot is approximation using radial basis functions to form an interpolated log-likelihood surface, reducing the need for model evaluations by a factor of 100. Ground truth is represented by white +. From Dalmasse et al. (2016).

In essence, the goal of DOCFM is to solve an inverse problem. Given magnetically-sensitive coronal observations, the challenge is to determine the magnetic field distribution that generates them. Solving such an inverse problem requires three things: a means of specifying the physical state (e.g., the distribution of density, temperature, velocity, and magnetic field), a well-defined forward calculation (i.e., the physical process relating the physical state and the observations), and the observations themselves. We have brought all three of these requirements together via the FORWARD software package, a community resource that may be used both to synthesize a broad range of coronal observables, and to compare synthetic observables to existing data. It enables forward fitting of specific observations, and helps to build intuition into how the physical properties of coronal magnetic structures translate to observable properties. We have also used FORWARD to generate synthetic test beds from MHD simulations (Fig. 1) in order to develop efficient optimization methods (e.g., Fig. 2).

As described in Table 1, many currently-available coronal observations have sensitivities to coronal magnetic field, including white light coronagraph data

Process	Physical-state dependency	Observation	Magnetic quantity probed
Thomson scattering	electron density	White-light pB, TB	Plasma structured by field (e.g. closed vs. open field boundaries, flux surfaces)
Collisional excitation	electron density, temperature	IR/Visible/EUV/SXR emission	Plasma structured by field (incl. loops, closed/open boundaries, flux surfaces)
Continuum absorption	chromospheric population density, electron density, temperature	EUV absorption features	Can indicate magnetic geometry suitable for prominence formation
Resonance scattering; polarization	electron density, temperature, vector magnetic field	Visible/IR spectra	B_{los} from Stokes V; Magnetic field direction from Stokes Q, U
Doppler shift	electron density, temperature, velocity	Visible/IR spectra	B_{pos} and field line direction from waves; flux surfaces from bulk flows
Thermal bremstrahllung	electron density, temperature, vector magnetic field	Radio emission (intensity and circular polarization) as a function of frequency	B_{los} from Stokes V
Gyroresonance	electron density, temperature, vector magnetic field	Radio emission (intensity and circular polarization) as a function of frequency	Surfaces of constant magnetic field strength at each frequency
Faraday rotation	electron density, temperature, vector magnetic field	Rotation of plane of polarization	B_{los} from rotation measure

Table 1. Physical processes operating in the solar corona, highlighting dependency on attributes of the physical state, which observations are sensitive to them, and diagnostic sensitivity to the 3D coronal magnetic field. From Gibson et al. (2016).

obtained by NCAR's COSMO K-Coronagraph (K-Cor) and extreme ultraviolet data obtained by NASA's Solar Dynamics Observatory Atmospheric Imaging Assembly (SDO/AIA). However, these measurements only indirectly depend upon magnetism. Observations in the infrared (IR) from NCAR's Coronal Multichannel Polarimeter (CoMP; Tomczyk et al (2008)) have allowed us for the first time to obtain daily observations that directly measure the effects of magnetism on the solar atmosphere through spectropolarimetry. These observations together measure of plane-of-sky magnetic field strength and direction (see Table 1) and have proven to be good diagnostics of coronal magnetic topology (Tomczyk et al 2007; Dove et al. 2009; Bak-Steslicka et al. 2013; Rachmeler et al. 2014). The U-CoMP telescope currently under development will increase the range of wavelengths available for spectroscopic and spectropolarimetric analysis, and also increase the field of view. The proposed much larger COSMO Large Coronagraph telescope (COSMO-LC) would also obtain circular polarization (Stokes V; Fig. 1) providing a measurement directly proportional to the line-of-sight component of the magnetic field strength so that all three components of the vector magnetic field are constrained. The overarching goal of DOCFM is to exploit these complementary sets of observations in inverting the coronal magnetic field.

‹ Super-Resolution Solar Model Achieves Order Out of Chaos   up   Provide Capabilities for More Accurate Predictions of Solar Output ›

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PROVIDE CAPABILITIES FOR MORE ACCURATE PREDICTIONS OF SOLAR OUTPUT

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.

‹ Untangling the Coronal Magnetic Field up Investigating the Onset of MHD Turbulence in the Corona: A Step Towards Better Solar Wind Forecasting ›

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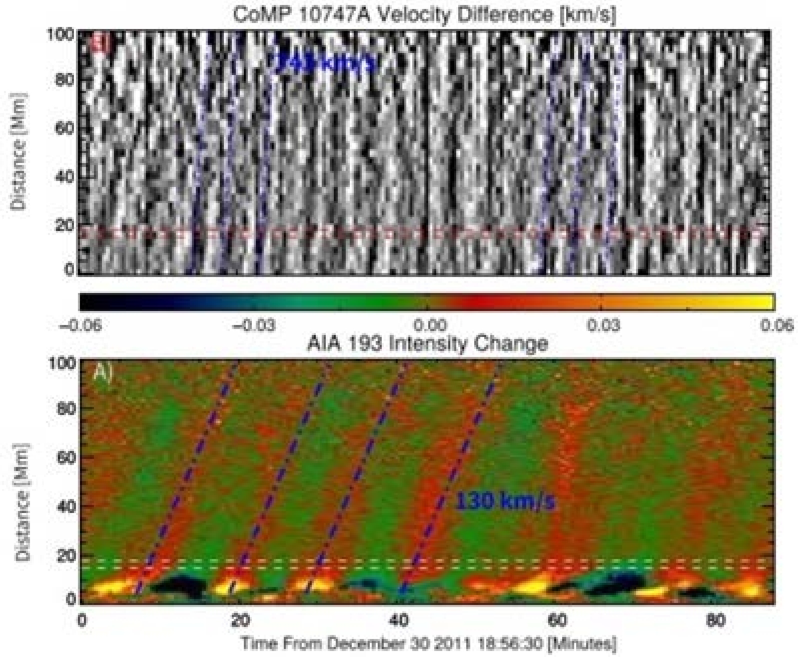
INVESTIGATING THE ONSET OF MHD TURBULENCE IN THE CORONA: A STEP TOWARDS BETTER SOLAR WIND FORECASTING

One of many elusive mysteries that affect our ability to understand the impacts of space weather events on society lies with understanding the stream of charged particles from the Sun that fill the solar system; the solar wind. The solar wind speed has extremes of a few hundred kilometers per second in benign conditions, to several thousand kilometers per second when storms are taking place, although a good average of the “fast” solar wind is about seven hundred kilometers per second. For many decades, since the pioneering work of Skylab scientists in the 1970s, we have associated slow and fast solar wind streams as originating in magnetically closed and open regions of the Sun’s corona. The former from active regions and the latter from regions that were dubbed “coronal holes” in the original work. Despite this correspondence, the means by which material gets into the wind, or how it can reach such ridiculous speeds, still eludes solar scientists.

Much like hurricane forecasting on Earth, a critical factor in determining storm path and arrival time lies in determining the wind structures that the storm is embedded in. In recent years HAO scientists have studied observations that may hold the key to the acceleration problem in coronal holes and also help in the closed regions. By measuring magnetic waves running through the Sun’s atmosphere called Alfven waves, named after the Nobel Prize winning Swedish scientist, HAO scientists have possibly revealed the onset of a critical turbulent process that takes place on both open and closed magnetic structures. Turbulence, in this case, is required to take the energy from the magnetic waves and use it to accelerate the particles away from the Sun.

Much like sound and water waves, these Alfvenic waves refract

(bend) and reflect depending on the material they are traveling through. Two critical observations have been made using the Coronal Multichannel Polarimeter (CoMP) at MLSO that demonstrate that conditions exist where Alfvenic waves can travel through each other - driving interference and turbulence - and also where they are travelling at high speed through slowly moving clumps material that likely produce multiple, persistent, wave reflections such that the waves, again, travel through one another gradually losing energy to the clumps of material as they both travel outward.



Alfven waves observed by CoMP

In the figure (right) we see Alfven waves observed by CoMP (top) traveling along an open magnetic structure at 750km/s as indicated by an inclined lines in these “space-time plots.” Those lines can be compared (bottom) to those produced by slower (150 km/s), moving (more inclined) clumps of material observed by the AIA instrument of the Solar Dynamics Observatory on the same solar structure. With the upgrade to CoMP in 2017 we will be able to trace this behavior in many more wavelengths and also to heights further away from the Sun, in which case we will see if the clumps of material gain speed with height, that is, they’re being accelerated, by the fast moving waves rippling through them. Should this come to pass, we will be able to study the solar wind acceleration process directly, and use that information to better improve forecasts of the solar wind conditions that greatly affect the predictions of solar storm arrival at Earth.

‹ Provide Capabilities for More Accurate Predictions of Solar Output up Slow Appearance of Sunspots Challenges Theory ›

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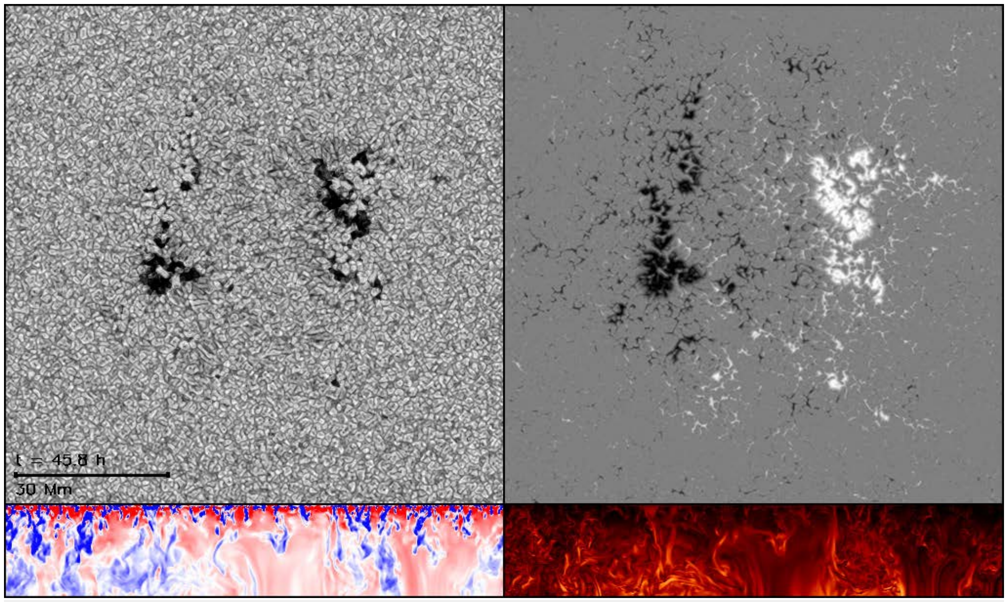
SLOW APPEARANCE OF SUNSPOTS CHALLENGES THEORY

Sunspot groups (active regions) are the most prominent manifestation of the 11 year solar magnetic cycle. Understanding how sunspots form and evolve provides crucial constraints on models of the solar cycle and is also central to understanding and predicting the impacts of the varying solar activity in terms of solar flares and coronal mass ejections. Sunspots form when bundles of magnetic field originating in the solar interior pierce the visible surface (photosphere) of the sun, but little is known about the structure and strength of such magnetic field prior to the appearance in the photosphere. Since sunspots are very strong magnetic field concentrations in the photosphere (about 10,000 times the strength of the earth's magnetic field), the prevailing models assumed that magnetic field connected to active regions is also strong in the solar interior. This assumption has been put to a test in a new study, which was published July 13 in the journal Science Advances.

HAO along with researchers from the Max Planck Institute for Solar System Research, The University of Göttingen, and NorthWest Research Associates have now shown that magnetic flux concentrations forming active regions on the sun emerge at a rate much slower than predicted by the prevailing current model.

In their study they compared satellite observations

from the NASA Solar Dynamics Observatory (SDO) and computer simulations performed by HAO scientist Matthias Rempel. It was found that typical emergence velocities cannot exceed 150 m/s in a depth of 20,000 km beneath the solar photosphere, which is a velocity comparable to convective motions. This shows that convection in the solar interior plays a crucial role even for active region scale flux emergence. This finding suggests that sunspots originate from a magnetic field in the solar interior that is sufficiently weak to be mostly passive with respect to convective motions. Understanding the details of sunspot evolution requires a proper characterization of the large-scale convection patterns in which they evolve.



Example of a flux emergence simulation performed by HAO scientist Matthias Rempel. The top panels show intensity (left) and the vertical component of the magnetic field (right), the bottom panels the vertical flow velocity (left, upflows red, downflows blue) as well as the subsurface field strength (right) on a vertical slice through the center of the simulation domain. Flux emergence simulations were compared to observational constraints in order to infer the maximum permissible sub-photospheric flux emergence velocity. Computing time was provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center under projects s1325 and s1326.

‹ Investigating the Onset of MHD Turbulence in the Corona: A Step Towards Better Solar Wind Forecasting

up

Community Modeling and Diagnostic Tool Development ›

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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.

‹ Slow Appearance of Sunspots Challenges Theory up Simulating realistic ionospheric structures using WACCM-X ›

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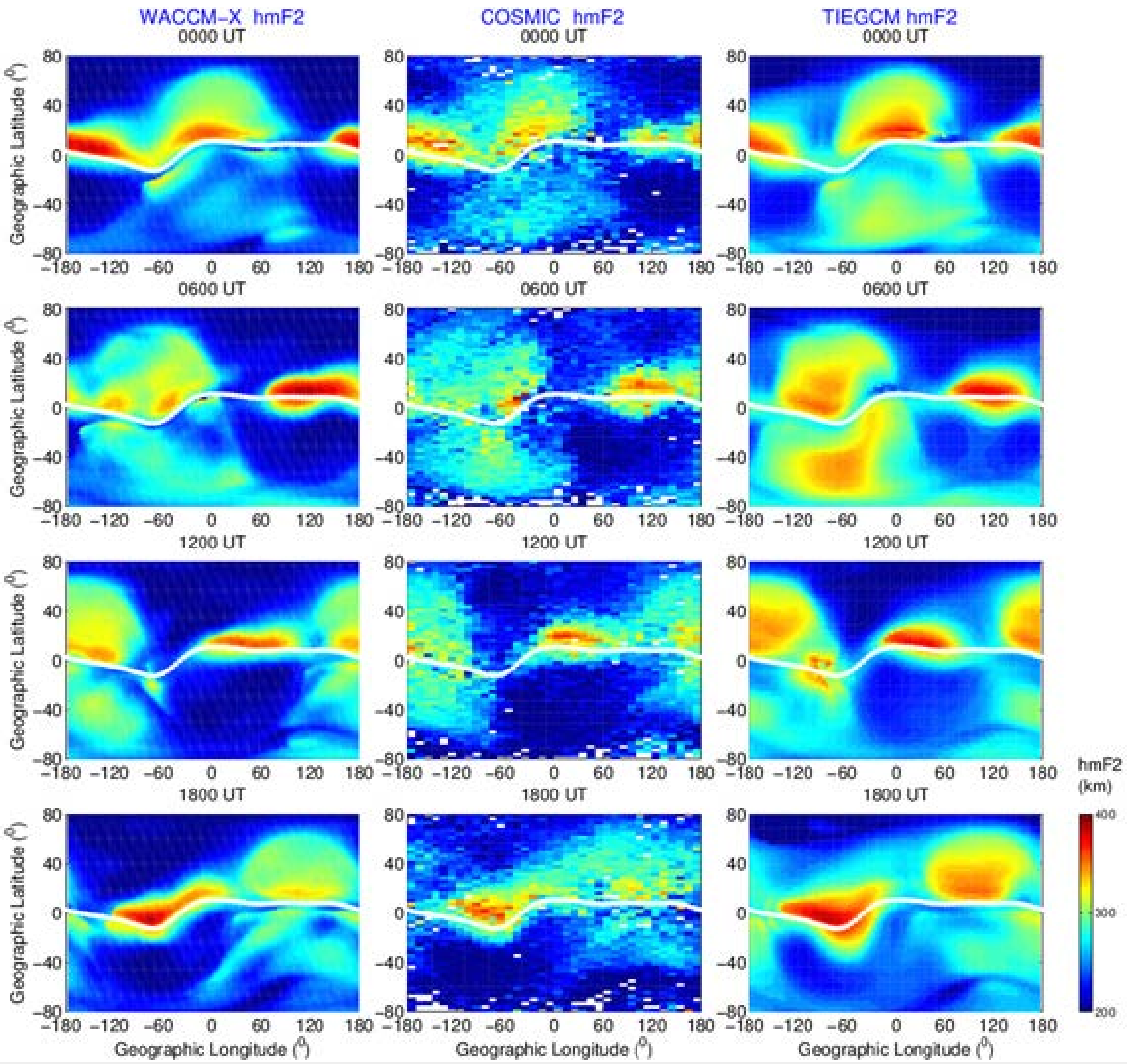
SIMULATING REALISTIC IONOSPHERIC STRUCTURES USING WACCM-X

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.

In the past year, we have further developed the WACCM-X dynamical core to correctly represent the thermosphere, and the thermospheric winds and temperature in the new model are now in good agreement with climatology. These improvements, along with the ionospheric dynamo module and the O+ transport module already included as interactive components of WACCM-X, lead to very realistic simulation of the ionospheric structures. Figure 1 shows the comparison of

height of ionospheric F-region peak (hmF2) obtained from WACCM-X simulation (left column), COSMIC measurement (center column) and TIE-GCM simulations (right column) for July 2008. It is evident from the comparison that WACCM-X produces very realistic hmF2 structures, including rather fine structure spatial variations, especially at dawn, dusk and night time.

This development was supported by NSF AGS-1138784, AFOSR FA9550-16-1-0050, and base fund.



Height of ionospheric F-region peak from (left) WACCM-X simulations, (center) COSMIC measurements, and (right) TIEGCM simulations. Both WACCM-X and TIE-GCM simulations use realistic F10.7 and Kp for July 2008. COSMIC measurements are for the same time period.

‹ Community Modeling and Diagnostic Tool Development up The Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) ›

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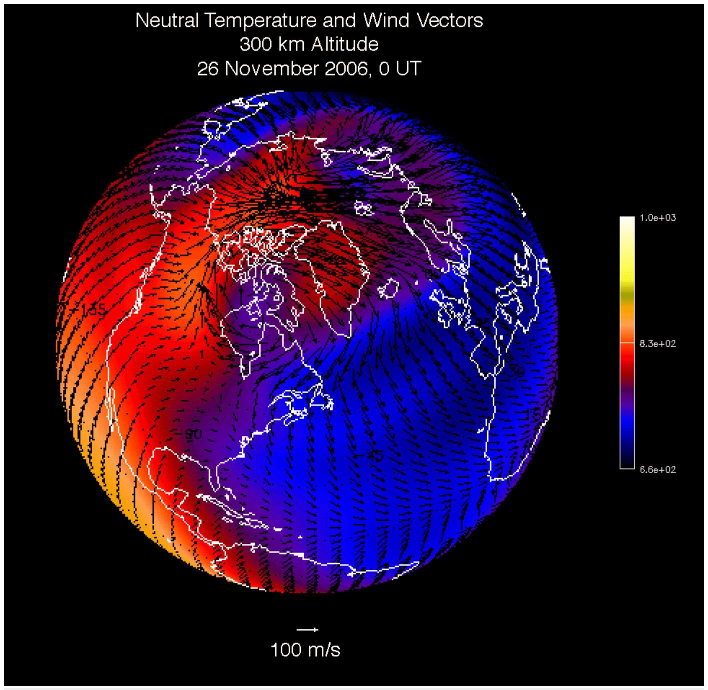
THE THERMOSPHERE-IONOSPHERE-ELECTRODYNAMICS GENERAL CIRCULATION MODEL (TIE-GCM)

The NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) is a series of numeric simulation models of the Earth's upper atmosphere, including the upper Stratosphere, Mesosphere, and Thermosphere, from ~100 to ~500 km altitude. TIE-GCM are three-dimensional, time-dependent models of the Earth's neutral upper atmosphere.

TIE-GCM is based on a long history of model development initiated by Ray Roble, Bob Dickinson, and Cicely Ridley, and carried on by Art Richmond, Ben Foster, and the Geospace section of the NCAR High Altitude Observatory (HAO). The entire section has been involved in its public release as an open-source community model, and in the recent development and release of TIE-GCM v. 2.0. The new version supports higher resolution (2.5° horizontal), extends to higher altitude, uses parallel computations for the electrodynamics, and produces a more accurate description of ionospheric structure. It is used by researchers in the University community and worldwide. Making the code stable, fixing



Winds and temperature at 300 km altitude simulated by the NCAR TIE-GCM v. 2.0, during the ramp-up to a geomagnetic storm

problems, documenting, and enabling installation on a variety of platforms from supercomputers to laptops, has been a major endeavor during the last several years, culminating in official release in March 2016 (see http://www.hao.ucar.edu/modeling/tgcm). This work is the basis for new development of a thermosphere-ionosphere capability in the NCAR Whole Atmosphere Community Climate Model - eXtended (WACCM-X). The next step for ionosphere modeling is to fully couple the ionosphere to the entire atmosphere, using the WACCM-X platform, thus making it a component of the Community Earth System Model. This will enable studies of the weather and climate in near-Earth space as it responds to the complex interactions between solar events and atmospheric variability.

‹ Simulating realistic ionospheric structures using WACCM-X | up | Including ionospheric outflow leads to sawteeth oscillations ›

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INCLUDING IONOSPHERIC OUTFLOW LEADS TO SAWTEETH OSCILLATIONS

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 magnetosphere. The magnetic field lines that form the magnetosphere pass through the upper levels of the Earth's atmosphere known as the ionosphere. HAO scientists Michael Wiltberger and Binzheng Zhang working with colleagues at SRI International and Dartmouth College have worked to model the outflow of mass from the ionosphere into the magnetosphere by including the Ionosphere Polar Wind Model (IPWM) to the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) framework. Accurate modeling of the fundamental mode of the magnetosphere-ionosphere system is essential in the creation of tools for predicting space weather, especially those aspects that can affect the operations of satellites.

Movie caption: Scientific visualization illustrating sawteeth oscillations within the magnetosphere-ionosphere system. The saw blade pattern shown in the open magnetic flux on the pattern leads to the name of this process as sawteeth oscilations.

Earlier research with the CMIT framework indicated a connection between ionospheric outflow and periodic responses in the

magnetosphere-ionosphere system. Scientists refer to this behavior as sawteeth oscillations because of sawtooth like pattern seen in the parameters such as the amount of open flux plotted in the bottom panel of the scientific visualization. The coupled system is periodically loading and unloading magnetic flux from the magnetosphere. The panel on the right-hand side of the visualization shows dynamics in the magnetotail. The pink line shows the region of close magnetic flux within the magnetosphere. Throughout the time series you see it growing in size followed by region breaking off and being released down the tail. The releasing of flux down the tail corresponds to the peaks of the sawteeth seen in the bottom trace. The two panels on the left show how this process setups a feedback loop with a release of flux triggering an injection of new material from the ionosphere which prevents the system from reaching equilibrium and resulting in a new tooth in the saw. Simulations that do not include the outflow only have one tooth and do not demonstrate the sawteeth behavior. Work is now underway to verify this model prediction with comparison to observations.

This work was supported by NSF grant AGS-1555801 and base funds.

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OBSERVATIONAL FACILITIES AND DATA SERVICES

Observations and observationally driven science are central to the vision and mission of the High Altitude Observatory, 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. Scientists at HAO, along with colleagues at the University of Hawaii, the University of Michigan, George Mason University and the Harvard-Smithsonian Center for Astrophysics, plan to build the Coronal Solar Magnetism Observatory (COSMO). The goals of this activity are to understand the physical processes that cause space weather and to develop the ability to predict the occurrence and severity of solar storms. In addition, HAO and ACOM labs are collaborating on a project to measure the corona during the 2017 eclipse. Over the last year they have been developing a Fourier Transform Spectrometer (FTS) to measure the infrared emission from the corona at 2–12 microns.

‹ Including ionospheric outflow leads to sawteeth oscillations | up | The August 21, 2017 Total Solar Eclipse ›

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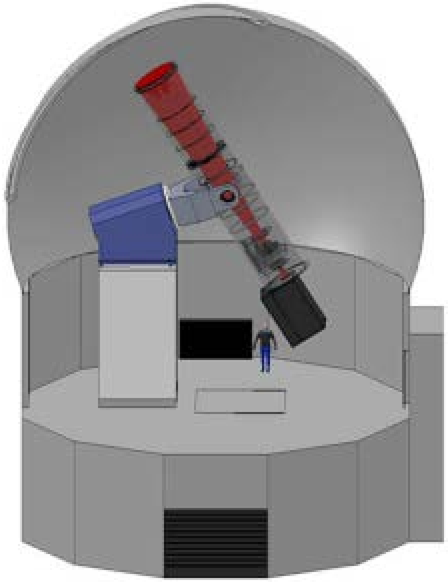
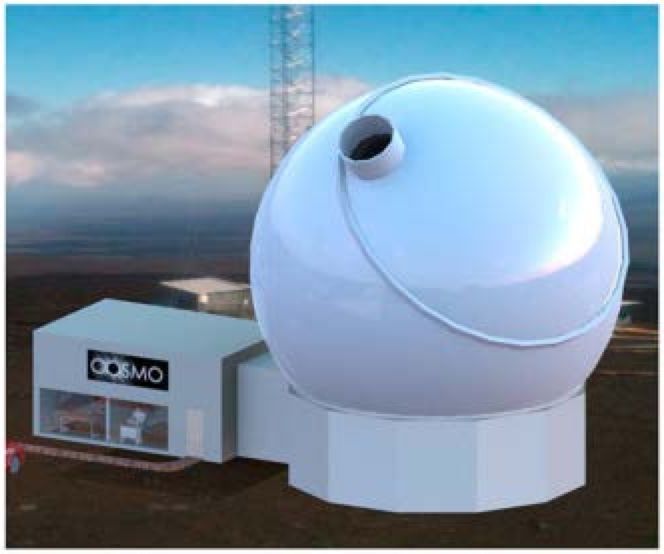
THE CORONAL SOLAR MAGNETISM OBSERVATORY (COSMO)

Evolving magnetic fields in the solar atmosphere can create explosive energetic solar storms that impact the earth. Known as space weather, these events can damage orbiting satellites, disrupt communications and GPS networks, disable power grids, and pose health risks to astronauts and airline passengers.

Motivated by society's need to protect human welfare and critical infrastructures, NCAR scientists at the High Altitude Observatory, along with colleagues at the University of Hawaii, the University of Michigan, George Mason University and the Harvard-Smithsonian Center for Astrophysics, plan to build the Coronal Solar Magnetism Observatory (COSMO). The goals of this activity are to understand the physical processes that cause space weather and to





(left) Cutaway rendering showing the inside of the dome housing the Large Coronagraph.
(right) Rendering of the exterior of the Large Coronagraph facility showing the control building and fifth/eighth's dome.

develop the ability to predict the occurrence and severity of solar storms. COSMO is a facility that will take daily measurements of the entire solar atmosphere, focusing on the magnetic fields that drive solar eruptive events. The primary instrument, the Large Coronagraph, will consist of a 1.5-m coronagraph that will measure the strength and orientation of magnetism in the outer solar atmosphere, the corona, as well as the density, temperature and motion of coronal plasma. Supporting instruments are a white-light coronagraph, the K-coronagraph that will monitor the evolution of the density and dynamics of coronal electrons, and an instrument called ChroMag that will observe the magnetism and plasma properties of the lower and middle solar atmosphere, the photosphere and chromosphere. This new facility will replace the current NCAR Mauna Loa Solar Observatory (MLSO) which has been collecting synoptic coronal data for over 50 years in support of the solar and heliospheric community.

We continue to make progress towards the completion of COSMO. The K-coronagraph was deployed to MLSO in September of 2013 and has been operational since. Data from the K-Cor can be obtained at: http://www2.hao.ucar.edu/mlso/mlso-home-page. The Large Coronagraph is in the planning and engineering development stage. A significant milestone was achieved in November 2015 when we completed a Preliminary Design Review for the COSMO Large Coronagraph where an external committee of experts from the community reviewed the maturity of the design and verified the feasibility of constructing the instrument. The PDR is documented extensively with engineering studies, preliminary designs, and vendor quotes for all major components (see: http://www2.hao.ucar.edu/cosmo/lc-pdr-documentation). And recently, funding has been obtained that will allow the ChroMag instrument to be completed in the next 2 years and put into operation at Mauna Loa.

Future efforts center on obtaining the remaining funds required to complete the Large Coronagraph. A rendering of the current design for the LC is shown in the figure.

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THE MLSO FACILITY GETS A NEW DOME AND OTHER RENOVATIONS

After 50 years of operation (1966–2016), the Mauna Loa Solar Observatory (MLSO), owned by the National Science Foundation (NSF) and operated by the High Altitude Observatory (HAO) at NCAR, received major building renovations. The most intriguing to witness renovation (see time-lapse movie), was the installation of a new dome. The old dome was removed on a Tuesday morning in January, and the new dome was installed before the end of the same day. This was no small feat since following its removal the main dome building had to be shortened by seven inches. Other important building renovations included new wiring, roof repair, and new exterior stairs.

The solar facility also experienced significant equipment installations and upgrades. HAO observers assisted with the completion of the University of Illinois TIDDBIT radio receiver deployment. Its purpose is to study gravity waves in the ionsphere. The TIDDBIT computer installation and data transference was provided by HAO at no cost.

Also of note, HAO completed design and installation of the Coronal Multichannel Polarimeter (CoMP) motorized objective lens focusing system in anticipation of

UCoMP deployment in late 2017. The UCoMP project will be carried out in collaboration between the University of Michigan and HAO in an effort to perform an upgrade that will increase both the field of view of the solar atmosphere that can be imaged and the range of the spectrum that it can observe.

Time-lapse video of dome replacement

A GPS receiver was installed at MLSO for monitoring ionosphere scintillations in the upper atmosphere to promote understanding through observations and high resolution modeling. Observational efforts will include deploying an all sky camera for imaging plasma and gravity waves, followed by Fabry Perot interferometer installation, which will observe neutral winds in the mesosphere and thermosphere.

Also see YouTube videos:
Dome removal West facing camera and
Dome removal East facing camera

‹ The Coronal Solar magnetism Observatory (COSMO) | up | A Comprehensive and Dynamic Instrumentation Group Supports Scientific Goals ›

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A COMPREHENSIVE AND DYNAMIC INSTRUMENTATION GROUP SUPPORTS SCIENTIFIC GOALS

HAO's Instrumentation Group (IG) is a dynamic engineering group working to support HAO scientists and PI's in their efforts to pursue scientific goals with the use of instrumentation. HAO IG is involved in conception, development, fabrication, deployment, and operations of these instruments around the world and in our backyard. The group maintains competencies in systems, optical, electrical, mechanical, and software engineering, making them an elite group with a rich knowledge of solar instrumentation and exciting new strategies to learn more about our Sun. The HAO IG also runs an engineering internship program each summer with a goal of increasing diversity in the engineering fields by giving undergraduate students exciting, real-world projects to work on.

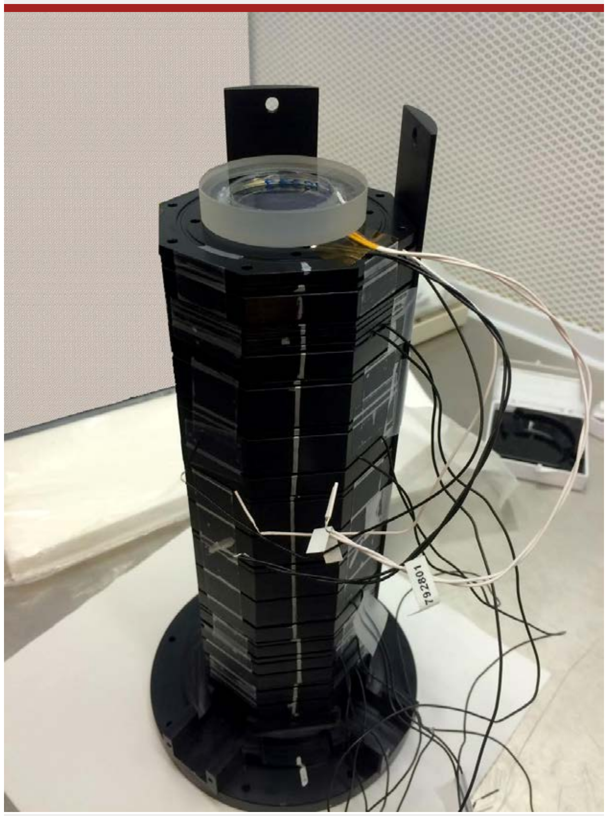
During 2016, HAO's IG has been involved in groundbreaking projects. The group has seen completion of SUNRISE Reflight, Slovakian Solar Chromospheric Detector (SCD), and Fabry Perot Inferometer (FPI) China III. They are well underway with Visible Spectro-Polarimeter (ViSP), upgrade to the Coronal Multi-channel Polarimeter (UComp), Chromosphere and Prominence Magnetometer (Chromag), and High Altitude Interferometer WIND Observation (HiWIND).

The SUNRISE refight was completed in 2013. Since then, data has been analyzed

and papers are being published to highlight the science that came out of the flight. The HAO instrumentation group has been intimately involved in this, as well as assisting with data recovery. Look for the papers to be published in the coming months. (NASA: NNX13AE96G)

Lomnicky Peak Observatory

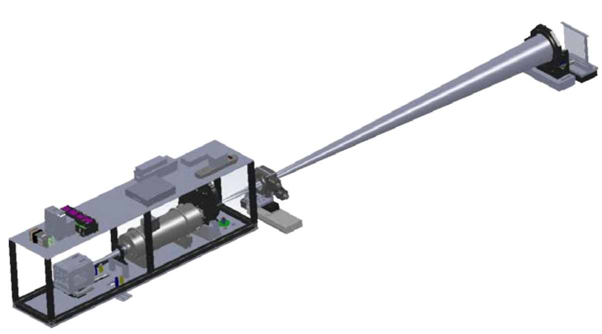
The Slovakian Solar Chromospheric Detector was successfully deployed at Lomnicky Peak Observatory of the Astronomical Institute of Slovak Academy of Sciences (SAS) in Fall, 2016. This instrument is for on-disc observations of solar flares. It will obtain spectropolarimetric data in several photospheric and chromospheric spectral lines of iron, hydrogen, helium, sodium, and calcium. HAO very much enjoyed working with partners at the SAS is one very interested in seeing the data begin to come out of the instrument now on board at the SAS Observatory. (SAS: HAO12155)



The Slovakia Solar Chromospheric Detector was successfully deployed at Lomnicky Peak

The group completed an extensive Preliminary Design Review (PDR) effort for COSMO in November of 2015. This extensive suite of instruments promises to be very important to HAO science and our mission in the coming yearsThe Fabry Perot Interferometer (FPI) created by HAO for the Chinese Research Institute of Radiowave Propagation (CRIRP), was completed in November 2016. This FPI will record the Doppler effect of the airglow radiation in the medium and high level atmosphere. It will use the interferometric diagram to confirm the atmosphere motion and spectrum change in the area of airglow radiation for obtaining the data of speed and temperature of the atmosphere. (CRIRP: 7MUS0161)

HAO has several projects that are well underway and will continue in 2017. The Visual Spectro-Polarimeter, ViSP, is an instrument expected to provide precision measurements of the full state of polarization simultaneously at diverse wavelengths in the visible spectrum, and fully resolving the spectral profiles of spectral lines originating in the solar atmosphere. The construction phase continues at this time with deployment expected in April of 2019. (AURA: C22017BN)



The Chromospheric and Prominence Magnetometer

The upgrade to the Coronal Multi-channel Polarimeter (UCoMP), with the University of Michigan is in full swing. The purpose of this project is the upgrade the CoMP instrument to make it capable of observing emission lines from 530-1083 nm. This involves the Lyot filter, detector, optics, mechanical upgrades, and computer/software upgrades. This is being led by E. Landi at the University of Michigan and S. Tomczyk at HAO. (University of Michigan: HAO31076)

HAO's Chromosphere and Prominence Magnetometer (ChroMag) is part of the COSMO suite of instruments at Mauna Loa and is designed to infer the magnetic field within and at the base of the solar corona. The instrument has been deployed at HAO's dome at the Mesa Lab in Boulder, CO and is nearing completion to be ready for deployment at Mauna Loa. (NSF: M0856145)

Dr. Qian Wu's High Altitude Interferometer WIND Observation (HiWIND) reflight project is also in full swing. The refurbishment of the HIWIND instrument is being completed and a long duration (approximately 30 days) science flight from McMurdo, Antarctica will take place. The purpose is to directly address questions related to thermosphere-ionosphere interaction. This extended flight will take place in December of 2017 and will be the first in Antarctica to take these types of observations. (NASA: NNX15AK75G)

Each summer, our IG group sponsors a summer internship program to give real-world engineering experience to undergraduates while increasing diversity in the field. HAO has committed to this program for the last four summers which is aimed at engineering students that are part of the CU BOLD program. Our interns have been getting essential experience on many projects as they complete work as part of a given project team. The fifth year promises to be unique for the interns as they will primarily focus their time on the eclipse projects. Interns are funded by NSF Base as well as the projects specifically noted in this article.

As part of our ongoing effort to support engineering education, HAO is collaborating with a senior design team at the University of Colorado to design and build a 3U cubesat. The student fabricated cubesat will be a piggyback payload aboard the HiWIND mission in Antarctica. (NSF: M0856145). Through this collaboration, HAO will develop a baseline competency for proposing follow-on space borne cubesat missions.

It is a very exciting time for HAO's Instrumentation Group.

The Chromospheric and Prominence Magnetometer (ChroMag) will measure and monitor the magnetic and thermodynamic conditions of the chromosphere

(ChroMag) will measure and monitor the magnetic and thermodynamic conditions of the chromosphere

The HiWind instrument will be deployed in December 2017

Example of a balloon launch at McMurdo, Antarctica

‹ The MLSO Facility Gets a New Dome and Other Renovations   up   Education and Outreach ›

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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.

‹ A Comprehensive and Dynamic Instrumentation Group Supports Scientific Goals   up   Providing Mentorship in Undergraduate Science and Engineering ›

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PROVIDING MENTORSHIP IN UNDERGRADUATE SCIENCE AND ENGINEERING

HAO is committed to serving a broad community of scientists and engineers. In doing so, it strives constantly to provide mentorship through real life experience to aspiring students in these fields. While our commitment runs broad and deep, our involvement in the Research Experience for Undergraduates (REU) and the CU BOLD Engineering program are two examples that we think exemplify this commitment; and we are really excited to be involved.

RESEARCH EXPERIENCE FOR UNDERGRADUATES

Every year, HAO works collaboratively with the University of Colorado through the NSF REU Grant program to invite undergraduates to apply for paid summer Research Experience. The candidates are chosen from a pool of highly motivated students interested in solar and space physics. Students come to Boulder, Colorado for 10 weeks to work on a research project with a mentor. The topic areas span the field of solar and space physics, from instrument development to observations and modeling.

The four REU students selected had a mix of backgrounds and areas of interest.

Eryn Cagni, from the University of Oregon, was mentored by HAO scientist Astrid Maute. Her topic was titled "Delineating the migrating solar and lunar semidiurnal atmospheric tides in general circulation models."

Emilyanne English was from the Wentworth Institute of Tecnology and was mentored by HAO scientist Yuhong Fan. Her topic was titled "MHD simulation of X-ray coronal jet produced by flux emergence."

Rosa Wallace was from the University of Colorado Denver. She had three mentors—HAO scientists Mausumi Dikpati, Giuliana de Toma, and Joan Burkepile. Her topic was titled "Three-dimensional potential-field source-surface modeling of the evolution of coronal structures."

Anna Parker was from Middlebury College and her mentors included HAO scientists Bidya Binay Karak, Lisa Upton, and Mark Miesch. Her topic was titled "Seeing Spots! Exploring the variability of sunspot tilt angles of sunspot cycles in observations and a supercomputer model."

INCREASING DIVERSITY THROUGH BOLD COLLABORATIONS

“We value the diversity of our staff and visitors, in perspective, gender, ethnicity and background, recognizing that this diversity is important to our organizational strength and excellence.” HAO’s mission statement is aligned with NCAR’s dedicated directive to increase diversity in the sciences and as part of our efforts, we created an engineering summer internship program for students in the CU BOLD program. Each summer HAO hosts three or four students.

The four BOLD students selected were varied in backgrounds and areas of interest.

Lauren McIntire developed a LabVIEW software interface for controlling a Fourier transform infrared spectrometer. Her work enabled the rapid and synchronous acquisition of signals from both an infrared detector and from a visible photodiode sensitive to interference fringes generated by a stabilized reference laser passing through a time varying interferometer. This instrument will be used during the total solar eclipse of 2017 by Principal Investigators Paul Bryans (HAO) and James Hannigan (ACOM) to search for spectro-polarimetrically useful lines in the solar corona.

BOLD engineering interns of summer 2016, Lauren McIntire, Diego Gomes, McKenzie Weller and Valerie Lesser

Diego Gomes spent the summer redesigning and fabricating a solar panel battery charge control printed circuit board. The improvements he made to the boards circuitry will allow higher solar panel currents and better handling of the systems switching between load and no-load conditions during flight. He also added additional telemetry channels to that the system can record engineering system data during future flight operations.

McKenzie Weller developed software graphical user interfaces (GUI’s) for controlling opto-mechanical linear stages developed for the Visible Spectropolarimeter (ViSP) Instrument. She wrote methods for both simulated and actual hardware control of the three camera focus stages as well as the concurrent motion control of the spectrographs slit station mechanisms.

Valerie Lesser investigated control systems for high altitude scientific ballooning systems. She interfaced with the SUNRISE gondola pointing platform and was able to write a standalone test environment for accelerating and decelerating the azimuthal positioning motor at the same time as writing diagnostic engineering data to a log file for subsequent analysis. Her work will enable balloon platform pointing control engineers to better investigate the non-linear behaviors’ of stiction (and other effects) within the system at low control velocities.

Our interns work on a diverse set of projects. Our 2016 interns were supported with NSF Base funds (M0856145) from the HAO directorate as well as from the NCAR Diversity Office, from an AURA grant (C22017AS), from a NASA Hi-Wind project

grant NNX15AK75G, and from a NASA grant for Sunrise II, NNX13AE96G.

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MMM DIRECTOR’S MESSAGE

Christopher Davis
NCAR Associate Director, MMM

Greetings and welcome to the 2016 MMM Annual Report.

A common theme that you will find in the achievements of FY’16 centers on pioneering simulations and demonstrations of next-generation prediction capabilities. These are in line with NCAR Grand Challenges, NCAR strategic priorities and MMM goals. This includes the increasing convergence of mesoscale and large-eddy simulations. Mesoscale fronts in the upper ocean and tropical cyclones have both been simulated in the regime where large, turbulent eddies are resolved. These powerful simulations are being mined for fundamental information about how turbulence affects larger scales and an underpinning for the interpretation of observations taken within turbulent systems. Using the NCAR ensemble (a collaboration with CISL), MMM scientists are continuing to explore high-resolution data assimilation and Weather Research and Forecasting (WRF) model-based ensemble forecasting techniques to probe the prediction of severe weather, both warm and cool seasons, as well as trace constituents and aerosols. The year has seen the development and demonstration of improved variable-resolution prediction capabilities with the Model for Prediction Across Scales (MPAS) for both severe convection and tropical cyclones.

A significant challenge that remains is the development of physical parameterizations that function well across a range of spatial scales. New approaches in cloud physics that model observable properties of precipitation particles, rather than partition particles arbitrarily into categories, were aggressively pursued during the past year. New research has shown how realistic canopies affect the turbulent exchange of fundamental atmospheric variables such as momentum, heat and water vapor, as well as trace constituents indicate new ways to represent land-atmosphere interactions. The performance of implicit convection representation across spatial

scales has also been investigated using the MPAS variable-resolution configuration. Collectively, the research in fundamental physical processes will be crucial for NCAR’s efforts to unify modeling capabilities across weather and climate.

This past year also saw major advances in research for the benefit of society. This ranged from new understanding of how the general public perceives and utilizes information about approach hazards, to the development and adoption of tools for industry to extract useful information from the complex collection of model-based projections of climate variability and change. MMM formed a new entity, the Capacity Center for Climate and Weather Extremes (C3WE). The Center encompasses programs to define and reduce risk from extreme weather (the Engineering for Climate Extremes Partnership – ECEP, and the Global Risk Resilience and Impacts Toolbox – GRRIT) and to increase the inclusion of indigenous populations into discussion and research about risks posed by climate change (Rising Voices).

I invite you to read more details about our recent accomplishments in the following pages.

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DATA ASSIMILATION

Data assimilation (DA) is another essential part of a state-of-the-community modeling system, as it facilitates objective comparison of model simulations to observations and provides initial conditions for model predictions. With the participation of all of NCAR's labs, the new DA program is developing new and improving existing DA techniques, as well as developing a common infrastructure, for the benefit of the broader scientific community. Closer integration of these techniques and statistics with model development and verification is needed not only to generate initial conditions but also to facilitate analysis of sensitivity and uncertainty, and to assess the benefit of new observations. Similar to the capacity of observations to improve model output, models can inform observational researchers of where gaps exist within current

understanding and sets of observations.

This past year the NCAR DA Program developed a postdoctoral program that has sponsored 5 postdocs to date. To increase coordination of data-assimilation activities at NCAR and foster development of common tools, the postdocs are jointly funded by specific projects within NCAR labs.

The NCAR DA Program organized and sponsored an international workshop "Blueprints for Next-generation Data-Assimilation Systems," in collaboration and coordination with the Joint Center for Satellite Data Assimilation. This workshop was convened 8-10 March 2016 at NCAR. Agenda and presentations are available at https://www.da.ucar.edu/workshops.

‹ NCAR Imperative 1: Conduct innovative fundamental research to advance the atmospheric and related sciences up Fundamental mesoscale research and dynamics of high-impact weather ›

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NCAR UCAR Mesoscale & Microscale Meterology Laboratory

2016 Annual Report

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FUNDAMENTAL MESOSCALE RESEARCH AND DYNAMICS OF HIGH-IMPACT WEATHER

Understanding the role of turbulent processes in mesoscale weather systems is a forefront area of research linking mesoscale and microscale meteorology, and is becoming practically important as the resolution of prediction models begins approaching scales where the largest turbulent eddies can be resolved. Processes such as boundary-layer turbulence, lateral mixing in vortical flows, and lateral and vertical mixing in clouds affect mesoscale characteristics of precipitation in ways that are not well understood or simulated. In addition, understanding of fine-scale processes within high-impact weather systems affects researchers' ability to accurately model the probabilistic character of such systems, and to understand how small-scale processes couple to create the damaging weather events that are disruptive to society.

In FY 2016 MMM staff performed and analyzed turbulence-resolving simulations of high-impact weather, including tropical cyclones and tornadoes, to better understand turbulent flows and improve representations of turbulence in coarse-grid simulations. Eddy-resolving simulations of hurricanes and tornadoes (Fig. X) provided some surprising results concerning the distribution of the strongest winds in space and time.

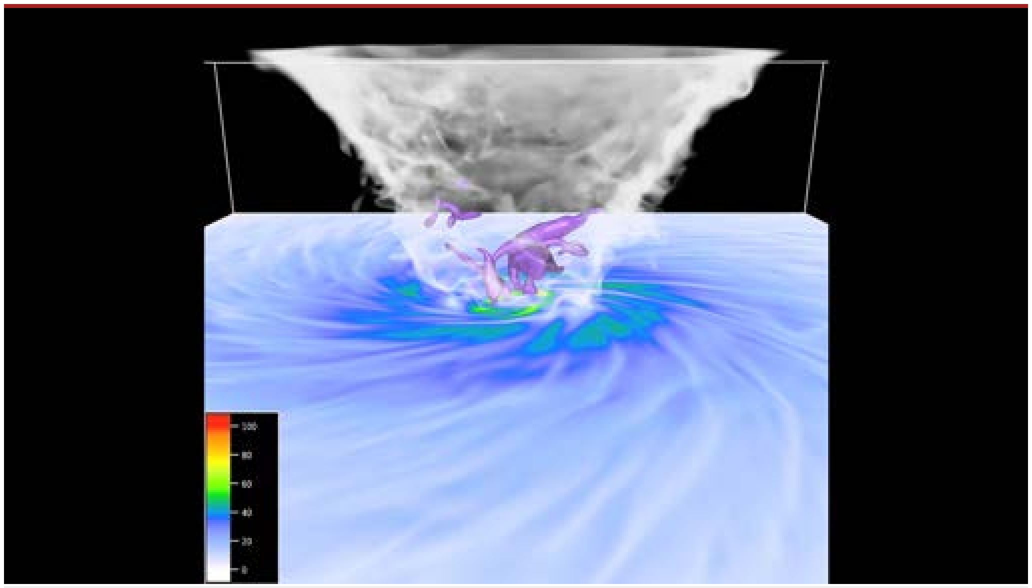

Figure X: A three-dimensional visualization of multiple-vortex tornado. The gray shading denotes a pressure surface and is analogous to the funnel cloud of a tornado. The purple shading shows an even lower value of pressure and indicates where local rotation is largest. The color shading at the surface (see legend on bottom-right) is wind speed (m/s) at 2 m above ground level. The visualization area is 2 km x 2 km horizontal and is 0.5 km deep.

For hurricanes, these simulations allow researchers to better interpret seemingly anomalous wind observations.

Other work this past year included use of high-resolution simulations of WRF and WRF-Chem to interpret field data and perform model evaluation. Data from several field projects were analyzed (MPEX, DC3, FRAPPE, SAS, and SEAC4RS), and related simulations performed and analyzed (Fig. X+1). In addition, MMM prepared WRF-tracer and WRF-Chem simulations for forecasting during KORUS-AQ and estimated the impact of future air quality over South Asia via NRCM-Chem simulations. The analysis of the wet removal of trace gases shows that the mildly soluble species, methyl hydrogen peroxide, is scavenged at rates higher than expected in severe convection, and may be a function of entrainment into the storm of cloud-free air and/or the size of the graupel region in the storm.

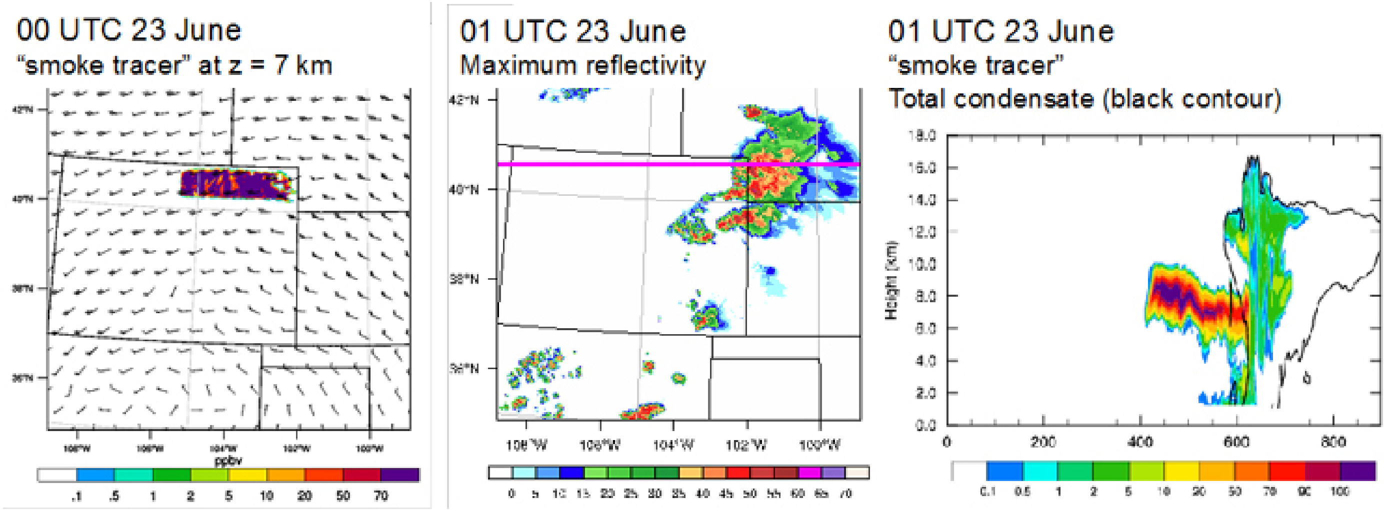

Figure X+1: Left: Cross-section at 7 km altitude of a tracer representing a biomass burning plume at its initial location. The tracer was initialized from 23:40 to 24:00 UTC; middle: Maximum reflectivity of the WRF-simulated thunderstorm at 01:00 UTC showing the location of a severe storm at the northeast corner of Colorado. The pink line marks the location of the vertical cross section; right: Vertical cross-section of the tracer at 01:00 UTC showing that up to 10% of the tracer is entrained into the thunderstorm (outlined by the black line). The tracer is transported to the top and bottom of the storm.

As a continuation of work started earlier, MMM scientists applied the CAWFE ™ coupled weather-wildland fire modeling system to the 2014 King Fire using very high resolution, visible and infrared land surface datasets collected before, during and after the event to give new insights into the behavior of high severity wildfires and their effects on the land surface. Results will be compared to remote sensing data from satellite and airborne fire mapping instruments. The importance of fine-scale variations of wind, and winds induced by the fire itself, on fire behavior may imply limited utility of predicting fire behavior using mesoscale analysis products.

Scientists also performed analysis and idealized simulations of observed terrain-induced flows pertaining to observations from METCRAX and HYMEX. The natural laboratory afforded by METCRAXIII has allowed demonstration of quantitative accuracy of theories of downslope windstorms.

‹ Data assimilation   up   Fundamental cloud microphysics research ›

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FUNDAMENTAL CLOUD MICROPHYSICS RESEARCH

Understanding the dynamical and microphysical processes that occur in squall lines is an important step to advancing fundamental understanding of microphysics-dynamics interactions across scales and the synergy between microphysical observations and the development of parameterizations to improve representation in models.

This past year, MMM scientists focused on research aimed at improving precipitation development in squall lines, which is a major contributor to the precipitation and severe weather encountered in the U.S. and beyond. The approach was to use three different bin-microphysical schemes—an advancement over earlier bulk microphysics schemes, in the WRF model

evaluations to improve the representation of microphysics and microphysics-dynamics coupling in WRF.

Scientists examined the sensitivity of the cloud dynamics (extent of the cold pool, maximum updraft velocities, etc.) to each of three bin-microphysics schemes, using the squall line which occurred on 20 May, 2011 as the case study. A comparison of the simulated squall line macro- and microphysical properties was made to the radar observations from multiple Doppler radars in and around the SGP ARM site. The WRF model output from the three schemes was compared to the Mesonet data (network of automated weather stations for observing mesoscale meteorological phenomena). Scientists used the coincident in-situ observations from the University of North Dakota Citation aircraft, to directly compare model and in-situ observations of: liquid and ice contents, size distributions, particle shapes and degree of riming. The model allowed researchers to evaluate the microphysical processes that lead to ice initiation, graupel and hail formation, the strength of the cold pool and the subsequent effects on the storm dynamics.

Substantial differences in the details of the simulated dynamic and thermodynamic structure were evident in the resulting simulations. Each scheme produced a squall line with features broadly consistent with the observed storm characteristics (e.g., in the reflectivity pattern, the vertical velocity statistics, the storm moving speed, and the evolutions of low-level air temperature, relative humidity and precipitation). However, significant differences in the details of the simulated system were found. For instance, the reflectivity patterns are remarkably different, cold pool extent and strength varied significantly, and the fundamental atmospheric structure in the vicinity of the mature system deviate among the simulations. All differences were attributed to the different assumptions of hydrometeor properties (e. g., their mass, terminal velocity). A key outcome of this research is that careful attention should be given to the representation of the ice microphysics in simulations of squall lines.

This conclusion leads into work that is being done by MMM scientists this year to quantify the specific properties of graupel particles (spherical or conically-shaped ice particles smaller than 5 mm—the building blocks of hail) and hail (spherical or oblate particles larger than 5 mm). Damage from hail accounts for more than $1 billion per year in the US and accurate forecasting of hail fall can potentially reduce damage and possible injury. During the summer of 2016, MMM scientists participated in a field program that collected hail falling to the ground and then studied the properties of these hailstones. Keeping the hailstones from melting, they performed 3-dimensional scans of the particles and weighed them (Figure 1).

Figure 1: Photo of a 3D-scan of an exact replica of the largest hailstone ever recorded, from

Vivian South Dakota. The replica was scanned and a 3D file was created. This movie shows the rotation of the 3D image.

To get the terminal velocity of hailstones—an essential property that determines their kinetic energy and thus damage and also an essential determinant of their growth within a thunderstorm, the 3-dimensional scans were printed at a weight similar to their actual weight. The printed hailstones were sent to Germany, where a group at the University of Mainz are measuring the terminal velocity of the hailstones in a vertical wind tunnel (see movie). This work will improve the representation of hail properties (e. g., mass, terminal velocity) in WRF and other models.

Figure 2: Movement of a simulated hailstone, printed from a 3D scan of a hailstone that fell in Nebraska in the summer of 2016, in a vertical wind tunnel in Mainz, Germany, a project with MMM scientists and the Miklos Szakall, University of Mainz. The goal of this effort is to measure the terminal velocity of hailstones and to develop relationships that can be used in the WRF model for representing the properties of natural hailstones. Click to view movie.

‹ Fundamental mesoscale research and dynamics of high-impact weather | up | Fundamental boundary layer and turbulence research ›

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FUNDAMENTAL BOUNDARY LAYER AND TURBULENCE RESEARCH

Scientists within MMM carry out basic and applied research on the structure and turbulent dynamics of the atmospheric and upper oceanic boundary layer, which are essential ingredients within weather, climate, observing technologies, and numerous applications.

In FY2016, scientists continued to perform and analyze state-of-the-art numerical simulations and observations targeting atmospheric stability's impact on turbulent exchange of momentum, energy, and scalars over complex land surfaces emphasizing the impact of vegetative canopies. Analysis of simulation data reveals that boundary layer scale structure

spatially segregates the turbulent exchange of momentum, heat, and moisture, thus revealing implications for parameterization of canopy exchange. The analysis of simulation data provides insight as to how boundary layer scales control turbulent exchange at the top of a canopy (Fig. 1).

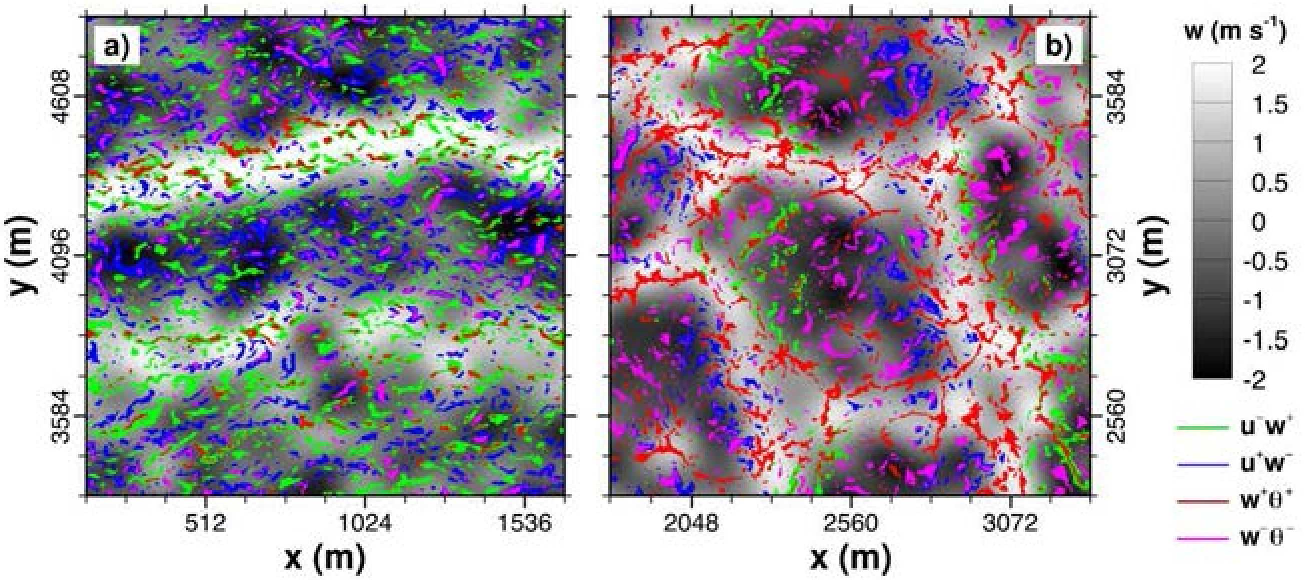

Figure 1: Instantaneous horizontal slices of low-pass filtered vertical velocity at $z/h = 6$ (gray scale) from two large-eddy simulations that resolve boundary-layer and plant canopy turbulence. Panel a) shows results for a case with weakly unstable (near-neutral) conditions, and panel b) shows results for a free-convection (no mean wind) case.

Other work included conducting large-eddy simulations (LES) of the upper ocean focusing on the multi-scale coupling between boundary layer turbulence, surface waves, and submesoscale turbulence over scales ranging from 1.5 m to 18 km. LES shows that at a fundamental level frontogenesis is halted by resolved boundary-layer turbulence, specifically horizontal fluxes. Petascale simulations of the upper ocean illustrate the coupling between boundary-layer and submesoscale turbulence and their impact on frontogenesis (Fig. 2).

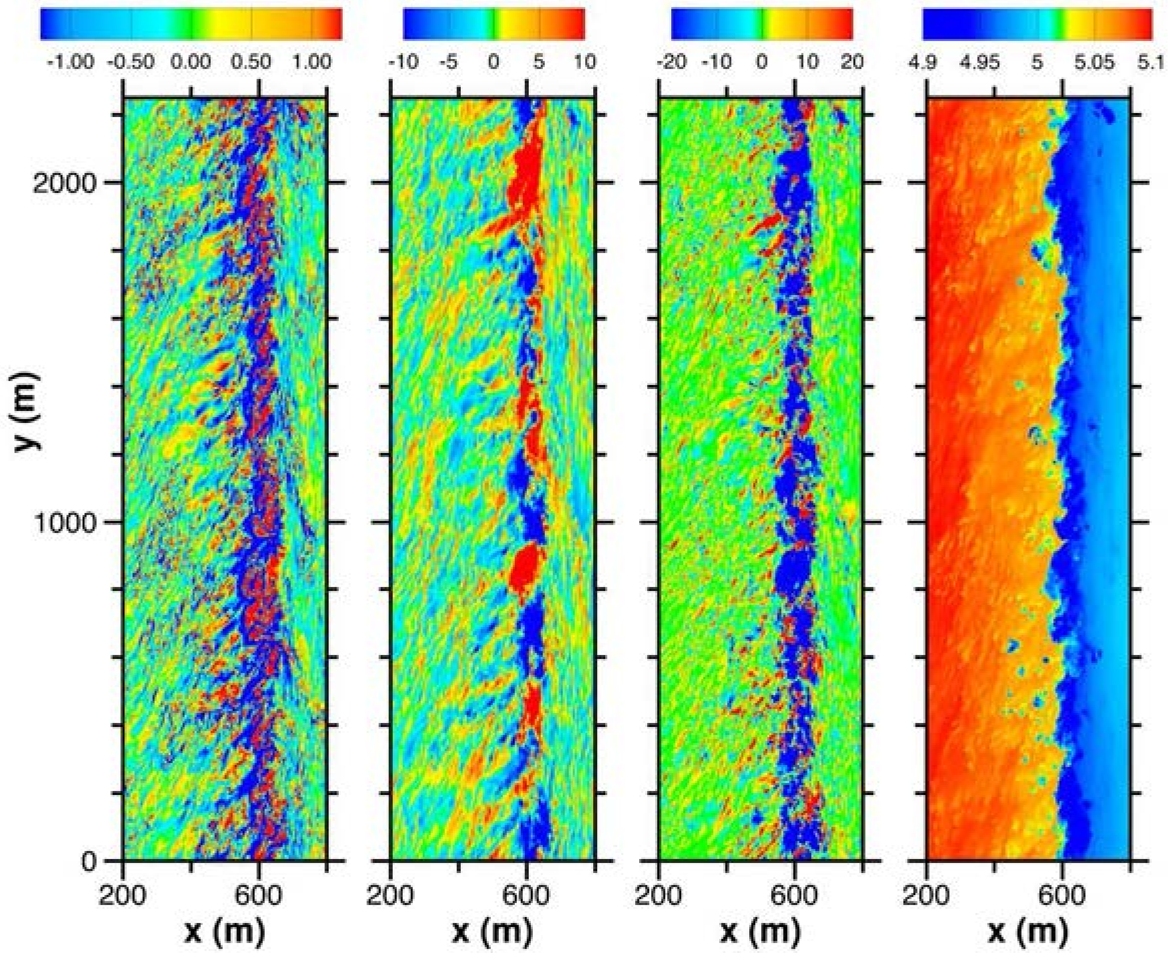

Figure 2: Flow fields from large-eddy simulations of boundary-layer induced frontogenesis in the ocean surface boundary layer near a time of frontal arrest. The currents are driven by northward (down-front) winds with friction velocity u_*. (left to right) the fields are vertical velocity w/u_*, the meridional turbulent velocity v'/u_*, horizontal co-variance $u'v'/u_*^2$, and temperature T [deg C] near the surface. The aspect ratio of the plots is 1 to 1 and only a narrow $x-y$ strip from the simulations is shown.

Scientists continued to analyze observational data collected in the CASES99 field campaign emphasizing the connections between vertical fluxes of momentum and scalars and mean fields under neutral and stable conditions in the atmospheric surface layer. Theoretical and observational analyses show different physical processes in transferring heat near the surface and in the overlying turbulent layer. A generalized total energy conservation expression can be used to interpret observations and can be used to determine turbulence not only in the surface layer but throughout the PBL. The HOST hypothesis is being further developed, which emphasizes the role of finite size turbulent eddies and total energy conservation in determining turbulence intensity. A generalized total energy conservation expression is under investigation (Fig. 3).

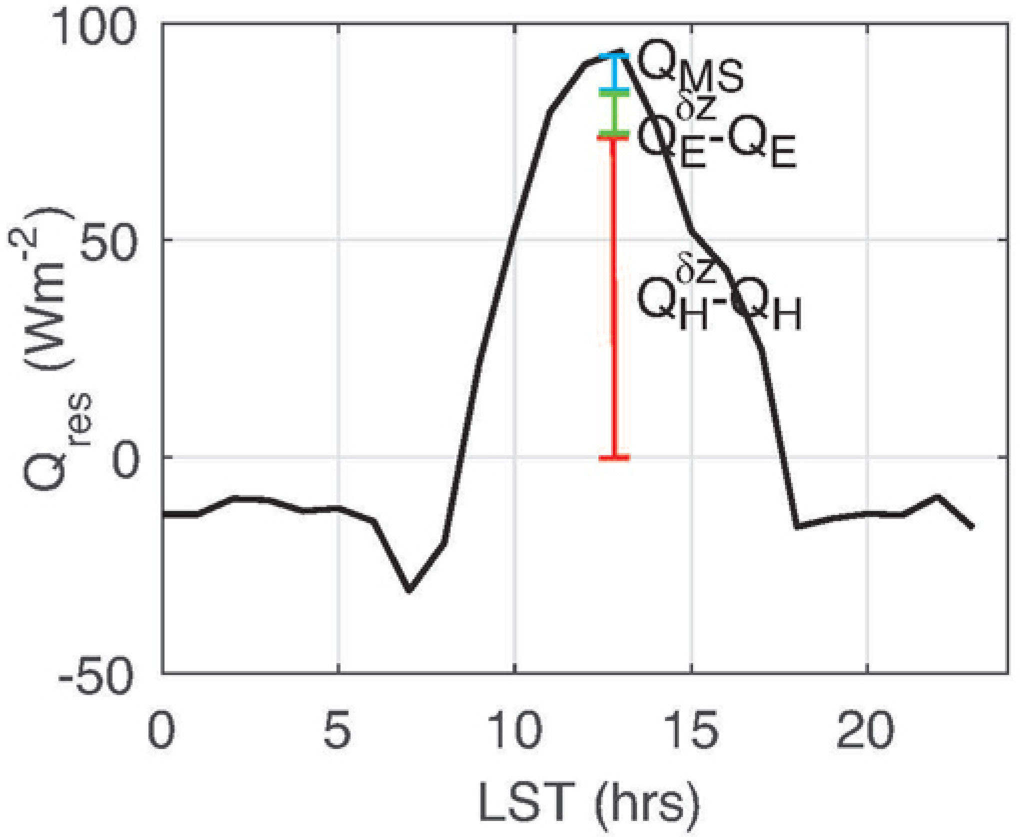

Figure 3: The surface energy imbalance Q_{res} based on the traditional surface energy balance (SEB) averaged over the entire CASES-99 field campaign. Q_{res} is mainly due to the significant decrease of the turbulent heat flux with height ($QH^{\delta z}QH$) caused by energy dissipation near the surface; this can be explained by total energy conservation.

This past year, scientists continued to identify regimes where sophisticated physics or data assimilation is needed in coupled atmosphere-fire models to predict wildland fires. Fuel maps developed entirely from remote sensing data (vs. remote sensing data combined with forest inventories) improve simulation of fire behavior and fire severity. Integration of fire remote sensing data from additional satellites improves the timeliness and accuracy of fire growth (see figure 4).

Observed soil burn severity and simulated severity using fuel data from 2 sources.

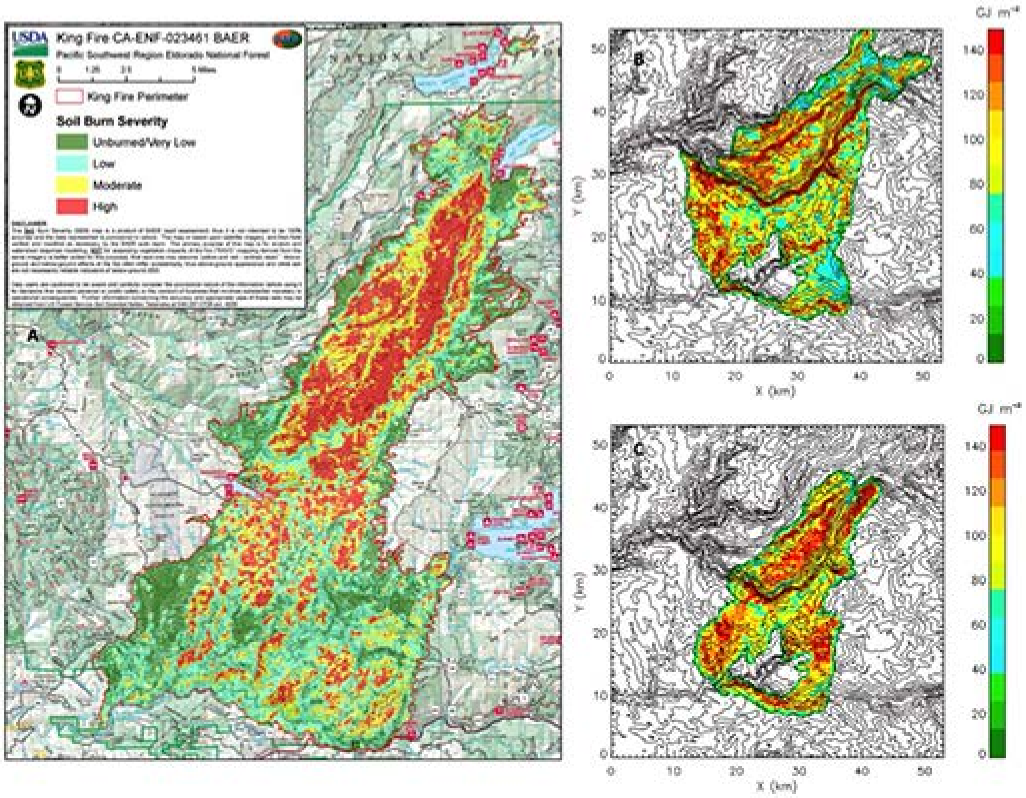

Figure 4: Observed and simulated soil burn severity using fuel data from two sources. (A) King Fire Burned Area Emergency Response (BAER) soil (BAER) burn severity map. Simulated sensible and latent heat flux summed over time at each point using fuel models from (B) the industry standard LANDFIRE database and (C) MapFUELS fuel models, derived from remote sensing data.

As part of the NCAR Geophysical Turbulence Program (GTP), scientists organized and hosted a workshop on geophysical turbulence bringing together researchers working on turbulence at small and large scales in the atmosphere, ocean, and Sun. The workshop provided a forum for a broad discussion of topics in geophysical turbulence by NCAR staff and the university community [see web page https://www2.hao.ucar.edu/events/GTPWorkshop2016].

‹ Fundamental cloud microphysics research up Investigating uncertainty in predictions ›

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INVESTIGATING UNCERTAINTY IN PREDICTIONS

Performance of convective-scale forecasts, especially probabilistic forecasts, lies at the forefront of hazard prediction. There are fundamental challenges to conducting data assimilation across the mesoscale and convective scale simultaneously, understanding how errors grow across scales, and understanding how to construct ensemble forecasts that are appropriately dispersive. Assessing the performance of the Model for Prediction Across Scales (MPAS) is vital to understanding the utility of regional refinement predicting high-impact weather events on the short-term (1-14 days) and statistics (weeks to years).

Understanding the performance of probabilistic convective scale forecasts and working with social scientists within MMM will improve NCAR's ability to communicate hazard information to decision makers and the public. Advances in convective-scale modeling with the Weather Research Forecasting (WRF) model have the potential to transfer into the operational High-Resolution Rapid Refresh (HRRR) model. Testing of MPAS through research applications has the potential to improve MPAS for hazard prediction on longer time scales.

During this past year MMM scientists Conducted cycled MPAS forecasts initialized with ensemble data assimilation, and are continuing extended (1-10 year) simulations to assess temperature and precipitation model biases on different time scales (diurnal, daily through decadal). Regarding the MPAS ensemble analyses and forecasts, both the MPAS model and the EnKF analysis systems have been considerably improved through various updates on the moisture initialization and acoustic filtering, and a new implementation of incremental analysis updates (IAU). These updates result in a significant bias reduction in the upper-level moisture and temperature, and the improved performance of variable-resolution meshes.

In support of the Short-Term Explicit Prediction (STEP) project, researchers created high resolution, continental-scale ensemble analysis using WRF/DART (Data Assimilation Research Testbed) and generated convective scale forecasts for 2015-16. The NCAR ensemble project has been operating continuously since Spring 2015 and provides daily, 10-member, convection-permitting ensemble forecasts over the full CONUS initialized from a continuously cycled 80-member ensemble analysis. These forecasts are found to have little forecast bias and considerable predictive skill across a broad spectrum of precipitation intensity (Schwartz et al. 2015). Also, newly developed severe storm surrogate diagnostic fields applied to convection-permitting ensemble forecasts provides discrimination of potentially tornadic storms from non-tornadic severe storms. Thus, explicit guidance of specific hazards associated with simulated severe storms is enabled (Sobash et al. 2016).

Other work in FY 2016 included the evaluation of the performance of WRF-Data Assimilation (WRF-DA) high-resolution data assimilation on convective forecasting and hydrological predictions using data from 2014-2015. WRF-DART and WRF-DA were both run in real-time during the summer of 2016 to examine their capabilities in convective-scale analysis and prediction during the STEP Hydromet 2016. An ensemble of analyses/forecasts with different physics and initialization techniques were run in real-time aimed for model uncertainty study. Analyses of the results from the real-time datasets are being performed. Scientists compared WRF/DART, WRF-DA and operational High-Resolution Rapid Refresh forecasts to establish a baseline for future development and improvement of a community data assimilation system. The real-time experiments with and without radar data assimilation indicated that radar data assimilation with hourly cycles significantly improve convective rainfall prediction for the first 12 hours. In addition, the design of the convective-scale data assimilation must consider the multi-scale nature of the atmospheric convection.

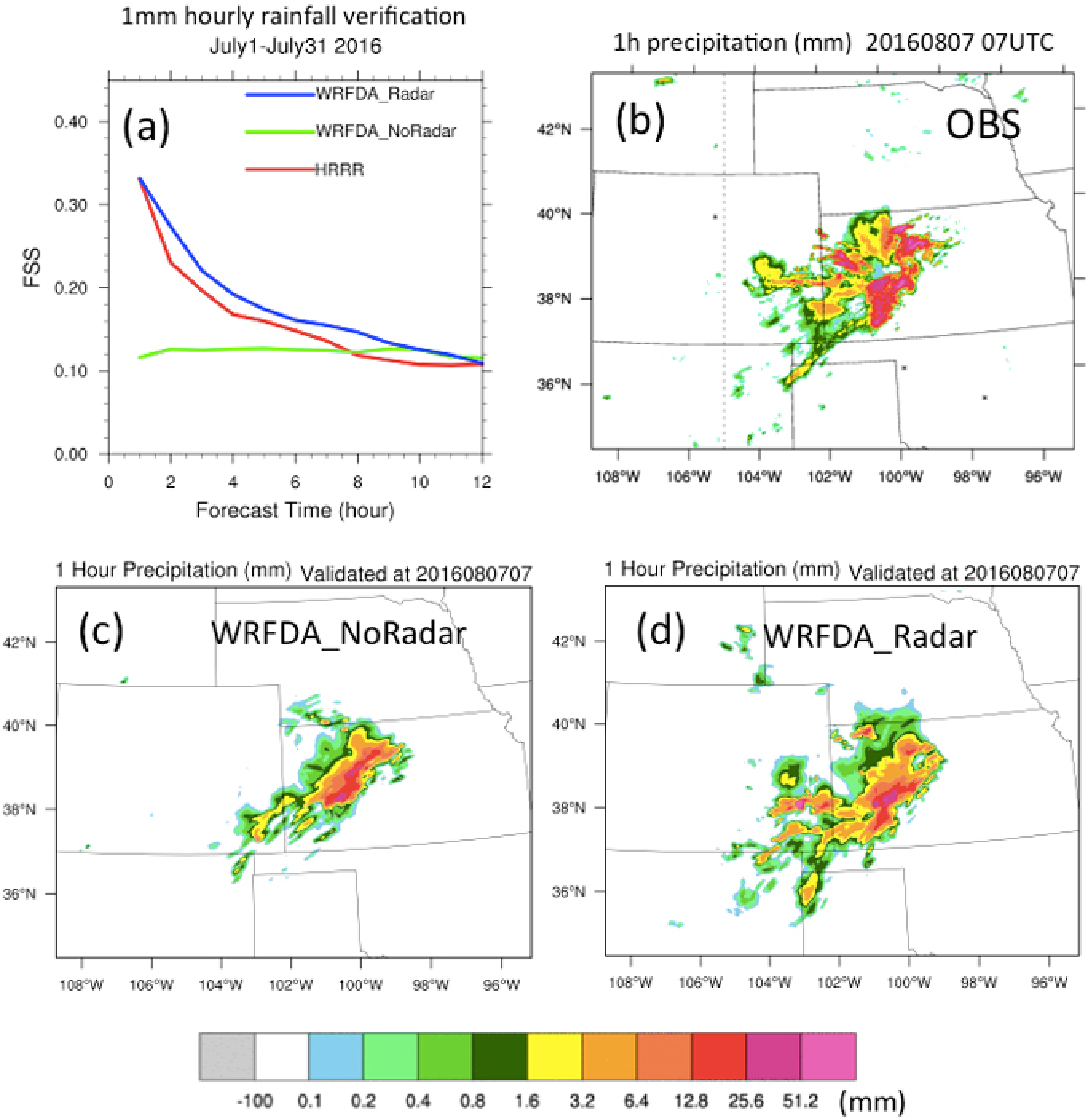

Figure: (a) Fractions Skill Scores (FSS) of 1mm hourly rainfall with a radius of influence of 10km for experiments WRFDA_Radar and WRFDA_NoRadar to show the impact of radar data assimilation. The FSSs were computed for the month of July over 248 0-12h forecasts (8 forecasts per day) for the 3km domain shown by (b). The FSS for HRRR (NOAA's operational 3km forecast) on the same domain is computed and shown for comparison; (b) Hourly rainfall from MRMS analysis valid at 07UTC,7 Aug 2016; (c) 7h forecast of hourly rainfall initialized at 00UTC, 7 AUG 2016 by WRFDA 3DVAR with conventional and radar data assimilation; (d) Same as (c), but radar data are not assimilated.

Improvement of convective forecasting critically depends on whether the data assimilation systems are able to take into account of convective-scale and large-scale uncertainties. And lastly, initial studies on combining the variational and ensemble-based data assimilation techniques showed promise; however, challenging issues regarding the appropriate

choice of perturbations to represent different scales of atmospheric motions are still the obstacles that require intensive studies.

Scientists also continued to conduct ensemble simulations with WRF and MPAS to evaluate the realism of forecast error growth and energy spectra. Error growth and forecast skill in ensembles without model-error representations will be compared to those with stochastic parameterizations. The parameter perturbations by themselves are not sufficient to generate the necessary dispersion in ensemble systems. However, the combinations of different stochastic parameterization schemes can outperform a multi-physics ensemble. This is the first study that uses correlated and anti-correlated parameter perturbations informed by parameterization experts. It is concluded that the error-growth properties at current horizontal resolutions is not sufficient for the model to simulate realistic error-growth. The best predictive skill is obtained by combining different models-error schemes rather than optimally tuning a single scheme. It is concluded that the nature of model-error schemes is too complex to be represented by a single scheme alone.

Furthermore, researchers investigated performance of hybrid (ensemble and variational) data assimilation for the Antarctic Mesoscale Prediction System (AMPS) and other mesoscale prediction efforts. The hybrid DA approach was implemented in AMPS. In a comparison evaluation with the standard 3DVAR approach previously used, it was found to slightly reduce errors, thus improving the guidance provided to the United States Antarctic Program forecasters. Scientists also examined issues related to ensemble data assimilation in the presence of a range of spatial or temporal scales. The cycled MPAS forecasts were initialized using both an ensemble Kalman filter from NCAR’s DART and hybrid variational-ensemble analyses from NCEP’s GSI.

‹ Fundamental boundary layer and turbulence research | up | ECEP® and Rising Voices ›

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ECEP® AND RISING VOICES

NCAR's Engineering for Climate Extremes Partnership® (ECEP) is a partnership between industry, commerce, indigenous peoples and other societal groups, academia, and government with a goal of developing robust, well-communicated predictions and advice on the impacts of weather and climate extremes to support resilient decision-making. This interdisciplinary group aims to increase understanding of climate adaptation through diverse ways of knowing, and societal resilience to weather and climate events.

The Rising Voices: Collaborative Science with Indigenous Knowledge for Climate Solutions program facilitates cross-cultural

approaches for adaptation solutions to extreme weather and climate events, climate variability, and climate change. The program brings social and physical scientists and engineers together with Native American community members to assess critical community needs and to pursue joint research aimed at developing optimal plans for community action towards sustainability. NCAR scientists and leading community members established the *Rising Voices* program to identify and define research and community priorities and to enable and promote important collaboration with Indigenous communities.

In FY2016, researchers documented the outcomes of the Rising Voices Three workshop which was held at NCAR in July 2015. The theme of that workshop was *Learning and Doing: Education and Adaptation through Diverse Ways of Knowing*. The workshop report is available for download on the Rising Voices website at RV3 Report. The 2015 Rising Voices Three workshop lead successfully to the 2016 Rising Voices Four workshop, with some attendees of both also participating in ECEP events providing cross-fertilization of ideas between the networks. The Rising Voices Four workshop was held on the Big Island in Hawaii in July 2016, and the theme was *Storytelling for Solutions*.

Following the two NCAR facilitated ECEP establishment meetings in 2013 and 2014, the first formal annual ECEP meeting was held in August 2015 at NCAR followed by another in 2016. The final workshop report is available for download on the ECEP website at 4th Annual Meeting Report. These meetings included ECEP Partners along with invited participants, and incorporated strategic discussion and technical workshop sessions. In 2016 invitees were expanded to include a wider audience participation (including environmental, agricultural and construction foci). Outcomes from the FY2015 meeting were presented at the AGU Fall meeting 2015, AMS Annual meeting 2016 and AMOS Annual meeting 2016. These reports informed future activities and understanding of important directions for ECEP Partners.

Photo: A group of the participants at the ECEP 2016 workshop.

In FY2016 a strategic plan was developed for future ECEP activities, integrating with the strategic plans for the Capacity Center for Weather and Climate Extremes (C3WE), Global Risk, Resilience and Impacts Toolbox (GRRIT®) and Rising Voices. In addition, several decision-making tools have been developed with collaborations from industry, Federal agencies and NCAR scientists.

‹ Investigating uncertainty in predictions up Extreme weather and climate information ›

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EXTREME WEATHER AND CLIMATE INFORMATION

NCAR research includes studies of how information about weather and climate extremes influences people's risk perceptions and decisions. This includes work investigating how people interpret and use weather forecasts and warnings and other types of weather and climate information. It also includes work investigating how people's perceptions of weather and climate risks and their risk management decisions are influenced by past weather experiences, worldviews, vulnerabilities, and other contextual factors. This research draws on theories, approaches, and methods from multiple social science disciplines, connected to atmospheric science efforts at NCAR and in the academic, research, and operational communities. Through this work, NCAR facilitates creative interdisciplinary exploration while building community capacity

for research and practice in this rapidly growing field.

In FY2016, MMM scientists and collaborators investigated how coastal residents' protective decisions as a hurricane approaches are influenced by forecast and warning messages, hurricane experience, worldviews, and other factors, using survey data analysis and other methods. The survey data analyses demonstrate the trade-offs of using extreme-impacts and location-specific messaging to promote hurricane evacuation. They present new findings on the role of individualist worldview in influencing people's responses to the risk posed by an approaching hurricane (see figure). They also present a novel analysis of how different types of hazard experience can influence protective decisions, mediated by risk perceptions and efficacy beliefs. In addition, scientists are using social media data analysis and agent-based modeling to understand how evolving information influences people's risk interpretations and protective decisions as a hurricane approaches and arrives.

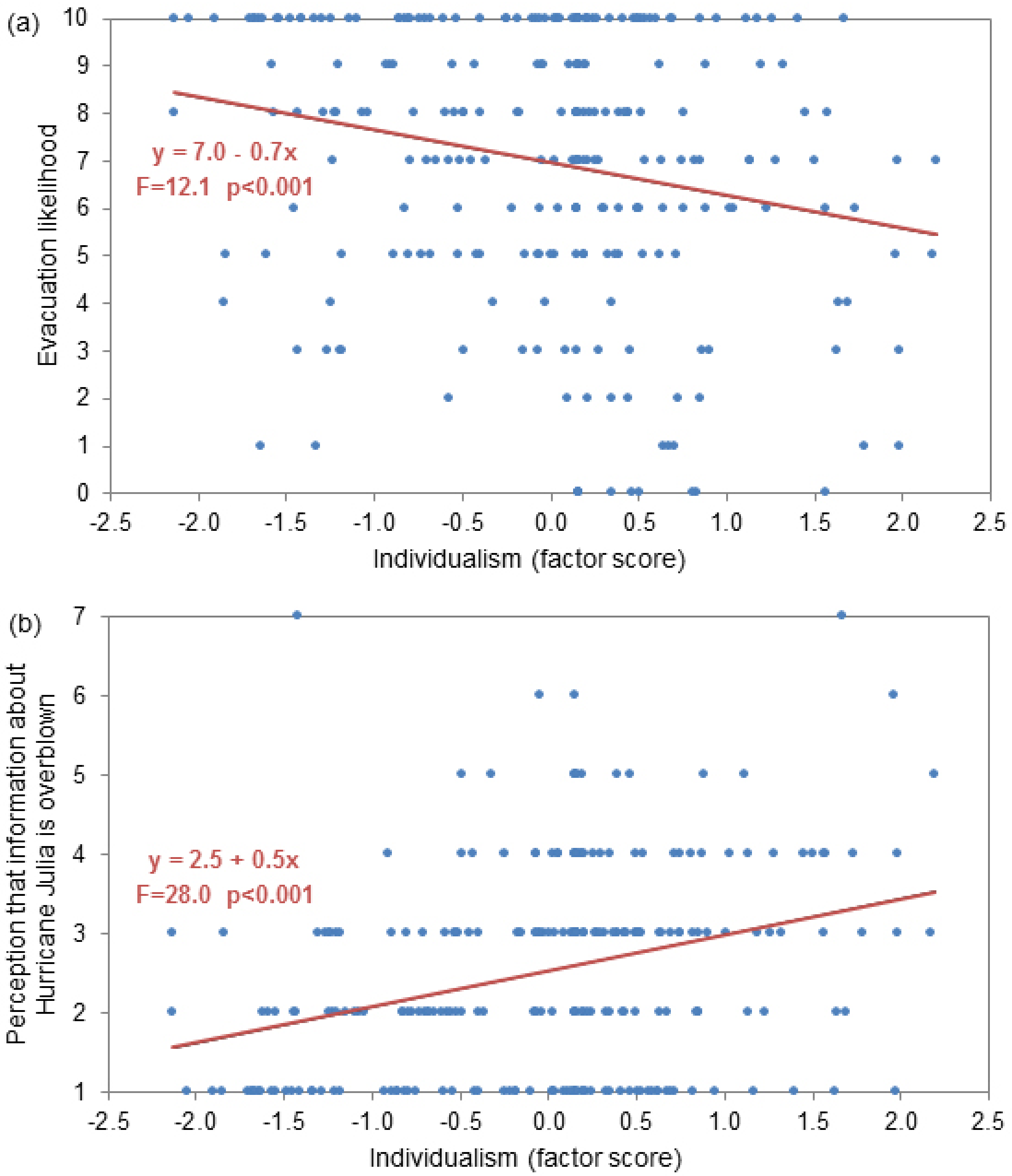

Figure: (a) Plot of each respondent's evacuation likelihood for a hypothetical approaching hurricane vs. their level of individualist worldview (blue circles), along with a linear best fit to the data (red line and equation with F- and

p-value). (b) As in (a), for respondents' perceptions that the information provided about the approaching is overblown. $p<0.001$ for individualism in both best-fit analyses. Data were derived from a survey with residents of coastal Miami-Dade County, FL. From Morss et al. (2016).

Other work included advancing understanding about how stakeholders interpret and use extreme weather and climate information at subseasonal to decadal timescales. Findings from this research show that cultural values can have important influences on people's perceptions of drought risks and on their preferences for drought risk management. An additional goal of this work is to design frameworks for integrating social and atmospheric sciences in ways that enhance the usability of weather and climate information.

‹ ECEP® and Rising Voices up NCAR Imperative 3: Develop, deliver and support a suite of advanced community models ›

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WRF DEVELOPMENT

WRF development efforts within MMM aim to improve performance and accuracy of the WRF model for simulations of all types of high-impact weather. WRF continues to grow and evolve to include emerging research and changing demands and applications. Support for model research and development helps users to transition their ideas into practice, benefiting the overall user population. Development efforts advance the entire WRF system, providing the atmospheric research and NWP communities with improved tools and capabilities. WRFDA and WRF-Chem improvements, and assistance with integration of their developments, advance the released versions of these two important systems.

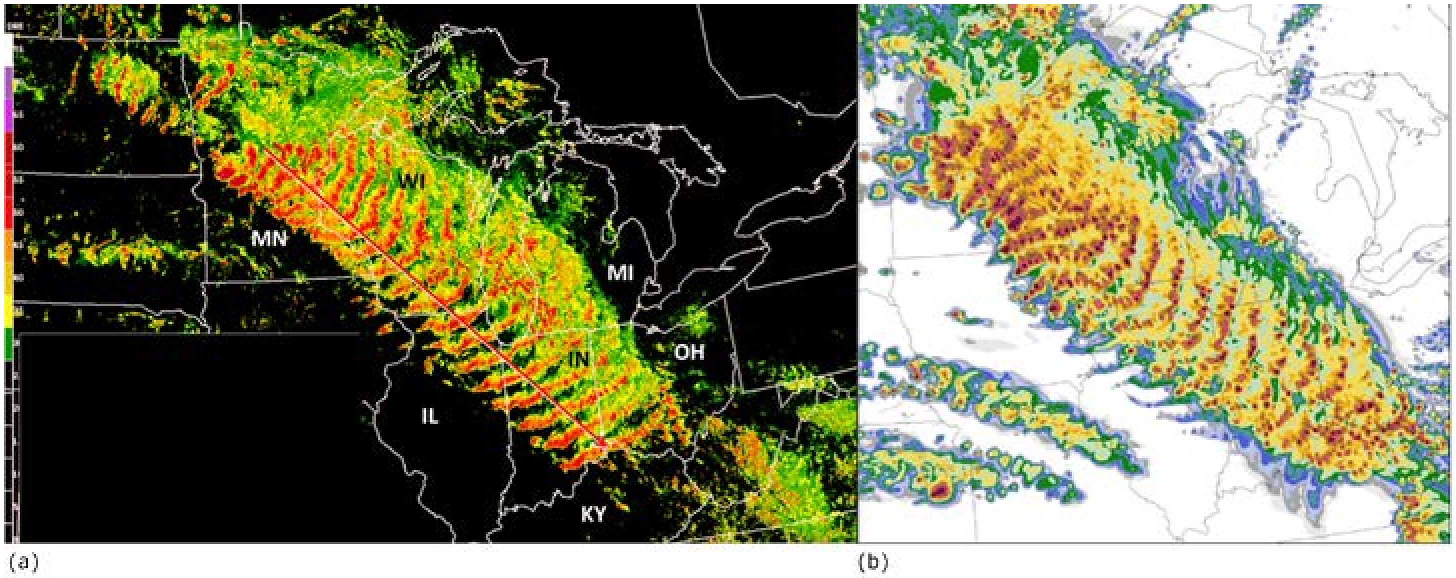

Figure: Example of WRF forecast capturing a squall line event (July 12–13, 2015) and verifying radar imagery. (a) NOAA Storm Prediction Center (SPC) image of composited hourly radar reflectivity for a squall line traveling from Minnesota to Ohio, July 12–13, 2015. Individual positions of the squall line are marked by enhanced reflectivity in red/orange, and the line progresses from northwest to southeast (from MN to KY). Approximate line lifetime and period captured in image is 2300 UTC 12 July–1800 UTC 13 July. (b) Composited hourly simulated reflectivity from a WRF forecast from the real-time MMM ensemble for 0200 UTC 12 July– 2100 UTC 13 July. Hours 26–45 from forecast initialized 0000 UTC 12 July 2015 shown.

In FY2016, new procedures for handling community input for the model were implemented. The first was the start-up of the WRF Physics Review Panel, which is designed to review new, proposed physics packages for the model in order to ensure their value. In addition, the Developers' Committee (DC) implemented new procedures to improve the code commit and ingest processes. In a significant shift, the DC implemented a new software control system, Git. Git offers advantages over the previous system, Subversion, that will improve the ability to test new code submissions and model versions. The system will facilitate the proposed sharing of physics code with MPAS, which is an element of MMM's effort to coordinate and align aspects of WRF and MPAS.

This past year two WRF releases were issued, and full details on the new features and packages are available at www2.mmm.ucar.edu/wrf/users/wrfv3.8/updates-3.8.html and www2.mmm.ucar.edu/wrf/users/wrfv3.8/updates-3.8.1.html. The improvements to model performance and behavior from the numerous changes are also noted on those webpages.

These new releases expanded the capabilities of the system, including WRFDA, WRF-Chem, WRF-Hydro, and HWRF. From a collaboration of NCAR and the NOAA National Water Center, WRF-Hydro was selected for full development and implementation as the NOAA National Water Model (NWM) (http://water.noaa.gov/about/nwm). It will be used for operational hydrological forecasting for the nation.

‹ NCAR Imperative 3: Develop, deliver and support a suite of advanced community models   up   Regional climate modeling ›

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REGIONAL CLIMATE MODELING

Researchers continue to work on the development of NCAR's coupled atmosphere-ocean, dynamical-statistical regional climate modeling which focuses on approaches to combine dynamical and statistical views of regional climate. Work within MMM is furthering understanding of the benefits of coupled atmosphere-ocean processes for regional climate simulation and for simulation of tropical cyclones.

In FY2016, MMM scientists simulated case studies of weather events using a coupled atmosphere ocean model. For example, figure 1 shows a snapshot from a coupled simulation of Hurricane Lili (2002). Ten historical Gulf of Mexico hurricanes were simulated under current and future climate conditions. Future changes in the joint probability of extreme winds and waves were assessed by fitting generalized extreme value distributions to the dynamical model data. This work established new approaches to combine dynamical and statistical modeling, which are being applied to community tools. Substantial improvement in our understanding of what is possible and otherwise for downscaling climate projections to

regional scale have been made, particularly in the statistical downscaling area.

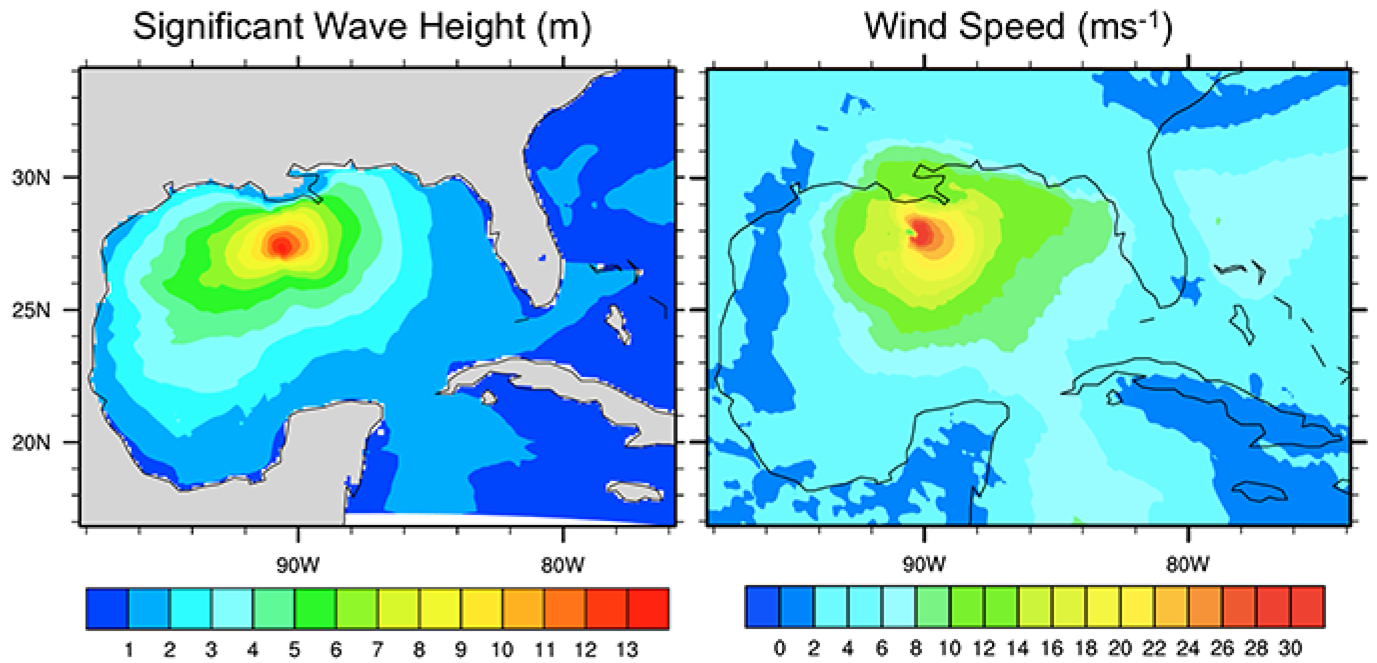

Figure 1: Wind-Wave coupled simulation of Hurricane Lili (2002) showing significant wave height (m, left) and wind speed (ms^{-1}, right).

‹ WRF development up MPAS development ›

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MPAS DEVELOPMENT

Development and testing of MPAS represents a major intellectual and computational challenge. It requires local and global high performance across a range of resolutions and the ability to simulate nonhydrostatic convective motions, as well as large-scale variability, with physical parameterizations that behave consistently and robustly as resolution changes across the globe. The testing will identify areas for prioritized development on the path to more unified earth system modeling.

In FY2016, scientists completed tests of MPAS in CESM/CAM5 for AMIP (multi-year climate) simulations, as well as an initial set of NWP simulations using CAM5 physics. Both AMIP and NWP (tropical cyclone cases) simulation results have been presented at the CESM/AMWG meeting and in a number of seminars. MPAS/CESM is ready for initial regional-climate applications that will allow for final tuning and configurations. Several U.S. research groups are beginning to use these MAPS/CESM capabilities.

In addition, scientists continued testing variable-resolution meshes that span the hydrostatic-nonhydrostatic regime, focusing on explicit forecasts of warm-season high-impact convective weather over the continental U.S. (CONUS). MPAS-A performance is being evaluated, specifically with regard to the scale-aware physics, for the NOAA Hazardous Weather Testbed (HWT) Spring Convective Forecast Experiment in Oklahoma. The resolution capabilities of MPAS have been re-affirmed in these forecasts, and new forecast accuracy/resolution measures have been developed and demonstrated based on observed and simulated 2D and 1D spectra of surface precipitation. Longer-term convective outlooks from convection-permitting MPAS should be useful to weather forecasters for longer-lead-time advisories.

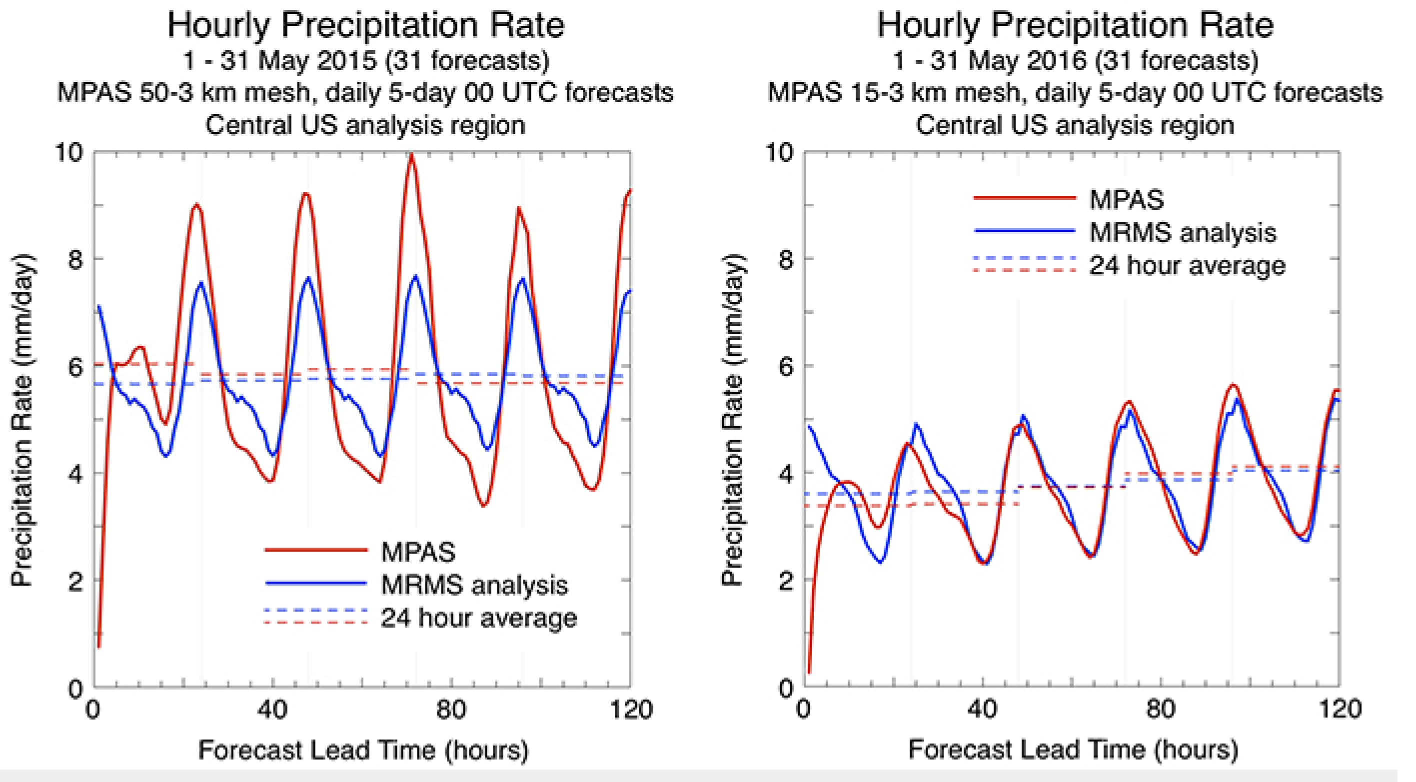

Figure: Precipitation rates from the MPAS-Atmosphere forecasts used in the NOAA Hazardous Weather Testbed Forecast Experiment. The dramatic improvement in capturing the diurnal cycle of precipitation in 2016 over 2015, evident in the near-elimination of the excessive peak precipitation rate and the underprediction of the nocturnal minimum, is the result of using the Thompson microphysics scheme in 2016 and the WSM6 scheme in 2015.

Other work this past year includes the completion of the port of the NOAA/NCEP supported version of the GFS physics package using the common physics interface supplied by NCEP. Reports were produced using GFS-physics-based forecasts and made publically available. In addition, initial testing and evaluation of a scale-aware physics package that allows simulations across the hydrostatic-nonhydrostatic scales was completed.

Ongoing work includes the simulation of a decade of current climate using MPAS uniform mesh at 120km, and assessment of the simulated mean climate in terms of circulation, temperature and precipitation patterns, and climate variability. A series of single-year simulations using different physics options will be conducted. The data to assess performance of the different model physics representations for temperature and precipitation patterns will be analyzed.

‹ Regional climate modeling | up | Data assimilation (DA) for WRF ›

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DATA ASSIMILATION (DA) FOR WRF

Development of DA systems for WRF and MPAS provides the foundation for NCAR research in DA and probabilistic prediction, and for subsequent support of these systems to the community. Predictions are improved through better initial conditions with reliable estimates of uncertainty and through improvements to WRF and MPAS themselves. Improvements in DA lead directly to improved predictions of weather, air quality and other applications.

In FY2016 NCAR scientists guided and coordinated externally funded and community developments in WRFDA, such as the 4D extension of the ensemble-based 3DVar, further improvements to the radar assimilation for convective-scale applications, and assimilation of radiances from geostationary satellites. Supported by externally funded projects, hybrid-4DEnVar algorithm development was completed. Non-echo radar DA is currently under development and other projects continue to show good progress such as the GOES-Imager radiance DA development and the multi-resolution incremental 4DVAR research and development. High spatial and temporal resolution radiance data from GOES-Imager have the

potential to improve forecast of convective rainfall, as demonstrated by a case study over the Mexico region (Fig. 1). Progress in 2016 also included the contribution from external collaborators of adjoint code for some WRF/Chem modules, which was merged into a branch of the WRFPlus repository.

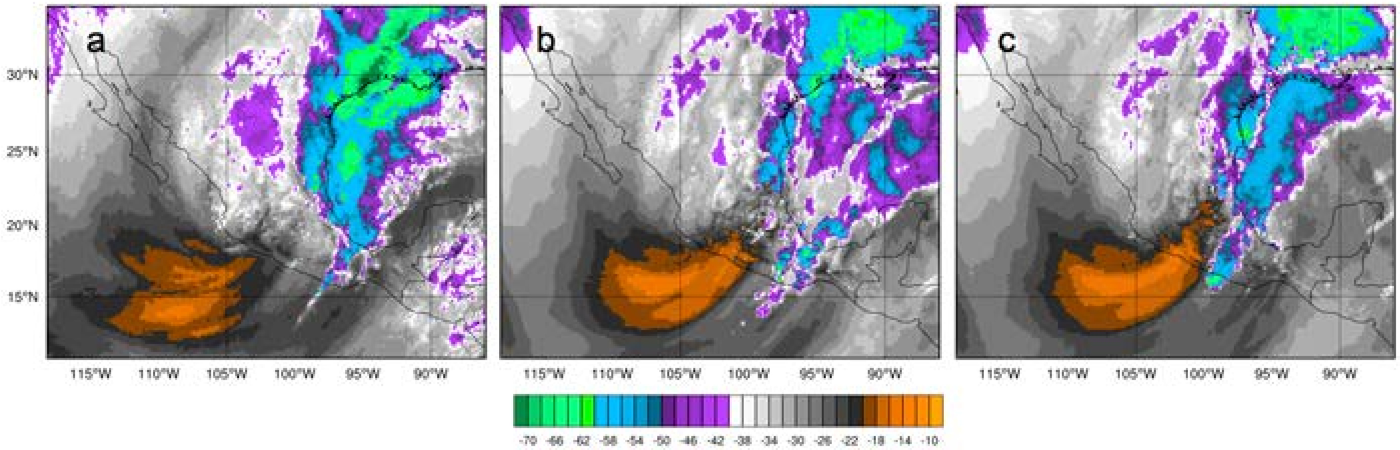

Figure 1: Brightness temperatures (in °C) of GOES-Imager water vapor channel from (a) GOES-13 observations valid at 00 UTC March 10, 2016 and the corresponding 24-hour WRF forecast initialized from the analysis (b) without and (c) with the assimilation of GOES-Imager clear-sky radiances. WRF model and hourly-cycling data assimilation were configured at 4-km horizontal resolution.

NCAR scientists also increased the robustness and diagnostic capabilities for real-time ensemble DA and prediction experiments. Diagnostics for real-time ensemble prediction now include surrogates, such as updraft helicity, for severe weather associated with convective storms.

Other work this past year included incorporating utilities in WRF and MPAS for computing and outputting time-averages of tendency terms. Time averages of analysis increments and physics tendency were used to diagnose the relationship of temperature biases in WRF to the convective parameterization. Code to accumulate tendencies from various physical parameterizations was implemented in WRF. This work on incorporating utilities in WRF and MPAS will be continued next year.

‹ MPAS development   up   WRF support ›

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WRF SUPPORT

WRF support provides a valuable service to the research and university communities and contributes to maintaining the pace of research advances across a spectrum of topics in mesoscale and microscale meteorology. WRF workshops and tutorials broaden the base of modeling experience and expertise in the community, and entrain the next generation of modelers. The WRF-based AMPS effort supports the NSF-funded United States Antarctic Program (USAP) in its scientific and logistical operations across Antarctica, improves high-latitude WRF capabilities and forecasting products, and advances Antarctic research and model development. AMPS's impacts continue to be in reduced costs and enhanced efficiency for the USAP and other Antarctic users in their activities across the high southern latitudes and improved safety for the USAP and associated personnel on the ice.

This past year MMM organized and hosted the 17th WRF Users' Workshop in June and completed two tutorials at NCAR, in January and July. The latter also included a WRFDA tutorial. Similarly, MMM's Regional Climate Section conducted a

regional climate modeling (RCM) tutorial at NCAR in August.

Photo: Participants of the January 2016 WRF tutorial at the NCAR Foothills Lab.

Outside of NCAR, MMM conducted a WRF tutorial in Guangzhou, China in December in collaboration with the Hong Kong University of Science and Technology, and MMM personnel taught WRF at the COAWST (Coupled Atmosphere Ocean Wave Sediment Transport Model) Workshop at the USGS facility in Woods Hole, MA in August. Approximately 200 researchers participated in the WRFUsers' Workshop and over 195 users were educated through the tutorials, in additional to those who accessed the online WRF tutorial. MMM also managed a help desk, which has handled about 475 e-mail inquiries per month. The influx of registrations to download WRF continued at a high level, with over 4,200 registered users expected for the calendar year. The cumulative number of peer-reviewed publications involving WRF is projected to be over 3,700 by the end of 2016.

MMM scientists continue to support the AMPS effort, and this fiscal year included the 2015–2016 Antarctic field season. The program continued to build the AMPS Archive on the Earth System Grid with periodic updates of model output. In a special support role, AMPS also provided NWP guidance for the weather forecasters of the NSF-funded ORCAS field campaign. This featured flights of the NCAR GV over the Southern Ocean. Lastly, in June, AMPS supported medical evacuation flights of USAP personnel from the South Pole Station. Special products from AMPS contributed to the success of the emergency mission.

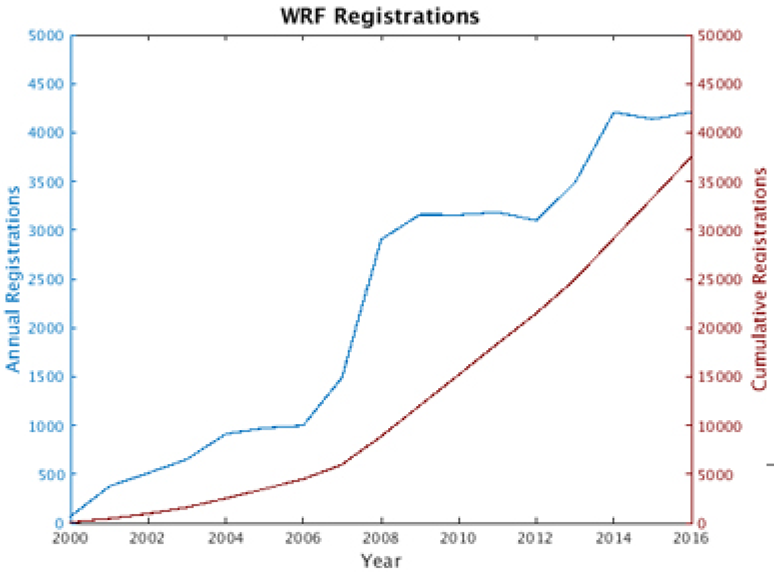

Figure: WRF annual number of user registrations (blue) and cumulative number of user registrations (red).

‹ Data assimilation (DA) for WRF up
WRF data assimilation (WRFDA) support ›

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WRF DATA ASSIMILATION (WRFDA) SUPPORT

Support of the WRF and MPAS DA systems fosters effective DA use across a broad community and with individual university principal investigators and graduate students, enhancing training and accelerating DA and numerical weather prediction for a variety of applications. Support provided by MMM staff includes organizing tutorials, answering WRFDA questions through the WRF help desk, posting Frequently Asked Questions related to WRFDA on the WRFDA web site to facilitate WRFDA use, maintaining the WRFPlus code, and incorporating new developments into the WRFDA release.

Highlights of the support provided in FY2016 include the three-day WRFDA tutorial held on 1-3 August 2016 which attracted 39 attendees. Tutorial presentations and handouts on data are posted online. The length of the tutorial was extended from the previous years' 2.5 days to 3 days and new and more advanced hands-on sessions such as cloud-radiance DA was offered. New this past year was a featured presentation from an invited non-NCAR researcher on WRFPlus-Chem and WRFDA-Chem.

The WRFDA support staff continued to receive and answer questions from WRFDA community users. On average, staff handle 20-40 WRFDA-related questions per month through the WRF help desk. The most frequently asked questions were posted as FAQs on the WRFDA website at http://www2.mmm.ucar.edu/wrf/users/wrfda/faq.html.

In FY2016, the WRFPlus and both the WRFDA V3.8 and V3.8.1 versions were released. The WRFDA V3.8 release included two main new features: a user-contributed dynamic constraint scheme and a clear-sky AMSR2 radiance data assimilation capability (externally funded). The other new capability, the all-sky AMSR2 radiance data assimilation, substantially improved Hurricane Sandy's track and intensity analysis and forecast by better depiction of the initial state around the tropical cyclone core area (e.g., better warm core structure, improved surface pressure and water vapor analysis), as shown in Fig. 1 and 2 The all-sky AMSR2 radiance DA was made available to the community via a beta release of WRFDA code along with documentation and a published paper (http://www2.mmm.ucar.edu/wrf/users/wrfda/beta.html).

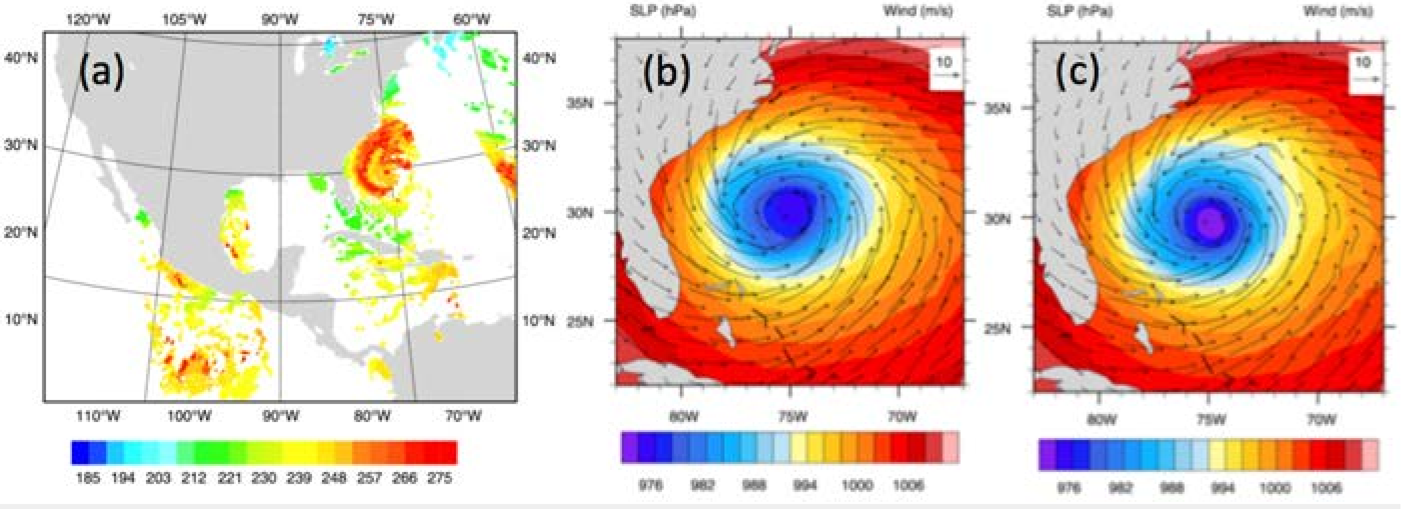

Figure 1: (a) AMSR-2 channel 9 pixels assimilated in all-sky assimilation but rejected in clear-sky assimilation at 18 UTC October 27, 2012. Sea-level pressure and surface wind analysis at the same time with (b) clear-sky and (c) all-sky AMSR-2 radiance assimilation.

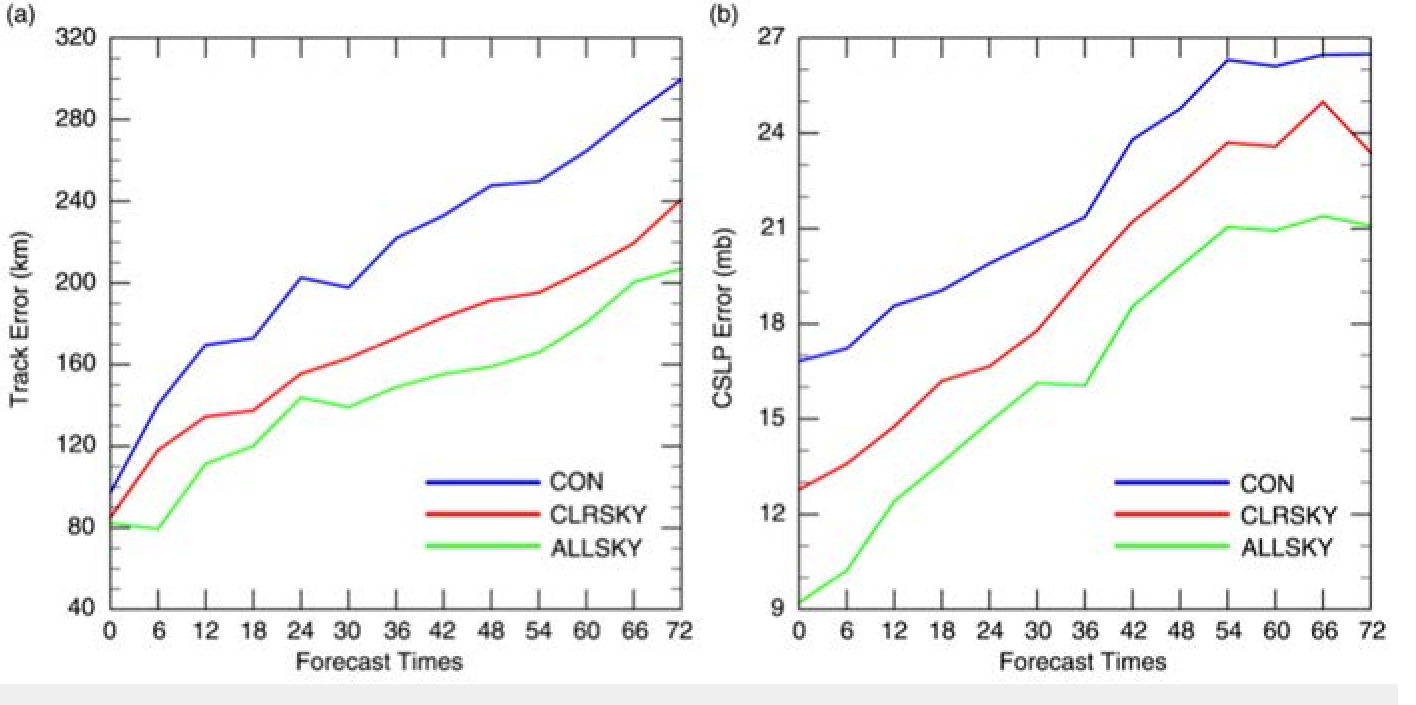

Figure 2: Aggregated (a) absolute track errors and (b) mean central sea level pressure errors as a function of forecast range from three experiments for Hurricane Sandy (2012). The error statistics are obtained from 13 72-h forecasts. CON: assimilate only conventional observations; CLRSKY: assimilate conventional data plus clear-sky AMSR-2 radiances; ALLSKY: assimilate conventional data plus all-sky AMSR-2 radiances. After Yang et al. (2016).

‹ WRF support up MPAS support ›

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MPAS SUPPORT

Since its FY 2013 release, a number of investigators in the university community and government laboratories have been evaluating MPAS for use in regional climate and numerical weather prediction applications or actively using MPAS in these applications. MPAS support is critical to successful use of the modeling system.

In FY2016, MMM staff organized an MPAS tutorial, and MPAS tutorial materials are now available online at the MPAS web site at https://mpas-dev.github.io/. Scientists continue to work on a limited number of physics suites, including a scale-aware physics suite for release. MPAS containing a mesoscale physics suite is now available. An MPAS release with a scale-

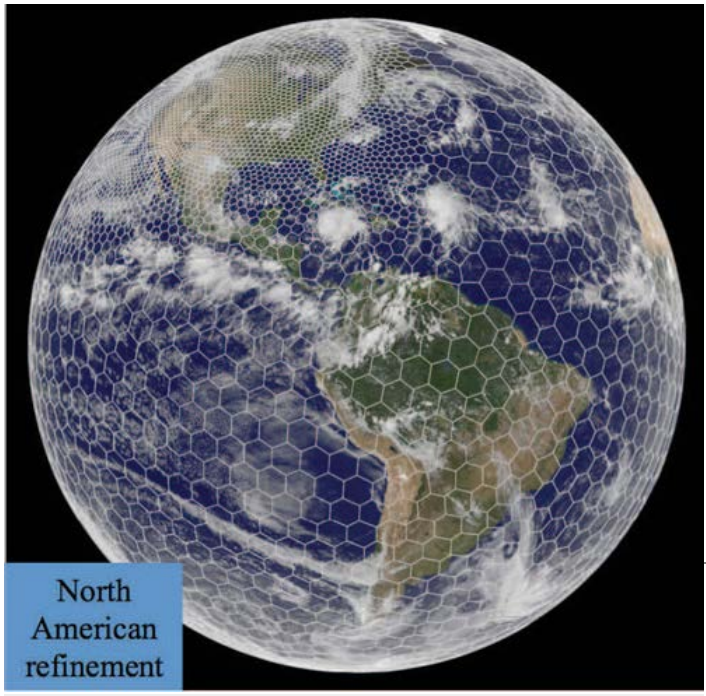

Figure: An example of the MPAS variable-resolution Voronoi meshes. The atmospheric component of the Model for Prediction Across Scales (MPAS-A) has been designed to provide seamless multi-scale numerical weather prediction (NWP) capability for large-scale (hydrostatic) and small-scale (nonhydrostatic) phenomena using uniform and variable-resolution unstructured horizontal meshes.

aware physics suite is planned to be released late in 2016.

‹ WRF data assimilation (WRFDA) support up
NCAR Imperative 5: Develop and transfer science to meet societal needs ›

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‹ MPAS support up Global resilience improvement program (Risk modeling) ›

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GLOBAL RESILIENCE IMPROVEMENT PROGRAM (RISK MODELING)

MMM scientists have established the **Capacity Center for Climate and Weather Extremes – C3WE.** C3WE comprises academic, private, public and community organizations dedicated to enabling and supporting collaboration, research, education, workforce development, and creation of actionable tools that supports the development of a global culture of resilience to weather and climate extremes based on cutting-edge science and distributed information technology. C3WE contains three programs: The **Engineering for Climate Extremes Partnership - ECEP®** promotes two-way discussions across diverse societal and expertise perspectives; the **Rising Voices** combines indigenous people's knowledge, practices, and priorities with climate science in support of adaptation planning; and, the **Global Risk Resilience and Impacts Toolbox - GRRIT®** aids society in reducing weather and climate impacts, building economic resilience, and improving disaster recovery.

In FY2016 scientists strengthened collaborations with societal partners through ECEP and Rising Voices, and worked to develop new GRRIT tools with the assistance of the partners including Climate-i for construction and Cyclone Damage Potential assessments (Fig. 1). In addition, new risk data were generated and made available on the C3WE website including for the Tropical Cyclone Risk Model (TCRM) and the Hybrid-WRF model for North Australia tropical cyclones. An

open-source risk model has many scientific and societal applications from understanding the value of climate adaptation and the drivers of risk, to risk management and policy implications, to designing adequate responses to weather and climate impacts. This understanding will benefit society at large.

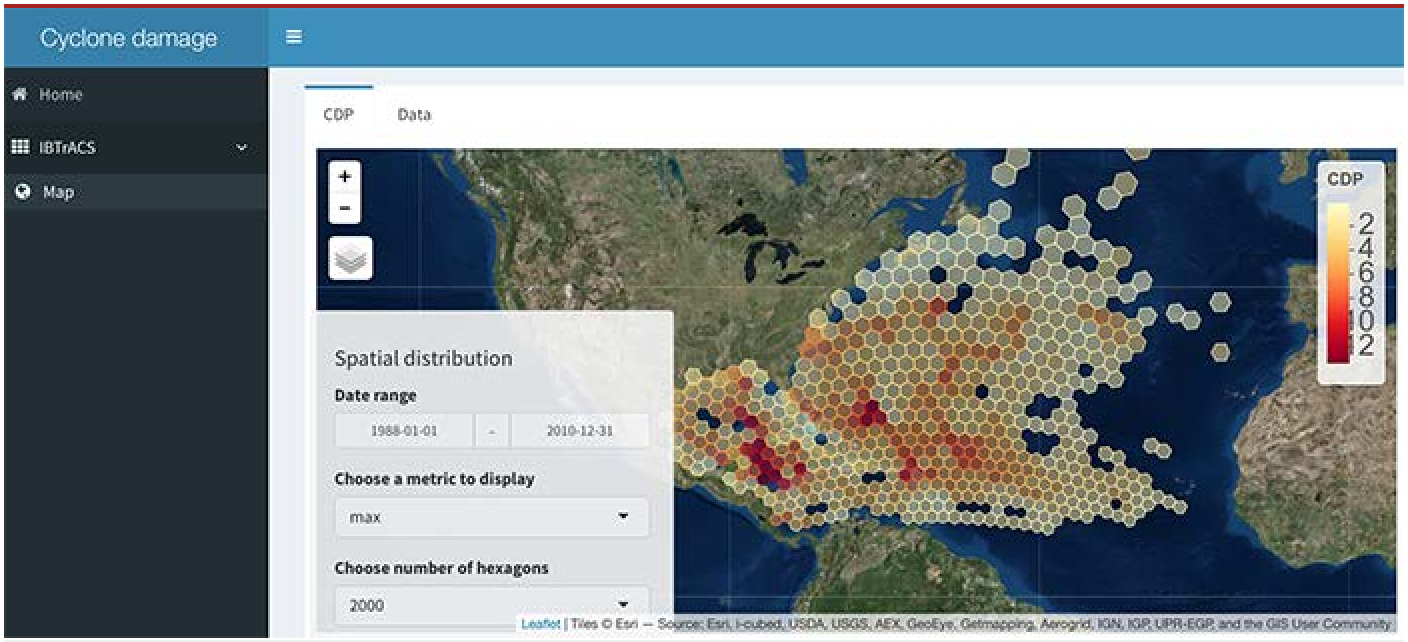

Figure 1: The Cyclone Damage Potential tool. Users can explore the damage potential of historical hurricanes through this web-interface, available at https://www.ecep.ucar.edu/cyclone-damage-potential-application.

‹ NCAR Imperative 5: Develop and transfer science to meet societal needs   up   Engineering for Climate Extremes Partnership (ECEP®) ›

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ENGINEERING FOR CLIMATE EXTREMES PARTNERSHIP (ECEP®)

The Engineering for Climate Extremes Partnership (ECEP) is a multidisciplinary network between research scientists and those involved in resilient decision-making aimed at reducing impacts from extreme events. Hosted by NCAR, ECEP facilitates a more comprehensive understanding of the scientific advances required to address societal resilience to weather and climate extremes, together with the development of relevant community support. ECEP's vision is to empower resilient decisions for weather and climate extremes through collaboration.

ECEP advocates a Graceful Failure approach to strengthen societal resilience. Graceful Failure accepts that some failures are inevitable and seeks to incorporate strategies to manage them in ways that minimize loss of life or property and allow a rapid recovery. The underlying philosophy is to help plan for resilient and rapid societal response in a manner that reduces the overall impact of failure.

Communication is a fundamental component of ECEP. In FY2016, MMM scientists convened collaborative focus groups to address the needs of the construction industry, and develop resources to assess and communicate weather and climate impacts. Using NOAA seasonal forecasts, a new tool was developed that helps construction managers to plan ahead for extreme and impactful weather events during the construction period – Climate-i for construction. The two-way

communication process was critical to help the partners learn about scientific advances, and changes in hazards, vulnerability and exposure, as well as for MMM scientists to gain understanding of the decision processes. Based on user feedback this tool can be expanded to other user communities.

Photo: Breakout discussion group at the 4th Annual ECEP Workshop.

Researchers also incorporated user needs to inform analysis and evaluation of existing regional climate assessments and predictions. Several decision-making tools have been developed with collaborations from industry, Federal agencies and NCAR scientists. The process of determining pertinent information and presenting it in a useful format is an ongoing effort and will be invaluable for future ECEP activities and in support of the Global Risk, Resilience, and Impacts Toolbox (GRRIT®).

‹ Global resilience improvement program (Risk modeling) up Risk communication ›

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RISK COMMUNICATION

NCAR scientists have been working together to advance knowledge about weather-related communication, interpretation and decision making in an effort to improve the development of atmospheric science information to meet societal needs. This work will benefit society by informing atmospheric science research and risk communication practice in ways that improve the usability and use of weather-related information

This past year scientists collected data from focus groups with members of the public to explore how risk communication interacts with people's dynamic vulnerabilities as a hurricane approaches and arrives. Focus groups were conducted in areas of New York City that were significantly affected by Hurricane Sandy, with an emphasis on populations that are less likely to be active on social media (such as Twitter; see figure). Focus group participants included people from Spanish- and Russian-speaking communities, seniors, and residents of public housing. Analysis of the data is ongoing; findings to date illustrate the important roles that social networks, communication technologies, cultural attitudes, and information about services and assistance play in how people access and use hazard information. This research presents a novel conceptualization of how risk information and information networks can empower protective actions that enhance adaptive capacity and reduce vulnerability to hurricane risks.

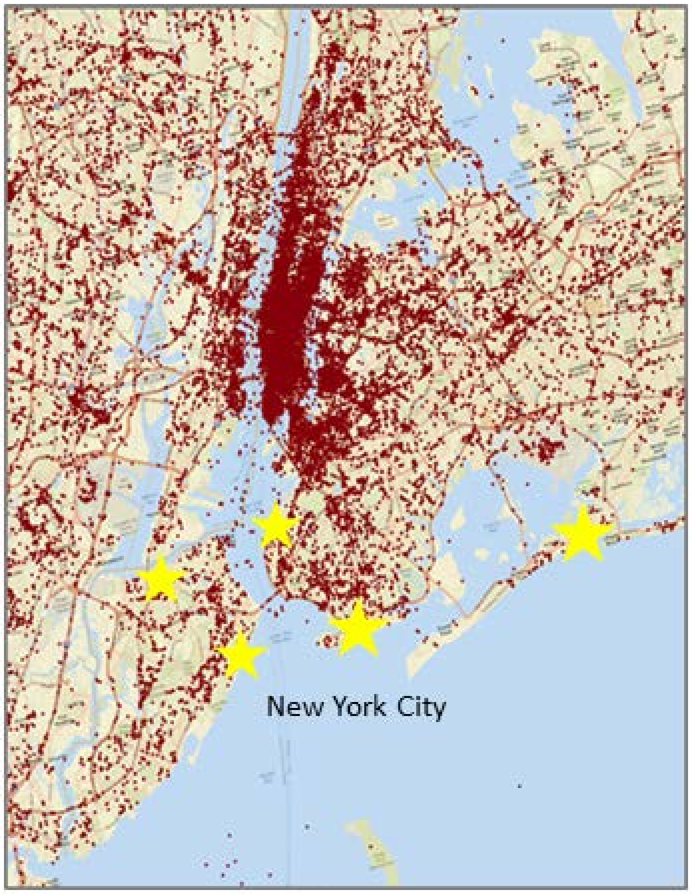

Figure: Neighborhoods in New York City where focus groups were conducted (stars), overlaid on a map of the locations of georeferenced tweets containing Hurricane Sandy keywords that were created during the period 22 October – 2 November 2012.

Other work being carried out within MMM includes analysis of how different aspects of tornado experience affect people’s risk perceptions and protective behavioral intentions, using survey data collected from residents of tornado-prone areas. This research provides two major advances compared to previous related research on hazard experiences. The first advance is development of a more comprehensive weather experience scale, which identifies several new dimensions of past hazard experience. The second is a new in-depth quantitative analysis of how different aspects of people’s hazard experiences are related to different aspects of their hazard risk perceptions. This analysis finds that experience with personal intrusive impacts from a tornado had the broadest influence on individuals’ tornado risk perceptions. By building understanding about the different ways that hazard experiences can influence people’s perceptions of and responses to risk, this work provides an important foundation for effectively communicating weather risks to populations with different types of hazard experiences.

This research fills important gaps in knowledge that can help forecasters, public officials, and others improve communication about weather risks with diverse populations. The research is also building knowledge about how diverse populations access, interpret and use different types of weather risk information, which is informing weather prediction research.

‹ Engineering for Climate Extremes Partnership (ECEP®)
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Research Applications Laboratory

STRATEGIC PLANS

MMM Strategic Plan

NCAR Strategic Plan

PREVIOUS MMM REPORTS

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RISING VOICES

Rising Voices addresses both the low levels of Indigenous students and researchers in atmospheric sciences and the vulnerability of Indigenous communities by leveraging NCAR's status as a national center and the breadth of expertise in its university community. Rising Voices brings cross-cultural experts and scientists together to address the challenges Indigenous communities face through research collaborations and in connection with many NCAR programs.

In FY2016, awareness was raised through Rising Voices about opportunities for cross-cultural collaboration between NCAR scientists and Indigenous community members. This was done primarily through an active listserve and through the Rising Voices Four workshop held in Hawai'i in July 2016. NCAR opportunities were promoted among student workshop attendees, professors who work with students at Tribal College and University institutions, and other professionals in tribal agencies. FY2016 also saw a successful NSF INCLUDES proposal funded that will support student, professor, and scientist collaborations in cross-cultural science.

Photo: Participants of the Rising Voices Four workshop stand in front of Mauna Kea on Hawai'i Island, Hawai'i.

A continuing effort at NCAR is to promote student and early career opportunities at NCAR with the outcome of increasing the participation of Native Americans, Alaska Natives and Pacific Islanders in NCAR education and outreach programs and in the geosciences in general.

Last year scientists also worked to develop a novel approach to evaluation based on culturally appropriate and diversity-sensitive metrics with the outcome of enabling assessment of cross-cultural diversity activities at NCAR and beyond. A workshop evaluation and social network analysis of participants was conducted and is being analyzed as part of a PhD dissertation. The development of metrics that encompass diversity can be shared in other contexts and used in other activities.

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STRATEGIC PLANS

RAL Strategic Plan

NCAR Strategic Plan

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DIRECTOR'S MESSAGE

Welcome to the Research Applications Laboratory's Annual Report for FY2016. 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.

Brant Foote - RAL Director

‹ 2016 RAL Annual Report
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2016 RAL ANNUAL REPORT

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NEXT GENERATION AIR TRANSPORTATION

Play a leadership role within the atmospheric research community to provide the necessary scientific underpinning and technology to support the weather and climate–related needs of the Next Generation Air Transportation System (NextGen).

- InFlight, Ground and Engine Icing
- Prediction of Storm Hazards for Aviation
- Turbulence
- Integration of Weather Information into Air Traffic Management

- Dissemination of Aviation Weather Information
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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 is the development of 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 FAA has recently begun funding icing research in the terminal area after a new rule was enacted regarding flight restrictions in known icing conditions. To improve the detection and forecasting of icing in the terminal area, the Terminal Area Icing Weather Information for NextGen (TAIWIN) program is conducting research focused on two key areas: improved ground detection of icing conditions (notably the detection of freezing drizzle) and improved performance and forecasting of freezing drizzle and freezing rain in numerical models. Improved ground detection of icing conditions has focused primarily on automated detection of freezing drizzle and ice pellets and improvements to feature-tracking algorithms for radar and satellite data are also being explored. The numerical modeling tasks funded under TAIWIN have focused on development of a time-lagged ensemble for better forecasts of icing conditions; improved aerosol initialization and fluxes in the models' identification of shortcomings of model initialization of clouds and precipitation; testing of new data assimilation methods; and improved blending of observations and nowcasts with numerical forecasts of icing conditions. A new flight campaign, the In-Cloud ICing and Large-drop Experiment (ICICLE), is being planned for 2018-19 to study microphysical cloud properties in order to better understand how icing conditions (particularly freezing rain, freezing drizzle and ice pellets) form and evolve over time.

The NextGen Surface Observing Capabilities (NSOC) Weather Observations Improvement (WOI) group has been developing a specification for the present weather sensor (PWS) replacement on the Automated Surface Observing System (ASOS). The current sensor, the Light Emitting Diode Weather Indicator (LEDWI), is currently at the end of its life and needs to be replaced. Various sensors are being tested to determine their accuracy with reporting drizzle/freezing drizzle and ice pellets to mitigate the gap in reporting those conditions since ASOS cannot currently report those precipitation types without being augmented by a human observer.

Ground deicing research continued with a focus on improving the NCAR snow machine to better match the indoor holdover times versus the outdoor holdover times observed in nature. The machine has typically shown more conservative (shorter) holdover times as compared to outdoor times the FAA is interested in determining why that is and correcting for it. Upgrades to the machine were also a focus for improving machine performance and reliability during fluid testing.

FY2016 ACCOMPLISHMENTS

In 2016, RAL continued work on a number of icing aloft projects for the FAA: 1) MICRO (Model for Icing Conditions in Real-time Operations), which incorporates 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 with the intention of addressing FAA regulations to discriminate between freezing drizzle and freezing rain. In 2016 an experimental version of MICRO was established to run on the CONUS domain for research purposes. 2) IPA (Icing Product-Alaska) adapts CIP and FIP for the Alaska weather and data environments. The forecast component went under review by the FAA's technical review panel (TRP) for approval as an experimental product this year. The diagnostic component of the algorithm is ready for evaluation by the FAA Quality Assurance Product Development Team. 3) Improvements to icing diagnosis using NEXRAD dual-polarization data. An initial dual-polarization Radar Icing Detection Algorithm, RaDIA, was implemented locally on data streams from two NEXRAD dual-pol radars. Engineers worked 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. 4) Engineers worked with NCEP to transfer CIP and FIP to its supercomputing environment WCOSS.

RAL staff working on the High Ice Water Content (HIWC) project joined with members of the European High Altitude Ice Crystals (HAIC) to evaluate and refine methods for detecting and nowcasting areas of HIWC. Research quality data from a series of joint field campaigns in Australia, French Guiana, and Florida were analyzed by the teams and are being used to assess diagnostic and forecasting capability. The evaluation process has resulted in an upgraded version of ALPHA (Algorithm for Prediction of High Ice Water Content Areas) which 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.

TAIWIN received its first significant funding from the FAA for 14 task areas. Ground detection of freezing drizzle, one of the continuing tasks from prior years, has been focused on utilizing the existing Automated Surface Observing System (ASOS) infrastructure to derive periods when freezing drizzle is occurring, even though the system cannot directly determine these conditions. Initial indications are that the algorithm is working very well and can be used to reprocess archived data for determining periods where freezing drizzle may have been occurring. Spatial variability of precipitation (primarily snow thus far) in the terminal area has also been a primary focus of prior TAIWIN efforts with the goal of determining how far apart surface observations are needed to accurately detect the changing weather conditions within the terminal area. A series of surface weather stations have been installed at varying distances apart (2 km to 10 km) along the Colorado Front Range to exam the spatial variability of snow and provide recommendations on surface station spacing. Radar and satellite tasks received their initial funding and efforts were focused on analyzing data to determine if they can contribute to determining spatial variability, as well as testing previously developed feature-tracking algorithms to test whether radar and satellite features can be tracked sufficiently to provide a near-term nowcast of icing conditions. Considerable effort also went into the model improvement tasks with most of the work focusing on the Time-Lagged Ensembles (TLEs)and cloud underproduction tasks. A new TLE of the HRRR model was developed and is currently being run in real-time within RAL. The modeling group is performing an initial verification of the TLE to determine if adjustments need to be made to the weighting of the different model runs. The cloud underproduction task also made significant progress and focused their efforts on development of a new cloud-fraction scheme for the WRF model to better forecast cloud development. And finally, model verification of precipitation types was also undertaken to assess the current ability of the operational WRF in correctly determining the location and type of precipitation at the surface.

RAL staff deployed and maintained sensors at four locations across North America including Boulder, CO; Grand Forks, ND; Pittsburgh, PA; and St. John’s, Newfoundland. The sites collected sensor and video data of all precipitation events during the winter of 2015-16. NCAR staff then examined all periods where drizzle/freezing drizzle and ice pellets occurred and reviewed all the video data during those periods to develop a human observation database for precipitation type on a minute-by-minute basis that the sensor data could then be compared to. Analysis of the sensor data is currently ongoing.

The ground deicing work focused on improving the NCAR snow machine through a significant upgrade of the LabView code and improved snowfall distribution in the machine utilizing fans instead of air jets. Outdoor testing also indicated that the shorter holdover times in the machine may actually be related to the design of the fluid testing assembly. Late season testing indicated the gap at the top of the assembly between the fluid test plate and the fluid catchment system may be too small, allowing snow to bridge the gap and wick the fluid away from the upper portion of the plate, causing a premature failure of the fluid. The end of winter conditions prevented any further testing to verify these observations.

PLANS FOR 2017

Development and testing of MICRO algorithms for diagnosis and forecasting of particle size distributions to address FAA

regulations will continue. IPA work will focus on determining the optimal operational setting for IPA in collaboration with the FAA. The transfer of RadIA to MRMS will continue. In-flight Icing team members will support the SNOWIE project in Boise, Idaho which will collect airborne and ground based data in icing conditions. The data set obtained in SNOWIE is expected to provide case studies for evaluating MICRO and RadIA, and to provide insight on plans for a dedicated icing field campaign in 2019. Scientific and logistical plans for this project, known as ICICLE, will be developed in 2017.

The HIWC team will complete evaluation of ALPHA using currently available data sets, and then apply ALPHA to compile statistics on the frequency and duration of HIWC conditions. A version of ALPHA will be implemented in Australian under an agreement with the Bureau of Meteorology to exchange information about its performance in a tropical environment.

TAIWIN will continue to focus its efforts on the aforementioned tasks, with the goal of publishing the results of the freezing drizzle algorithm work, the TLE work and the clould underproduction work. An AMS presentation on efforts relating to freezing drizzle, spatial variability, model verification work, and cloud underproduction are being planned. Flight campaign goals will also be established and potential university collaborators will be explored to participate in an NSF proposal for the project.

The NSOC WOI program is expected to wrap up the data analysis portion of the study and provide recommendations to the FAA on the specifications that industry sensors will need to meet in order to be considered for implementation on the ASOS system. NCAR staff will continue to contribute to the task as necessary to support data requests and attend meetings to present results in support of finding a new replacement sensor for the LEDWI.

The snow machine work is expected to continue with a focus on improving the design of the tray assembly, more outdoor versus indoor testing, and upgrading the APS Aviation snow machine to match the current version of the NCAR snow machine. A request is also being explored from the FAA to possibly build a third machine for use by APS Aviation at its icing facility in Montreal.

‹ Next Generation Air Transportation up Prediction of Storm Hazards for Aviation ›

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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 for airport operations safety from lightning for outdoor workers. In addition, efforts have continued in terms of enhancing our understanding of numerical weather prediction model performance, which enables effective harvesting of model predictions for convective storm initiation and probabilistic forecasting.

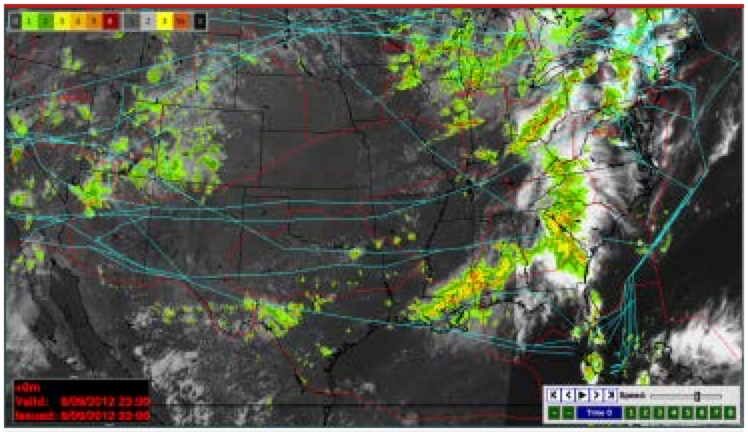

Figure 1. Analysis and forecast products made available to aviation planners via a web-based display.

FY2016 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) and, as of this past year, also throughout the rest of the year. 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 and better capturing storm initiation.

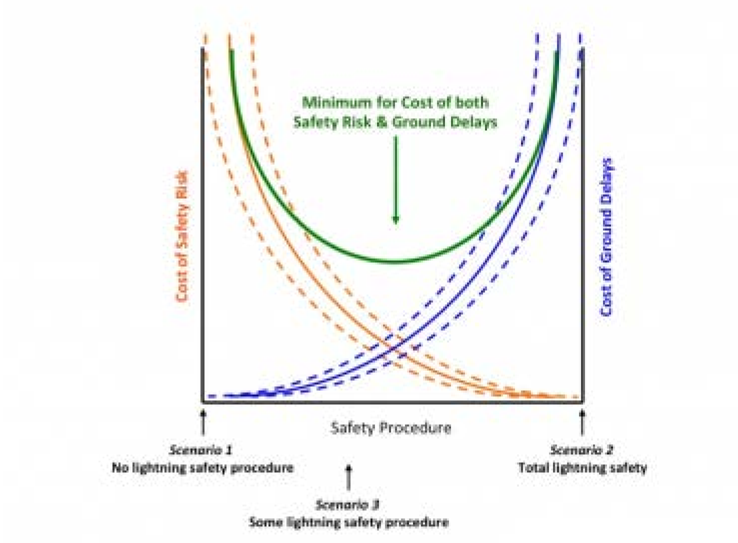

Figure 2. Economic balance between remaining safety risk and incurred air traffic delays as a function of lightning safety procedure.

Significant research has been devoted to understanding the safety risk of 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. 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 substantial impacts on traffic in/out of an airport and potentially cause ripple effects through the national airspace system. Recent analyses have been geared toward quantifying both the remaining risk of outdoor workers exposed to lightning threats and the air traffic ground delays incurred due to implementing lightning safety ramp closures (Figure 2) as a way to identify opportunities for improved ramp closure decisions and traffic management under thunderstorm impacts.

Unexpected initiation of large-scale convective storms can exert substantial impacts on air traffic as well. Using data mining approaches and ensemble forecasts, our research this past year has continued toward early identification of areas prone to develop large-scale storms, including assessment of how well numerical weather prediction models capture those storm initiation areas. The substantial prediction uncertainty is reason for developing probabilistic convective storm

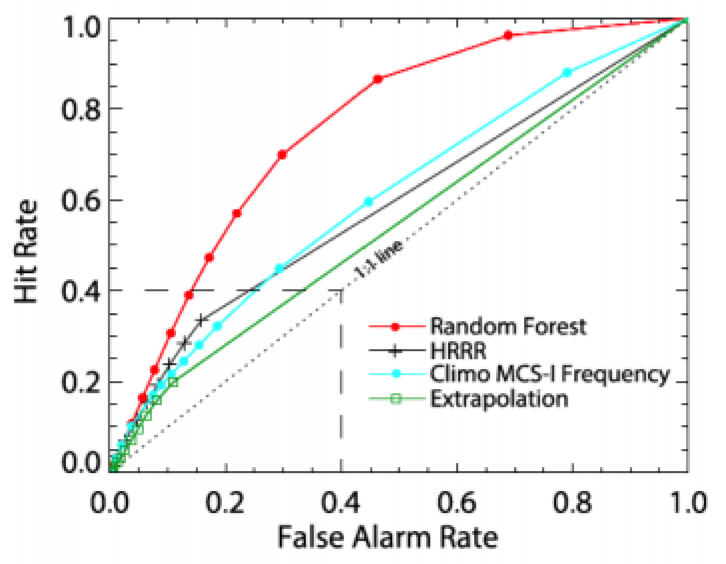

Figure 3. Receiver operating characteristic (ROC) curves for matched 2-hour random forest predictions (red), 4-hour forecasts of composite reflectivity from HRRR (black), mesoscale convective system initiation climatology (cyan), and 2-hour extrapolations of radar-based vertically integrated liquid maps (green) for summer 2013 data.

guidance products using ensemble forecasts. A data mining and statistical learning method known as a random forest (RF) has shown substantial skill (Figure 3) generating 2-hour forecasts of the likelihood for initiation of mesoscale convective systems over the United States based on using a range of radar reflectivity, satellite imagery, and numerical weather prediction (NWP) model diagnostics. In a separate effort, we have been developing a probabilistic convection guidance product based on global ensemble forecasts for strategic transoceanic air traffic planning (see oceanic weather).

FY2017 PLANS

Research and development will 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. CoSPA forecasts are now 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.

‹ InFlight, Ground and Engine Icing up Turbulence ›

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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. According to some estimates, turbulence encounters account for well over 75% of all weather-related injuries on commercial aircraft and amount to at least $200M annually in costs due passenger and crew injuries and aircraft damage. 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 understandings 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 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 the effects of 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 ($m^{2/3}/s$).

AUTOMATED *IN SITU* EDR MEASUREMENTS

Despite the continued reporting of the frequency and severity of turbulence encounters, our understanding of the nature and genesis of aviation-scale atmospheric turbulence remains limited. However, research to better understand the nature and causes of free atmosphere aviation-scale turbulence has been hampered in part by a lack of reliable observational data. Until recently, verbal pilot reports (PIREPs) have typically been the only source of information about the location and severity of turbulence. These reports are, unfortunately, incomplete (since 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 given 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 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.

FY2016 Accomplishments

Currently the *in situ* EDR software package is implemented on Delta Air Lines (DAL) 737 and 767 aircraft, and 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

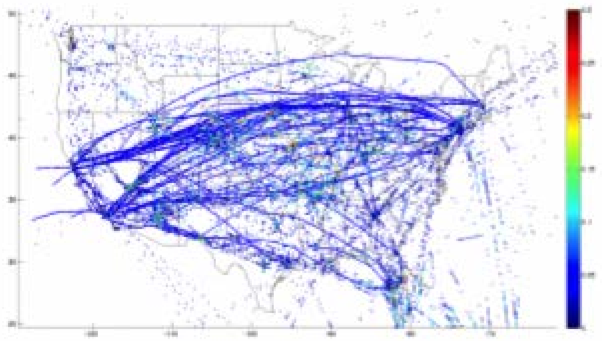

Figure 1. In situ EDR observations of turbulence automatically reported by UAL 757, DAL737, DAL767, and SWA737 aircraft for the 24hr period on 5 June 2015. The color scale is the EDR intensity (m2/3 s-1). EDRs > ~0.3 indicate areas of at least "moderate" turbulence intensity for a mid-sized commercial aircraft.

years; the highest priority is implementation on international aircraft to enhance global coverage. Modifications to the algorithm have been made to accommodate B777 aircraft which has a 10-Hz sampling rate, compared to the others already implemented which are 8-Hz. 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.

FY2017 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.

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) which uses 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 within cloud. The results are merged (or "mosaicked") 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.

FY2016 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. Transfer of the NTDA system to the National Weather Service's *Multi-Radar/Multi-Sensor*(MRMS) was begun.

FY2017 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. Implementation on the MRMS system will be completed.

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 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 ($m^{2/3}$ 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 out to 18-hrs lead time, 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., METARs gust information) 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).

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.

FY2016 Accomplishments

A major upgrade to the GTG product (GTG3) was released and made available on the ADDS website 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 the development of a global GTG, using the GFS, UKMet Office and ECMWF global NWP models.

FY2017 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. Testing and evaluation of the global GTG will continue, with an expected delivery to the World Aviation Forecast System (WAFS) in 2018. 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.

Figure 3. Example (16 UTC 15 Nov 2011) of turbulence associated with banded structures in a N. Atlantic storm.

FY2016 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 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 was investigated (see Fig. 3), and the results published in the *Monthly Weather Review*. Such 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.

FY2017 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.

‹ Prediction of Storm Hazards for Aviation   up   Integration of Weather Information into Air Traffic Management ›

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2016 RAL ANNUAL REPORT

2016 NCAR ANNUAL REPORT

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 the annual report.

WEATHER INTEGRATION ACTIVITIES WITH NOAA

Under an Aviation Weather Cooperative Agreement (AWCA) with NOAA, RAL has transitioned weather prediction capabilities from research to operations across federal agency lines for NextGen interim capabilities with the National Weather Service (NWS) and assisted with various other activities. The key research and development areas supported by the AWCA included ceiling and visibility, inflight icing, turbulence, and summer and winter storms. The focus was on enhancing meteorological analysis and prediction capabilities for aviation weather hazards, and how human would interact with decision support tools. The period of performance for the NOAA AWCA has ended, and at this time no continued funding is available.

WEATHER INTEGRATION ACTIVITIES WITH NASA

Currently RAL is supporting the NASA UTM—Unmanned Aerial System (UAS) Traffic Management system—development by researching how weather, and in particular turbulence, affects UAS performance. Details of the RAL research and development efforts are discussed in the weather impacts on UAS section of the annual report.

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 the UTM Weather Workshop (co-hosted with NASA), Oceanic Weather in the Cockpit Planning Workshop (with FAA), Lightning Impacts on Air Traffic Workshop (with FAA and Greater Orlando Airport Authority), a Congressional Briefing on Aviation Weather, and the NCAR Explorer Series Lecture on Aviation Weather. 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, and professional organizations such as AMS and AIAA.

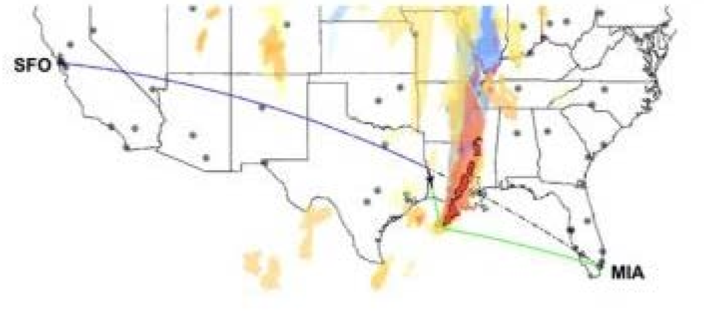

Figure 1. Trajectory flown under an adaptive nudging approach (purple and green path, aircraft position shown by arrow) to avoid weather hazards compared to the shortest distance (dash-dotted line)

HALABY FELLOWSHIP

between the San Francisco (SFO) and Miami (MIA) airports. Convective storms are shown in yellow, turbulence in red, and icing in blue colors.

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 a 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, conducting research broadly aimed at improving the integration of weather into decision support tools for improved weather avoidance and air traffic management.

Manuela Sauer, the first Halaby Fellow, focused her research on exploring the potential benefits of considering multiple weather hazards for optimally routing flights. She examined tradeoffs for various scenarios of making a route decision before takeoff versus nudging a flight en route as weather hazards are encountered (Figure 1). Upon completion of her fellowship, she was awarded a Post-doctoral Fellow appointment through NCAR's Advanced Study Program and is continuing her research into weather—air traffic integration.

‹ Turbulence | up | Dissemination of Aviation Weather Information ›

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2016 NCAR ANNUAL REPORT

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 21st 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 focused in two 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; and
2. 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 Weather (CSS-Wx) 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 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.

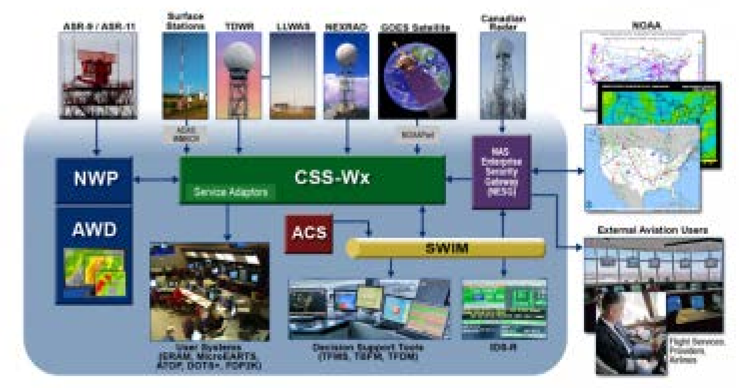


Figure 1. Diagram of FAA NextGen Weather Architecture with CSS-Wx in a central role

FY2016 Accomplishments

In FY2016, the FAA CSS-Wx program has been proceeding with acquisition of the system through a contract to a commercial vendor for implementation and operational deployment of the CSS-Wx system in the FAA National Airspace System. Based on years of experience during the development of CSS-Wx program concepts and proof of concept prototypes, NCAR/RAL acts as a subject matter expert to the FAA advising the agency about technical issues related to the contractor's development of the system.

In addition, RAL acted as the FAA's technical expert and worked with experts from the Open Geospatial Consortium, the International Civil Aviation Organization (ICAO) and the World Meteorological Organization (WMO) to establish new data service standards and weather data format standards.

FY2017 Plans

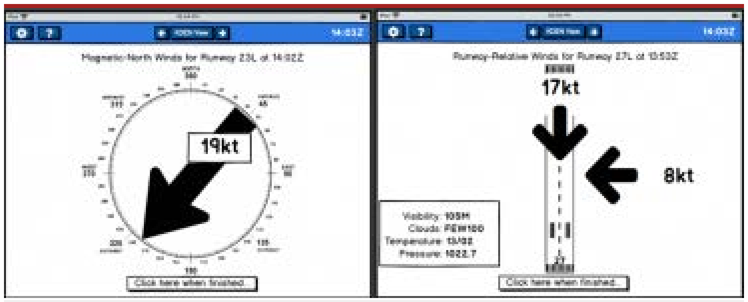
The focus for FY2017 is to continue supporting the FAA's acquisition process for CSS-Wx, including providing technical guidance to the FAA and the CSS-Wx commercial vendor. RAL will also continue its work on data service standards and weather data format standards in concert with the OGC, the ICAO and the WMO.

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.

FY2016 ACCOMPLISHMENTS

Based on input from the National Transportation Safety Board, NCAR/RAL is collaborating with the FAA to evaluate what techniques could be used in mobile met displays to address scenarios that commonly result in accidents for general aviation aircraft. Since many GA accidents are attributed to winds at the airport during landing and takeoff, NCAR and the FAA are evaluating the effectiveness of different methods to depict airport winds.



Figures 2 and 3. Examples of north relative and runway relative wind depictions

FY2017 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 complete the evaluation of runway wind depictions and incorporate the results into the recommendations.

‹ Integration of Weather Information into Air Traffic Management | up | Oceanic Weather ›

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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 probabilistic 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.

FY2016 Accomplishments

This past year efforts were focused on refining the methodology of fusing data from multiple global numerical prediction centers and bias-correcting the probabilistic guidance product. Significant progress was made on adding an adaptive-scale, dynamic bias correction process to allow automated adjustments for model errors. In addition, the cloud top height guidance product has been expanded to multiple flight levels. 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.

Efforts continue to refine "truth fields" based on satellite and global lightning data to enable assessment and calibration of the probabilistic convective storm hazard guidance products. The two truth fields are called the Cloud Top Height (CTH) and the Convective Diagnosis Oceanic (CDO) products and are discussed more fully in the following section. An effort is underway to analyze flight position data from the Aircraft Situation Display to Industry (ASDI) to better quantify thresholds that define convective hazards (Figure 1). The truth field development is largely based on efforts previously funded by FAA and NASA efforts for the detection and nowcasting of oceanic convection and can be viewed at http://www.rap.ucar.edu/projects/ocn/realtime_sys.

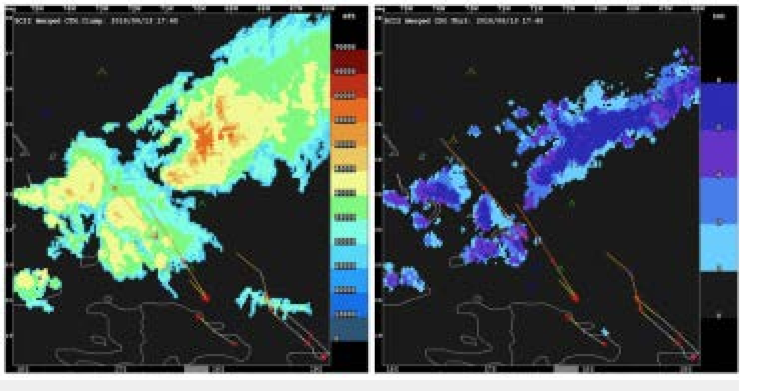

Figure 1. Display of Cloud Top Height (CTH; left) and Convective Diagnosis Oceanic (CDO; right) products. Both products are overlaid with ASDI flight tracks shown with the orange/yellow lines and a red arrowhead that indicates flight direction. Aircraft current position is shown with the red box with 15 min flight legs before and ahead of the aircraft. Turbulence pilot reports are also indicated (Λ). The region shown is north of Haiti and the Dominican Republic.

This effort is in close collaboration with the NWS Aviation Weather Center (AWC) which currently receives products from RAL's prototype system and provides feedback based on evaluations it conducts for its Aviation Weather Testbed.

FY2017 Plans

During the coming year, the prototype capability will be further enhanced based on performance assessment and feedback received from AWC forecasters. In addition, the cloud top product will undergo further fine-tuning and calibration. The truth field will also be improved, as the performance assessment hinges on that. Collaboration with AWC will continue and efforts will be expanded to examine the UK Met Office ensemble as another contributor to the probabilistic guidance product.

GLOBAL WEATHER HAZARDS

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, the CTH and the CDO, are providing realtime, operational strategic guidance to Lufthansa Airlines pilots. The products are uplinked into the flight deck and subsequently displayed on an Electronic Flight Bag (EFB) developed by Lufthansa Systems/Lido and named the eRouteManual (eRM). An application, called WxClient, displays the CTH and CDO products on the eRM. A global domain is covered between the latitude limits of 50°S to 70°N.

In late 2014, NCAR, Lufthansa Airlines and Basic Commerce & Industries, Inc. (BCI) completed a feasibility study in which the CTH product was uplinked to a tablet on selected aircraft over a limited domain. Lufthansa Airlines pilots found that the CTH product assisted in identifying and strategically avoiding convective storms that were beyond the range of the aircraft's onboard radar. Because of the success of this study, a second, 2-yr commercial effort was begun in early 2015 to expand the CTH coverage to a global domain, to add the CDO product to better depict the location of hazard regions and to display both products on the eRM's of B747-8 enroute aircraft of Lufthansa Airlines. For this effort, a fourth partner was added, the Weather Solutions Division of the Sutron Corporation, which provides the meteorological data sets and houses the operational servers that create the two products. To minimize communication costs, the original gridded data sets from each product are re-defined as polygons (Figure 2) at various contour levels and served to the aircraft via an Open Geospatial Consortium (OGC) interface, called the Web Feature Service (WFS). The convective hazard polygons are displayed over the navigational charts on the eRM and provide situational awareness of convective hazards over the planned flight route to the pilot.

Figure 2. Lufthansa Airlines EFB display of the CDO and CTH polygons. Color shapes represent the CDO interest values as follows: green is ≥2 and yellow is ≥3. The grey shapes are CTH contours beginning at ≥30 kft with darker shapes indicating higher contours at increments of 5 kft to a maximum of ≥50kft. The area shown includes Inter-Tropical Convergence Zone (ITCZ) over the northern part of South America. Storm motion vectors are shown with red arrows.

FY2016 Accomplishments

The CTH/CDO system was successfully run during the fiscal year, providing convective hazard guidance to Lufthansa Airlines pilots. The products are commercially available through BCI.

FY2017 Plans

The contract with BCI will end in FY2017, but a follow on contract is expected.

WEATHER TECHNOLOGY IN THE COCKPIT FOR OCEANIC REGIONS

The FAA Weather Technology in the Cockpit (WTIC) Remote Oceanic Meteorology Information Operational (ROMIO) Program is working to analyze oceanic aviation inefficiencies in current or future NextGen operations caused by gaps in either the available meteorological information or in the technology utilized in the cockpit. This effort has the purpose of implementing an operational demonstration to uplink convective weather products into the cockpit of domestic airlines for the purpose of analyzing operational gaps.

During FY2015, a previous WTIC-funded effort wrote the ROMIO Operational Plan that considered all aspects of the demonstration from the availability and ingest of meteorological data sets, to the creation of weather products and to their dissemination to the aircraft via the NextGen WFS. Other considerations included the training of the flight crews on the capabilities and limitations of the CTH product, understanding how pilot decision making might be facilitated with the CTH product and soliciting flight crew feedback on the product and on the EFB display. Selected airlines were surveyed to determine their interest and ability to participate in a demonstration. An example of the CTH product as displayed on a cockpit simulator EFB is shown in Figure 3.

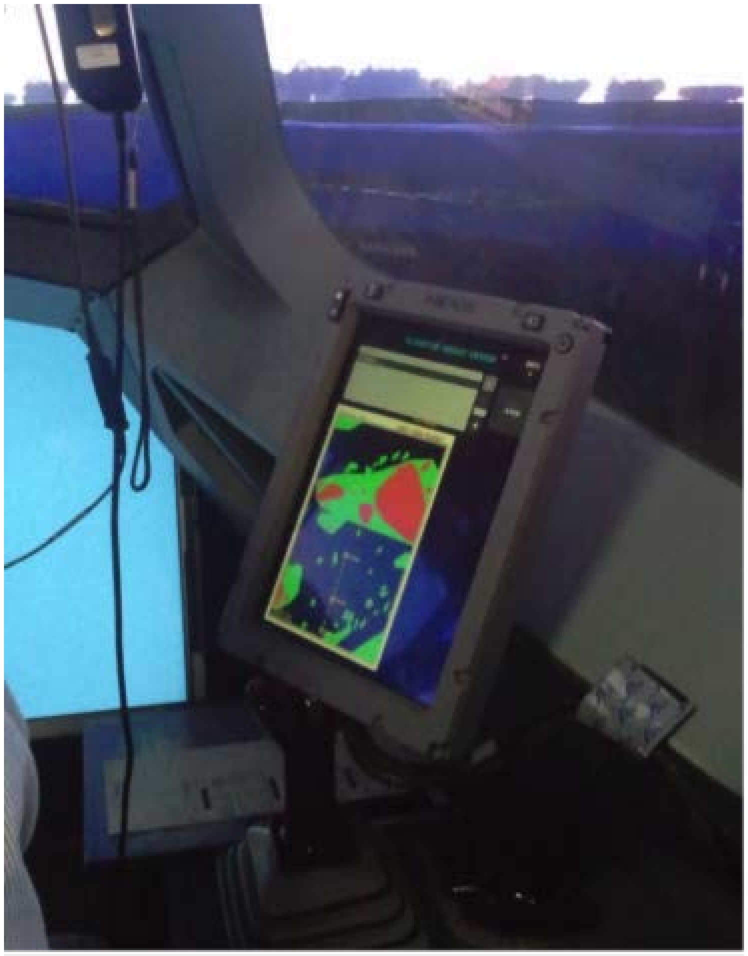

Figure 3. The EFB display of the CTH product during an earlier WTIC simulation demonstration.

In late FY2016, the WTIC ROMIO effort began the execution of the Operational Plan. The ROMIO Program is planned for three phases. Phase 1 will implement the Plan from product creation to uplink onto an EFB. This includes all efforts discussed above, from pilot training to communication links to the design of the EFB display to collection of pilot feedback. Phase 2 will commence the operational demonstration that will last for one year. Phase 3 will include a validation effort to examine pilot feedback to determine how the products filled existing gaps in meteorological information or in the technology utilized in the cockpit.

See Dissemination of Aviation Weather Information for more information on the FAA WTIC program.

FY2016 Accomplishments

The WTIC ROMIO Program began Phase 1 in September 2016.

FY2017 Plans

Implementation of Phase 1 of the Operational Plan will be accomplished during FY2017. A kickoff meeting with representatives of the FAA, NCAR, BCI, AvMet, United Airlines, Delta Air Lines, American Airlines and Lufthansa Airlines will be held 12-13 October 2016 in Boulder. Other activities that will be accomplished this year include coordination with the airline international operations and weather dispatch offices, coordination with the Oceanic Air Route Traffic Control Centers (ARTCC) at Houston, Miami and Oakland, an FAA Safety Review Board (SRB) must approve the ROMIO demonstration plan, approval from the Institutional Review Board must be obtained, the plan for operation of the satellite processing system that creates the CTH and CDO products will be revised and the Operational Plan will be revised as needed. BCI is funded to create the uplink display for pilot use. A separate engineering effort will design, implement and test the communication links from product creation to uplink to the aircraft to ensure readiness for the demonstration.

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WEATHER IMPACTS ON UNMANNED AERIAL SYSTEMS

BACKGROUND

Unmanned aerial vehicles (UAVs) are rapidly becoming an important component of the national airspace, especially at low altitudes (less than about 1,500 ft or 450 m AGL). To cope with the increased UAV traffic demands, NASA is developing the *Unmanned Aerial Vehicle Traffic Management System* (UTM), which includes separation management, scheduling, demand capacity imbalance, contingency management, trajectory definition and prediction, and importantly, wind and weather. Since many UAVs are very small in size they are quite susceptible to turbulence-induced loss-of-control and trajectory

excursions. Thus, an important weather factor to consider in the management system is atmospheric turbulence. 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 three foci: (1) establish automated means for forecasting turbulence levels in the atmosphere that affect UAVs, (2) develop and test translation algorithms to provide a turbulence hazard metric given the state of atmospheric turbulence, and (3) support a workshop on the effects of weather on UAVs to be held at NASA Ames 19-21 July 2016.

ACCOMPLISHMENTS IN FY2016

Task 1

Task 1 involves modifying NCAR's Graphical Turbulence Guidance (GTG) (Sharman et al. 2006) which has been operationally available on NOAA's Aviation Digital Data Service and is hosted by the National Weather Service's Aviation Weather Center and displays on the Aviation Digital Data Service (ADDS, http://www.aviationweather.gov/adds/) since 2003. Uniquely, the GTG products provide forecasts and nowcasts of atmospheric turbulence intensity levels in terms of a well-known turbulence metric known as the energy (or eddy) dissipation rate (EDR). EDR is the International Civil Aviation Organization (ICAO) mandated metric for atmospheric turbulence, but computing EDR for operational use requires input from numerical weather prediction (NWP) models, which are too coarse to properly resolve atmospheric eddies that affect UAVs. So the major emphasis this first year has been on developing techniques to properly quantify EDR at low levels from coarse NWP model output. This is done by carefully comparing EDR candidate algorithms to (a) EDR calculated from very high resolution large-eddy simulation (LES) models, and (b) EDR data from field programs.

The year 1 Task 1 primary goal is to establish algorithms for the robust computation of EDR derived from relatively coarse-resolution models over areas of interest. The first area of interest has been designated as the Reno-stead Airport in Reno, NV. The Reno-stead site is one of six sites chosen by the Federal Aviation Administration to be an approved test site for developing UAV technology. It is in relatively flat terrain but is just east of the Sierra Nevada mountains. To support an upcoming field program there in the summer of 2016, uncalibrated EDR will be furnished in real-time along with other weather information (winds, temperature, pressure, humidity, ceiling and visibility) based on the operational High-Resolution Rapid Refresh (HRRR) NWP model (http://ruc.noaa.gov/hrrr/). The production HRRR grids (1800x1060x50 grid points) will be pulled in real-time, then cut down to a 30kmx30kmx3km domain centered on Reno-Stead, and the data subsets will then be provided to NASA to support UAV testing. Sample data sets have already been provided to NASA Ames for testing, and once the variables and format has been agreed upon, the data will be provided in real-time. Beside that though, efforts have been underway to calibrate the EDR output to ensure it properly represents the actual turbulence levels in the atmosphere. This is being done in two phases.

First, GTG turbulence diagnostics for EDR estimation need to be evaluated in the context of atmospheric boundary layer (ABL) turbulence. This is a critical task given the different nature of the quasi-two-dimensional turbulence that exists in the upper troposphere and lower stratosphere, and for which the GTG algorithms have been developed and calibrated, and the three-dimensional turbulence present in the ABL. Second, candidate EDR algorithms must be compared to EDR measurements from a suite of sonic anemometers on a 300-m tower as part of a recent field campaign near Boulder, CO. This provides a good reference data set to compare to model data. Both of these data sets (the anemometer-derived EDR and the LES-derived EDR), can be used to ensure the coarse- resolution models can properly forecast EDR at the low levels of interest to UAVs.

Task 2

Task 2 takes the output EDR from Task 1 and maps this atmospheric metric into an aircraft (i.e., UAV-specific response). The first year's

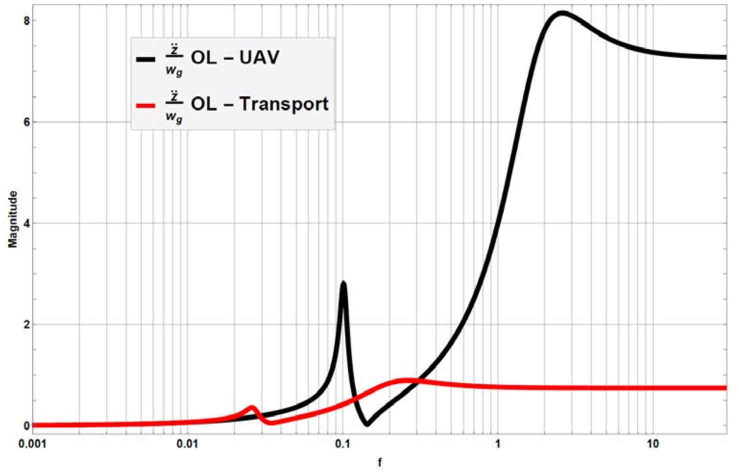

Figure 1. Open loop acceleration output from vertical wind input frequency response functions for small UAV (black) and mid-sized transport aircraft (red).

activities have focused on the development and implementation of a UAS simulation capability. This work is further divided into two sub-areas: wind field simulation and fixed-wing, controls- fixed UAS simulation. For mid- to large-transport aircraft, the predominate response to turbulence is in the body-axis vertical direction, and is due primarily to the vertical component of the wind. Hence, the wind field and aircraft simulations simplify to the single wind component and a two-degree of freedom (pitch and vertical displacement) aircraft model, respectively. Furthermore, as we analyze the aircraft along a straight and level flight path (say, the x-direction), we only require the single wind component along a single direction, i.e., w(x). For the UAS application, more degrees of freedom – including lateral motions – will be important. This also means that the wind field simulation will need to accommodate more components and more locations. For example, with rolling motions, the pertinent wind component is still the vertical one, but it is the lateral distribution of these winds across the wings that are important. Hence, we will need w(x,y). With yawing motions, the lateral wind distribution along the flight path is important, so v(x) is required. In the first year, the focus has been on the controls-fixed longitudinal aircraft dynamics and the vertical acceleration response to turbulence, but preparations were made for the analysis of controls-free (i.e., autopilots) and lateral dynamics. For the longitudinal dynamics, a full three degree of freedom aircraft model was implemented, including the longitudinal and vertical translational velocities, the angular velocity around the aircraft y-axis (i.e., “pitching” velocity), and elevator control. Closed loop (i.e., with autopilot) attitude hold and altitude hold (with inner attitude hold) frequency response models were also developed for the small UAS. These closed loop models take as input a vertical or horizontal wind, which in turn drives the elevator to produce the desired response (i.e., stable attitude or altitude condition). Figure 1 illustrates the open loop (i.e., without autopilot) vertical acceleration response of a small UAS and a mid-sized transport aircraft to vertical wind input. As expected, the UAS is much more sensitive to vertical gusts – especially for small spatial scales (frequency axis is related to spatial scales via , where V is the vehicle’s airspeed). Figure 2 shows the impact of the autopilot (red curve) versus no-autopilot (black curve) for the small UAS. It can be seen that the autopilot tends to damp the low frequencies, but amplifies the higher ones.

Task 3

Task 3 provided support for the Weather and Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Workshop from July 19–21, 2016, at NASA's Ames Research Center, Moffett Field, California. NASA Ames and NCAR organized and co-sponsored a two-and-a-half-day workshop bringing aviation weather, Unmanned Aerial Systems (UAS) traffic management (UTM) researchers, and UAS operators together to discuss weather impacts and requirements to enable safe and efficient low-altitude UTM. The workshop included two days of presentations covering the UTM system, the current aviation weather system, weather phenomena and their impact on UAS operations, and weather integration into UAS operations. The final half-day comprised two panel sessions; one panel discussed user experiences with weather in the field and the second discussed weather research needs for UAS operations. About 80 people attended the workshop representing industry, academia,

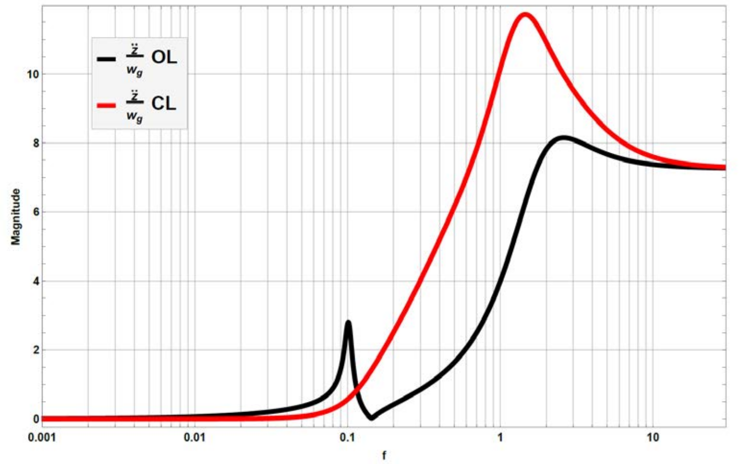

Figure 2. Comparison of open loop (black) versus closed loop (red) acceleration output from vertical wind input frequency response functions for small UAV.

government, and research organizations. The organizers will be using this workshop to engage a crosscutting group of users and weather researchers to inform weather product development and research to enable all-weather access for small UAS (sUAS) operations.

PLANS FOR FY2017

RAL will continue to work with NASA to provide low-level forecasts as required for their UTM system, as well as continue to develop UAS turbulence/winds hazard metrics for other fixed-wing UAS. Specific work areas for the three Task areas are listed below.

Task 1:

- Perform longer term WRF mesoscale simulations and tower measurements analysis (1 month) in order to have a statistically robust database to correctly evaluate the EDR forecast methodology.
- Implementation of the Kolmogorov method in the GTG algorithm.
- Evaluate the performance of the HRRR product using the GTG algorithm to forecast EDRs within the ABL.
- Propose and test possible improvements to the implemented method to forecast EDRs.
- Carry out WRF multiscale simulations for some selected cases as a higher-fidelity approach to improve the proposed methodology and our understanding of three-dimensional effects caused by local turbulence, and ultimately its implications for UAVs and UTM.

Task 2:

- Include lateral modes in the aircraft simulation.
- Implement an autopilot for the three degree of freedom models: for both longitudinal and lateral dynamics.
- Perform analysis with simulated wind fields.
- Investigate other response metrics besides vertical acceleration. For example, lateral acceleration, “attitude” metrics (e.g., pitch or roll rate), or aircraft kinetic energy state.
- Investigate rotary wing UAS (if time/resources allow).

Task 3:

- One of the key results of the NASA/NCAR Workshop was the agreement that a UAS Weather Users’ Group is needed to help focus and direct research and development efforts regarding weather integration into UAS operations and UTM. To start this process, a smaller, more focused group is being assembled, the UTM Weather Integration Steering Group. It is intended that this group, comprised of representatives from government, researchers, and industry, will provide guidance to UTM researchers, developers, operators, and decision makers. This group will have a broad-based membership, reflecting the disparate aspects of UAS operations, and will be tasked with developing a plan that delineates the initial requirements, scope, and an implementation roadmap for weather-integrated UTM. This initial group will work closely with the larger, and more wide-ranging UAS Weather Users Group.

‹ Oceanic Weather up International Aviation ›

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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).

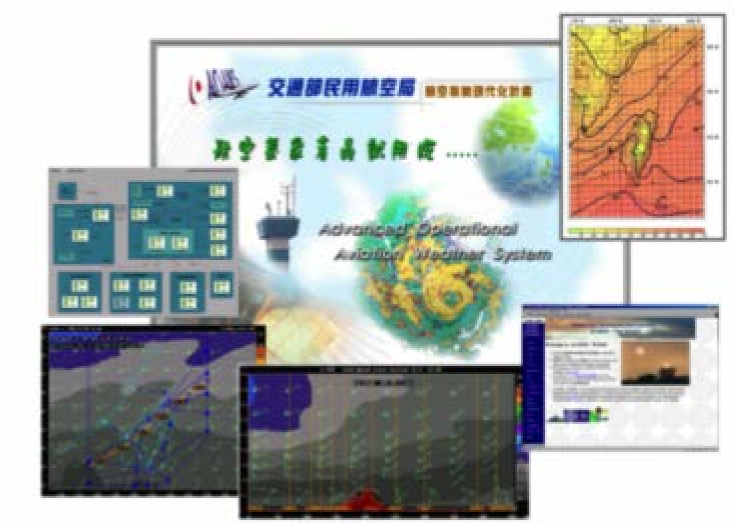

Figure 1 Composite image showing several AOAWS end-user display components

FY2016 ACCOMPLISHMENTS

The AOAWS project has suspended further development to give the system users time to gain experience with the existing products and assess their future needs. Accordingly NCAR/RAL focused on support of AOAWS continued operations and maintenance. RAL's role in this process has been to deliver third tier support addressing issues and making changes that are best addressed by the original system developers. One significant change to the system this year was the transition from the Japanese Meteorological Agency (JMA) MTSAT-2 satellite data to the JMA Himawari-8 satellite data. RAL made changes to various parts of the system software to accommodate this transition and delivered a new release the incorporated these changes.

In addition to the AOAWS program, NCAR /RAL contributed to a number of small but safety critical aviation weather projects. These projects primarily focused on windshear detection and were located in Africa and southeast Asia.

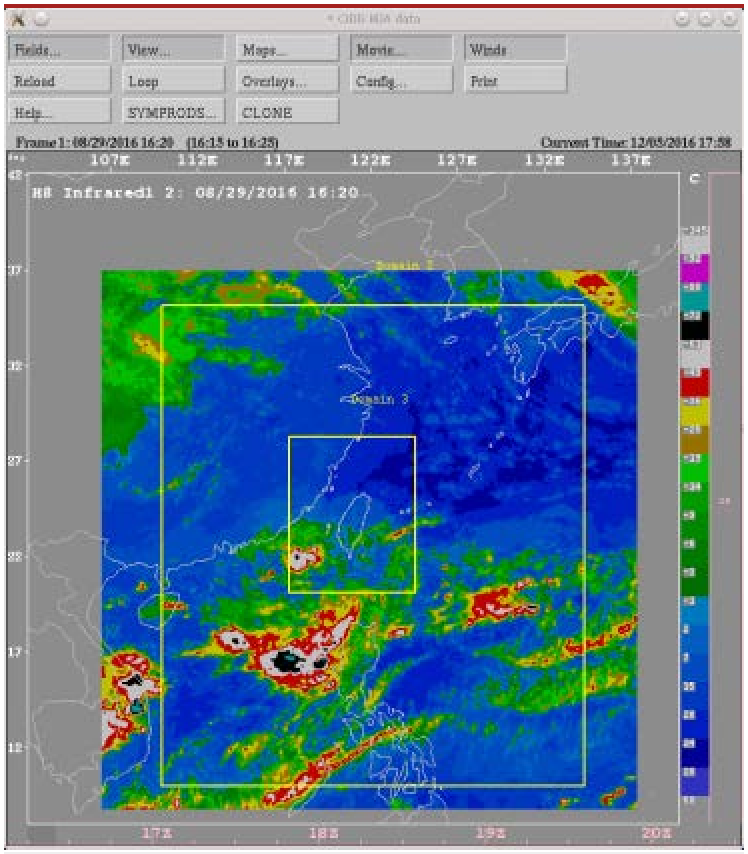

Figure 2 Image showing display of the HIMAWARI-8 satellite data

FY2017 PLANS

In FY2017, NCAR/RAL will continue to focus on providing third tier support for the AOAWS system. Also in FY2017, RAL will collaborate with the CAA of Taiwan to develop plans for a new program aviation weather technology advancements in Taiwan. The new program is envisioned to be a combination of scientific and technical updates to existing capabilities as well as new capabilities that reflect the state of the art in atmospheric science and engineering.

In FY2017, NCAR/RAL will also continue to develop program opportunities with new and existing international sponsors to deliver capabilities ranging from small wind shear detection systems to larger scale location specific aviation weather systems.

‹ Weather Impacts on Unmanned Aerial Systems up Ceiling and Visibility Products for Alaska ›

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2016 RAL ANNUAL REPORT

2016 NCAR ANNUAL REPORT

CEILING AND VISIBILITY PRODUCTS FOR ALASKA

BACKGROUND

Poor weather conditions, particularly restricted visibility and low cloud tops, were the leading cause of fatal general aviation (GA) accidents in Alaska from 2001-2012. Traditional weather observations from Alaska's widely dispersed airfields inadequately forewarn of weather likely to be encountered along routes between stations or, in particular, through

hazardous mountain passes with localized conditions. In 2014, the National Transportation Safety Board (NTSB) included “GENERAL AVIATION: IDENTIFY and COMMUNICATE HAZARDOUS WEATHER” on its Most Wanted List to improve transportation safety.

In January 2016, scientists and engineers at the National Center for Atmospheric Research’s Research Applications Laboratory NCAR/)RAL received funding from the Federal Aviation Administration’s Aviation Weather Research Program (FAA/AWRP) to provide enhanced ceiling, visibility, and flight category products to the Alaska Aviation Weather Unit (AAWU). This effort, which includes collaborations with MIT Lincoln Laboratory and NOAA’s Global Systems Division (NOAA/GSD), is aimed at producing rapidly-updated, high resolution, gridded products of ceiling heights and visibility (C&V) conditions across Alaska. The Ceiling and Visibility Analysis – Alaska (CVA-AK) products serve as a “first guess” estimates of C&V conditions across Alaska at or near instrumented and non-instrumented airfields and along data-sparse routes between airfields including treacherous and heavily-traveled mountain passes.

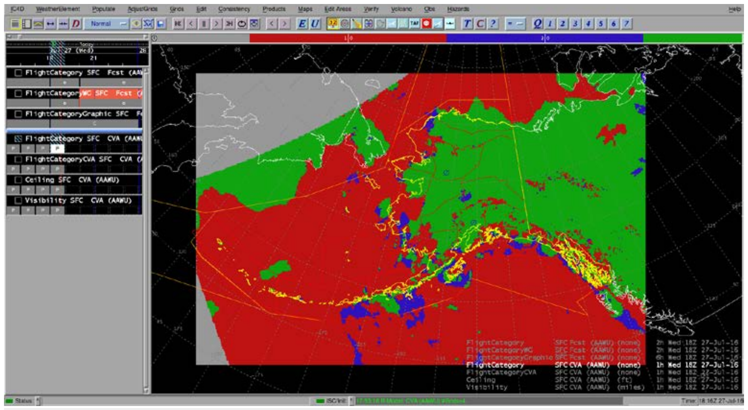

Figure 1. NCAR/RAL CVA-AK Flight Category product displayed on the AAWU forecasters IC4D system. Red, blue, and green regions represent the following flight categories for pilots: Instrument Flight Rules (IFR), Marginal Visual Flight Rules (MVFR), and Visual Flight Rules (VFR), respectively.

The CVA-AK product combines ceiling and visibility information from the latest EMC RAP model with METAR observations of C&V using data fusion techniques to produce Flight Category, Ceiling Heights and Visibility gridded fields. These fields are updated every 20 min and hourly analysis products are viewable by AAWU forecasters on the IC4D display system that they use to produce their aviation forecasts. Future versions of the CVA-AK product will include geostationary and polar orbiter satellite observations and visibility estimates retrieved from the FAA web camera imagery collected in Alaska and output from the Alaska HRRR model, when it becomes operationally available.

2016 ACCOMPLISHMENTS

Real-time CVA-AK products

An initial version of the CVA-AK was installed at the AAWU in May 2016. The 2 h forecast of ceiling and visibility from the 11 km RAP model forms the base layer. METAR ceiling and visibility surface observations are ingested and compared to the RAP values at those sites (grid points), showing agreement or disagreement with the model. A sequential set of decisions are made in blending METARS with RAP fields that take into account, for example, the distance of the METAR site from a model grid point and the terrain difference between a METAR site and model grid point. The CVA-AK products are interpolated to a 6 km AK National

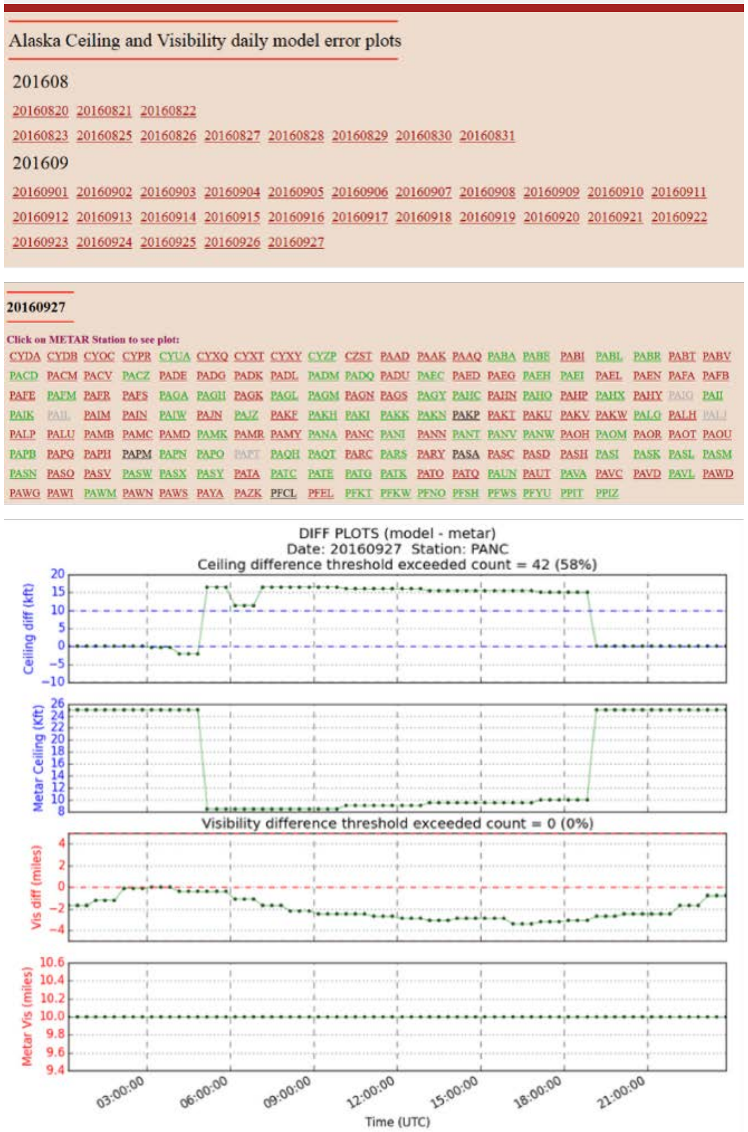

Figure 2. **Top panel**: Daily selection menu; **Middle panel**: Station selection menu; **Bottom panel:** C&V difference plots and

corresponding METAR observations.

Digital Forecast Database (NDFD) grid. Ceiling, visibility and flight category products are updated every 20 min with most recent METAR reports, but only the output on the hour are currently displayed on the AAWU forecasters' IC4D display system (see Fig.1).

RAP model ceiling and visibility estimates are compared to METAR measurements collected every 20 min at Alaska METAR sites. Daily and weekly error plots (offsets between RAP and METAR values) of ceiling and visibility estimates are being generated automatically for AAWU forecasters to view online. The offset values are calculated as Model minus METARS. Negative values show where the model is under estimating the ceiling and/or visibility. Daily plots and weekly plots are produced daily and can be accessed at the following links. Weekly plots contain that day and the 6 days prior to it.

https://www.ral.ucar.edu/projects/nowcast/cv/alaska/daily
https://www.ral.ucar.edu/projects/nowcast/cv/alaska/weekly

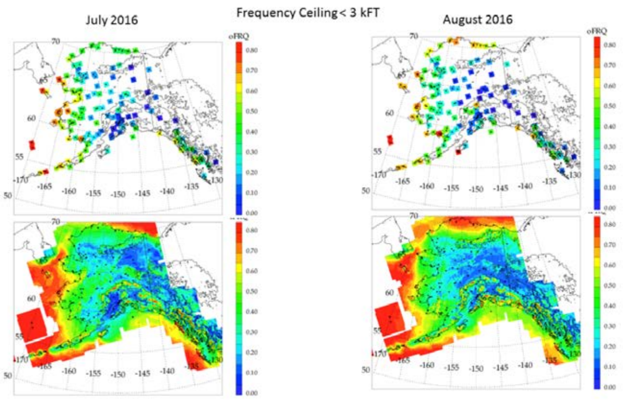

Figure 3. A comparison of the frequency of occurrence of ceiling heights of 3000 ft or less across the state of Alaska for July and August 2016.

Clicking on the link for the daily plots will pop up the menu, shown in the top panel in Fig. 2. Selecting day 20160927 pops up the middle panel for selection of a specific METAR station. Plotted in the bottom panel are differences (offsets) between Model and METAR values at a particular METAR location.

Forecasters are using the CVA-AK product daily in producing their C&V and Flight category forecast products for the Alaska aviation community. An online survey has been setup for the forecaster to provide their subjective feedback on CVA-AK product performance.

METAR-RAP Comparative Analysis

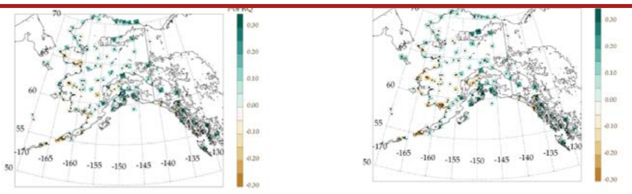

Figure 4. Frequency difference (modeled minus observed frequency) plots.

Because of the sparseness of surface observing stations in Alaska that measure C&V, very-short range forecasts from the RAP model must be used to fill in between reporting stations when generating the C&V analysis product. Understanding the level of consistency between surface-based observations and RAP forecasts of C&V is critical for developing a useful analyses product. One aspect of the C&V forecasts we have been studying is their ability to represent observed long-term trends. Figure 3 below provides a comparison of the frequency of occurrence of ceiling heights of 3000 ft or less across the state of Alaska for July and August 2016. The surface observations are shown as small (~30 km) tiles in the top panels and the RAP 2hour forecast data values are shown in the middle panels as much larger tiles. A number of distinct regimes are evident in both observations and the RAP model data including (1) greater frequency of low ceilings along coastal regions, (2) minima in low ceiling frequency in the Anchorage area and (3) increased frequency of low ceilings across the North Slope in August. The model provides much greater detail in terms of resolving coastal and terrain driven gradients in the frequency of low ceilings, but notable biases in the model predictions are also evident. These differences become more clear when looking at frequency difference (modeled minus observed frequency) plots shown Fig. 4. In both months, the RAP model shows a consistent over forecasting bias in the center of Alaska and an under-forecasting bias in the southwest. Also interesting is the gradient seen across some of the coastal tiles (especially along the North Slope in July) where the variation in bias across the tile is due in part to the lack of representativeness of the observation extended over the coastal waters. These

comparisons can be used to remove first order bias in the model and to better understand the representativeness of the surface observation measurements and how this information should be spread in the gridded C&V analysis product.

PLANS FOR 2017

A statistical verification will be conducted assessing the performance of the CVA-AK products. Alaska is a large state with varied terrain, and many regions have no observations. Thus, evaluation for baseline product skill will be conducted using a cross-validation approach offline from the real-time system. Some METARS stations will be withheld from product creation and used to verify the product. Two sets of 25 stations be used in this process to evaluate the product performance, as shown in the two panels in Fig. 5.

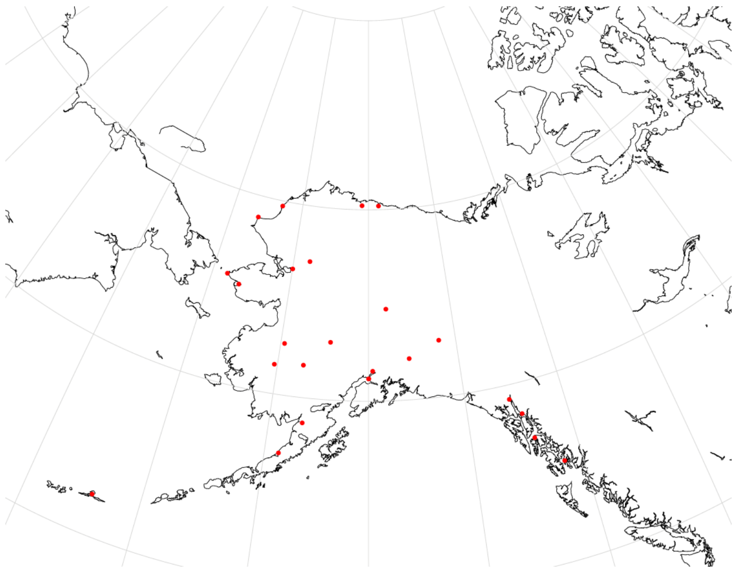

Figure 5. METAR stations that will be withheld from the CVA-AK product and used as truth data, during post-analysis, statistical evaluation of the product.

Forecasters are using the CVA-AK product daily in producing their C&V and Flight category forecast products for the Alaska aviation community. An online survey has been setup for the forecaster to provide their subjective feedback on CVA-AK product performance.

Based on results from the monthly and seasonal comparative analyses and the statistical verification of performance, as discussed above, an updated version of the CVA-AK products will be installed at the AAWU office in May 2017. Ingest and blending of satellite geostationary and polar orbiter imagery into the product will also begin.

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- Wildland Fire Modeling and Prediction

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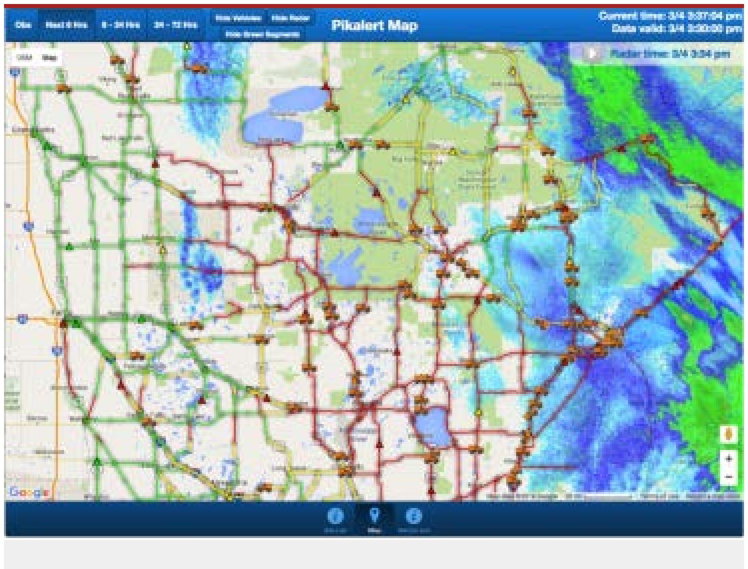
SURFACE TRANSPORTATION WEATHER

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.



FY2016 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

Figure 1. Pikalert® Display over Minnesota

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.

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 FY2016 RAL made several enhancements to the Pikalert® system. Dual-polarization radar data, which greatly increases the ability to detect precipitation type via radar, was added to the Road Weather Hazard (RWH) module. The system can now better distinguish between rain, snow, and ice events, which also improves the pavement condition assessments. The precipitation and visibility algorithms were also enhanced by adding surface station observations and adjusting logic based on case studies, and road state observations were added to enhance the pavement condition algorithm. Utility of the display was also enhanced in many ways, including temporal consistency of alerts, adding additional road segments, support for IE10, roadway camera imagery on select segments, and adding an on/off button for radar and green segments.

Travel Time Forecasting

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 used machine-learning to create a model to predict travel times on I-70 that depends not only on time of day and day of week, but also the forecast weather conditions.

Enhanced Products for Alaska

Building on the success of an RWIS-based EMDSS for the Alaska Department of Transportation (AKDOT) in Fairbanks, RAL updated its technology for Alaska by installing the Pikalert® System with EMDSS on 1-mile segments in Fairbanks and additional segments in the Kenai Peninsula, expanding EMDSS coverage. Vehicle-based sensors and the Alaska-specific High Resolution Rapid Refresh (HRRR-AK) model were also added and help the system address Alaska’s highly variable weather conditions.

The WYDOT CV Pilot

RAL participated in the first phase of the Wyoming Department of Transportation (WYDOT) Connected Vehicle (CV) Pilot,

which is a USDOT-funded initiative to move developed CV technologies out of the research arena and into operational deployment. During FY2016, RAL collaborated with the WYDOT CV Pilot team to complete Phase 1, which was the planning stage involving several deliverables such as a Concept of Operations, Application Deployment Plan, Performance Measures, and an Outreach Plan. RAL and the team will move into Phase 2 in FY2017-FY2018, which is the development phase.

FY2017 PLANS

Pikalert®

RAL will continue to work with state partners in Minnesota, Michigan, Colorado, Nevada, Alaska, and Wyoming to create enhanced functionality in the Pikalert® System. New functionality will include incorporating additional Connected Vehicle data, improving the road weather hazard algorithms based on differing geographic regions, and continuing to seek partners in new states.

Colorado Department of Transportation

RAL scientists will continue work with CDOT in the coming year. Activities will include deployment of the travel time prediction system and use of Pikalert® to automatically assign values to Variable Speed Limit zones, which utilize electronic speed limit signs that may be adjusted to lower speeds during adverse weather to improve safety.

Forecasting Blow-Over Events

RAL will participate in Phase 2 of the WYDOT CV Pilot to provide Pikalert coverage in Wyoming. This work will focus on the I-80 highway in Wyoming which has significant winds causing truck blow-over events. RAL will install the Pikalert® system over I-80 to investigate 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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2016 Annual Report

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STRATEGIC PLANS

RAL Strategic Plan
NCAR Strategic Plan

PREVIOUS RAL REPORTS

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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.

FY2016 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

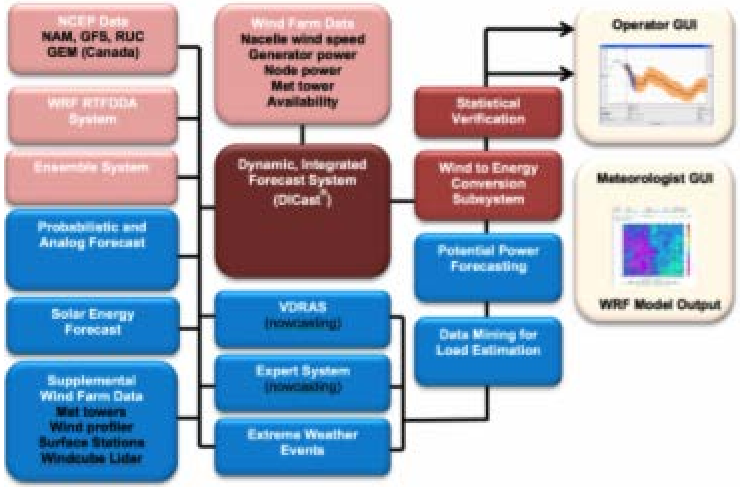

Figure 1. Schematic diagram of the comprehensive wind power forecasting system.

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). The most recent collaboration with Xcel Energy was completed during FY15, but during FY16, the team completed several publications on the results. The first provides an overview of the advances made during the course of the project (Kosovic et al. 2016). A second looks at the impact of assimilating wind speed observations from the wind farms into the Weather Research and Forecasting (WRF) model, finding that it can make a substantial improvement in the forecast (Cheng et al. 2016)

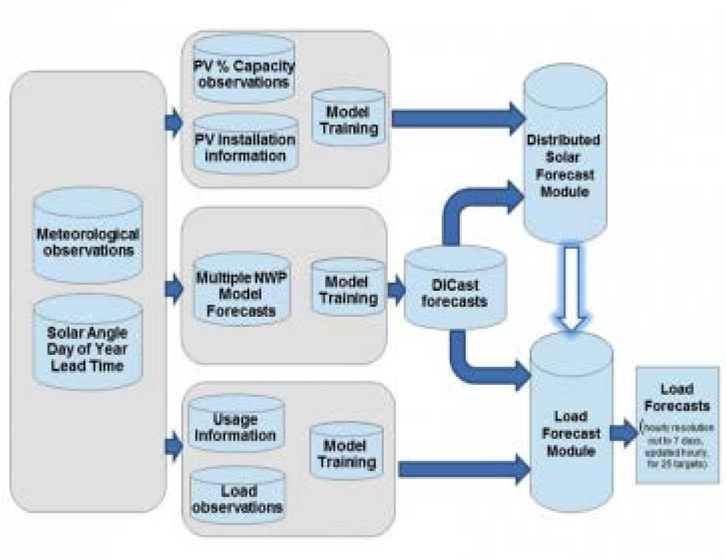

Figure 2. High-level architecture of the blended DPV/load forecast system.

The third paper recently submitted describes NCAR's work in building both distributed photovoltaic (DPV) solar and load forecasting systems and when it is necessary to combine the two (Haupt et al. 2016a). Figure 2 provides a view of the architecture of the load plus distributed solar forecasting system.

The DPV forecasting system takes a “top down” approach, due to the lack of detailed data regarding site specific solar power production because most of it is “behind the meter” and appears as a decrease in load. For the same reasons, it is difficult to completely independently assess the accuracy of the DPV forecasts because very few sites report power output from their solar panels. Figure 3 displays the normalized RMSE at six sites of the Boulder Valley School District (BVSD) where production data are available. These errors represent the median of six months (Jun - Nov 2014) of Intraday (0-15hrs) and Day Ahead (24-39hrs) forecasts initialized at 1100 UTC. Note that most nRMSE values are less than 3%. Also note that Day Ahead forecasts do not exhibit degraded accuracy.

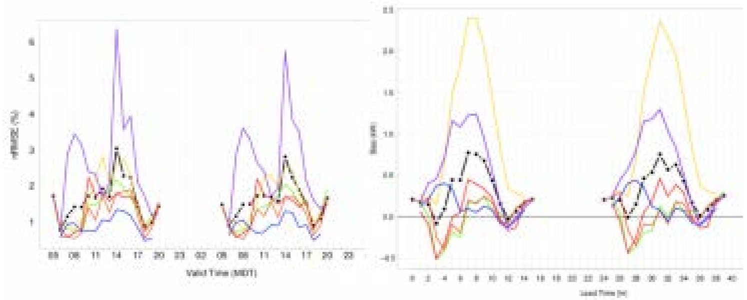

Figure 3. Normalized RMSE (left) and Bias (right) at six sites,

The load forecast is highly dependent on weather conditions, as seen in Figure 4, which plots electric load as a function of temperature, with each point colored by Julian day of the year. For temperatures colder than about 12°C, the load values increase in an approximately linear fashion. Similarly, as the temperatures rise above 12°C, they increase in a quadratic or perhaps exponential manner. As expected, Julian days associated with late fall, winter, and early spring are predominantly on the left side of the plot, while late spring, summer and early fall values

appear on the right side. One can also discern a more subtle pattern: light blue and blue-green points (denoting spring to early summer) tend to represent smaller loads than those experienced at other times of year for the same temperature. This may be in part a reflection of humans tolerating greater temperature variations during a seasonal transition, or may demonstrate the impact of other weather variables (e.g., longer-term temperature trends, cloudiness or precipitation). In any case, this plot illustrates both the importance of daily, weekly and seasonal usage patterns and temperature, while also suggesting the complexity of accurately predicting electrical loads. This connection of weather to load was critical for constructing the load forecasting system. The load forecast performance was evaluated by analyzing the real-time results over a two-month period after the latest version of the forecast was implemented. The real-time system's day-ahead performance, evaluated for the 20-43 hour lead-times for each 11 UTC forecast, shows errors within approximately 1.25% of maximum monthly load.

indicated by the broken line colors, from data averaged over a 6 month period.

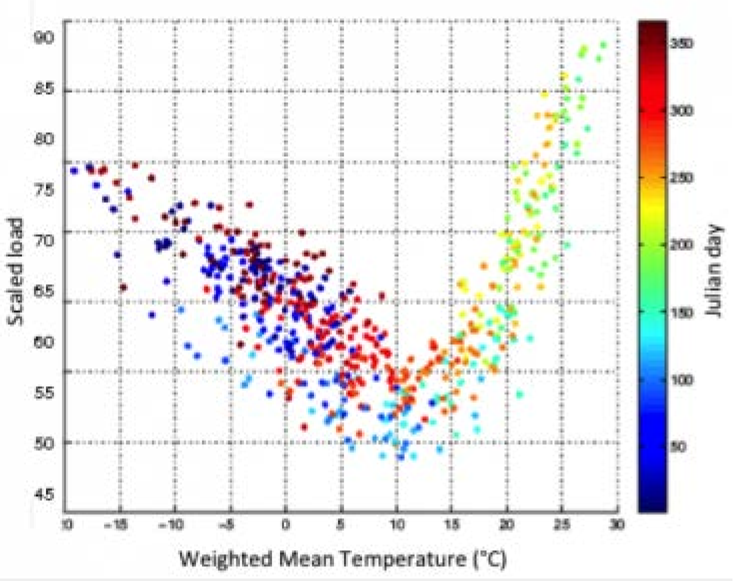

Figure 4. Scaled PSCo net loads at 2 UTC vs. the weighted average temperature from ten METAR sites, with the color scale representing the Julian day.

Finally, we assessed how much the solar forecast impacts the net load forecast. Does it impact the forecast currently and, as the capacity grows, will that growth necessitate direct inclusion of the DPV forecast as an input to the load forecast? We found that DPV is beginning to become discernable in the net load, but, the DPV capacity is growing rapidly in Colorado, seeing a factor of ten increase in five years. Many of the same variables used in the DPV forecast are already included in the load forecast, however. Unsurprisingly, an initial analysis suggested that the load forecast therefore implicitly includes information regarding the output of the DPV without explicitly including that forecast. It is only during the most rapid growth in DPV deployment that explicitly including the DPV forecast in the load forecast became necessary.

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, 2016). 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.

This project was successfully completed in FY16. The project focused on identifying elements of a value chain, beginning with the weather that causes a deviation from clear sky irradiance and progressing through

monitoring of observations, modeling, forecasting, dissemination and communication of the forecasts, interpretation of the forecasts, and through decision-making, which produces outcomes that have an economic value. The system was evaluated using metrics developed specifically for this project, which provided rich information on model and system performance.

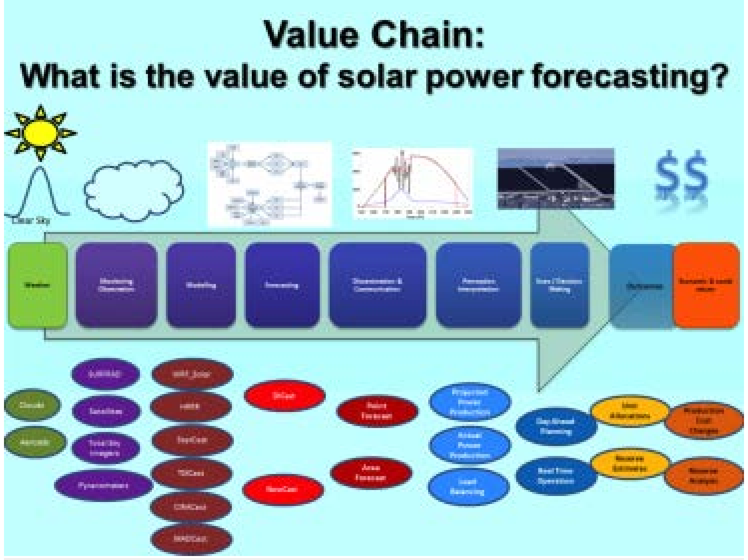

Fig. 5. Value chain of implementing a weather decision support system for solar power. At the bottom are the components of the NCAR team's system that build toward providing an economic impact of this system.

Research was conducted on the very short range (0-6 hours) Nowcasting system as well as on the longer term (6-72 hour) forecasting system, which were then blended, converted to power, analog ensemble applied to for the SunCast™ Solar Power Forecasting System. The shortest range forecasts are based on observations in the field. TSICast operates on the shortest time scale, with a latency of only a few minutes and forecasts that currently extend to approximately15 min. This project facilitated research in improving hardware and software so that the new high definition cameras deployed at multiple nearby locations allow discernment of the clouds at varying levels and advection according to the winds observed at those levels. Improvements over "smart persistence" are about 29% for even these very short forecasts. StatCast uses pyranometer data measured at the site as well as concurrent meteorological observations and forecasts. StatCast is based on regime-dependent artificial intelligence forecasting techniques and has been shown to improve on "smart persistence" forecasts by 15-50%. A second category of short-range forecasting systems employs satellite imagery and uses that information to discern clouds and their motion, allowing these systems to project the clouds, and the resulting blockage of irradiance in time. CIRACast was already one of the more advanced cloud motion systems, which is the reason that team was brought to this project. During the project timeframe, the CIRA team advanced cloud shadowing, parallax removal, and implementation of better advecting winds at different altitudes. CiraCast shows generally a 25-40% improvement over Smart Persistence between sunrise and approximately 1600 UTC. A second satellite-based system, MADCast, assimilates data from multiple satellite imagers and profilers to assimilate a three-dimensional picture of the cloud into the dynamic core of WRF. This allows advection of the clouds via the WRF dynamics directly. During 2015, MADCast provided at least 70% improvement over Smart Persistence, with most of that skill being derived during partly cloudy conditions. After WRF-Solar™ showed initial success, it was also deployed in nowcasting mode with coarser runs extending to 6 hours made hourly. It provided improvements on the order of 50-60% over Smart Persistence for forecasts extending to 1600 UTC. The advantages of WRF-Solar-Nowcasting and MADCast were then blended to develop the new MAD-WRF model that incorporates the most important features of each of those models, both assimilating satellite cloud fields and using WRF-Solar™ physics to develop and dissipate clouds. MAE improvements for MAD-WRF forecasts from 3-6 hours are improved over WRF-Solar-Now by 20%. While all the Nowcasting system components provide improvement over Smart Persistence individually, the largest benefit is derived when they are smartly blended together by the Nowcasting Integrator to produce an integrated forecast.

The development of WRF-Solar™ under this project has provided the first numerical weather prediction (NWP) model specifically designed to meet the needs of irradiance forecasting. The first augmentation improved the solar tracking algorithm to account for deviations associated with the eccentricity of the Earth's orbit and the obliquity of

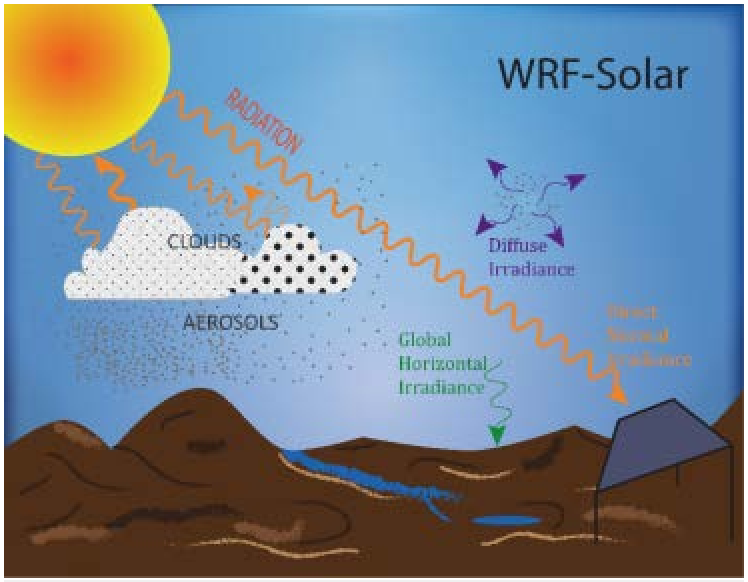

Figure 6. Sketch representing the physical processes that WRF-Solar™ improves. The different components of the radiation are indicated.

the Earth. Second, WRF-Solar™ added the direct normal irradiance (DNI) and diffuse (DIF) components from the radiation parameterization to the model output. Third, efficient parameterizations were implemented to either interpolate the irradiance in between calls to the expensive radiative transfer parameterization, or to use a fast radiative transfer code that avoids computing three-dimensional heating rates but provides the surface irradiance. Fourth, a new parameterization was developed to improve the representation of absorption and scattering of radiation by aerosols (aerosol direct effect). A fifth advance is that the aerosols now interact with the cloud microphysics, altering the cloud evolution and radiative properties, an effect that has been traditionally only implemented in atmospheric computationally costly chemistry models. A sixth development accounts for the feedbacks that sub-grid scale clouds produce in shortwave irradiance as implemented in a shallow cumulus parameterization Finally, WRF-Solar™ also allows assimilation of infrared irradiances from satellites to determine the three dimensional cloud field, allowing for an improved initialization of the cloud field that increases the performance of short-range forecasts. We found that WRF-Solar™ can improve clear sky irradiance prediction by 15-80% over a standard version of WRF, depending on location and cloud conditions. In a formal comparison to the NAM baseline, WRF-Solar™ showed improvements in the Day-Ahead forecast of 22-42%.

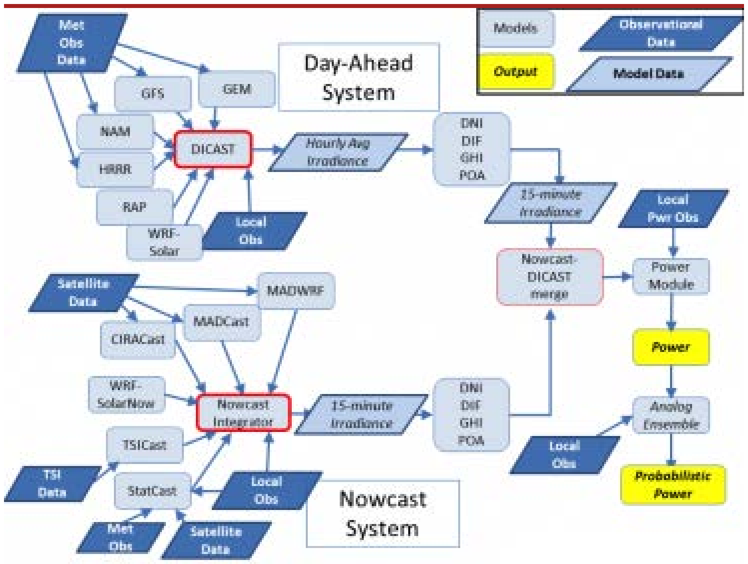

Figure 7. The engineered SunCast™ system.

The SunCast™ system requires substantial software engineering to blend all of the new model components as well as existing publicly available NWP model runs (Figure 7). To do this we use an expert system for the Nowcasting blender and the Dynamic Integrated foreCast (DICast®) system for the NWP models. These two systems are then blended, using an empirical power conversion method to convert the irradiance predictions to power, and then applying an analog ensemble (AnEn) approach to further tune the forecast as well as to estimate its uncertainty. The AnEn module decreased Root Mean Square Error (RMSE) by 17% over the blended SunCast™ power forecasts and provided skill in the probabilistic forecast with a Brier Skill Score of 0.55. In addition, we developed a Gridded Atmospheric Forecast System (GRAFS) in parallel, leveraging cost share funds.

An economic evaluation based on Production Cost Modeling in the Public Service Company of Colorado showed that the observed 50% improvement in forecast accuracy will save their customers $819,200 with the projected MW deployment for 2024. Using econometrics, NCAR has scaled this savings to a national level and shown that an annual expected savings for this 50% forecast error reduction ranges from $11M in 2015 to $43M expected in 2040 with increased solar deployment. This

amounts to $455M in potential discounted savings over the 26-year period of analysis.

Lidar Support for Wind Energy

RAL researchers worked closely with faculty and students from the University of Colorado to deploy lidars in field studies relevant for boundary layer meteorology and wind energy applications. In 2016 RAL's lidar was deployed at Gordon's Ridge in Oregon, east of the Columbia River Gorge in support of the Wind Forecast Improvement Project 2 (WFIP2). The focus of WFIP2 is on development of new surface layer and boundary layer parameterizations for high-resolution numerical weather prediction models. NCAR vertically profiling lidar is deployed together with four additional vertically profiling lidars, four scanning lidars, two surface flux stations, 10 microbarographs, four radiometers, 17 sodars, 11 wind profiling radars, 28 sonic anemomenters mounted on one 80-meter tower, seven 10-meter towers. The year-long field study will yield unprecedented, long-term, high density, and high quality data that will be used for verification of new surface layer and boundary layer parameterizations for high-resolution simulations of flows in complex terrain.

Wind Forecast Improvement Project in Complex Terrain Near the Columbia River Gorge

As a member of the DOE-funded Wind Forecast Improvement Project 2 (WFIP2) team 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 planetary boundary layer (3D PBL) parameterization that will account for the effects of surface heterogeneities and enable more seamless coupling between mesoscale and microscale simulations. During 2016 the RAL team completed development of the 3D PBL parameterization and commenced with testing and verification of the parameterization using data from the WFIP2 field study near the Columbia River Gorge. Following verification of the new parameterization it will be included in the community numerical weather prediction model the Weather Research and Forecasting model.

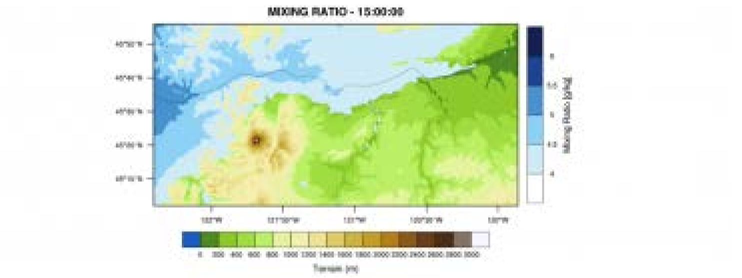

Figure 8. Simulation of a gap flow through the Columbia River Gorge. The mesoscale simulation was carried out with a three-dimensional turbulent boundary-layer mixing parameterization using 100 m grid-cell-size gird. Blue contours show water vapor mixing ratio. Underlying terrain is shown with green to yellow to brown contours. Mount Hood can be seen at about 45.37 degrees latitude and -121.69 degrees longitude.

Mesoscale to Microscale Coupling for Renewable Energy

A 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). NCAR 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. In FY16 the team focused on nonstationary cases, specifically modeling

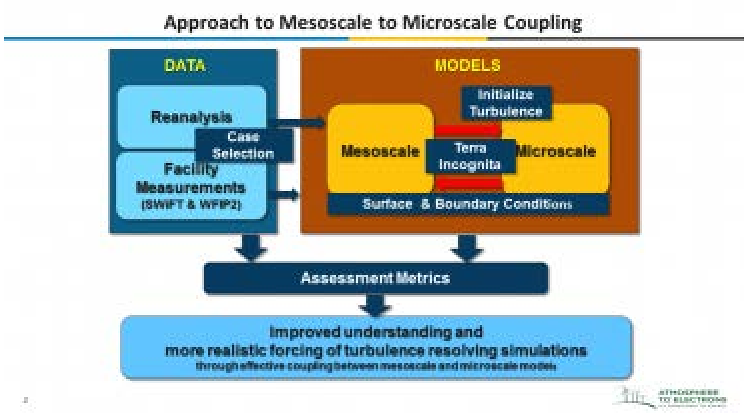

Figure 9. Process for coupling mesoscale to microscale simulations for wind plant management.

the coupled mesoscale-microscale system over diurnal cycles and during frontal passage. NCAR performed formal statistical assessment tailored to the needs of wind farm production. A major finding is that it is important to couple the mesoscale model to the microscale in order to produce the full forcing needed to model the details of the flow and turbulence at the right scales. More specifically, nesting the microscale in the mesoscale is an important feature, because the nesting allow continued coupling of the physical parameterizations into the scales of the wind plant. The impact of this project is expected to include improved wind plant operation and control. The team completed documenting the results of the first year results (Haupt et al. 2015) and the second year results (Haupt et al. 2016) of the nonstationary cases.

With a view toward a stepwise increase of complexity beyond the canonical, steady flat terrain cases assessed during year 1, this year's activities focus on nonstationary cases, also over flat terrain (with year three efforts targeting nonstationary cases over complex terrain). Section 3 of this report describes the nonstationary cases selected for this year's activities, as well as the metrics chosen for their assessment. As in year 1, the test site was the SWiFT facility in West Texas, with two unsteady meteorological cases representing a typical diurnal cycle with a nocturnal low-level jet (November 8, 2013) and a frontal passage (May 12, 2014). An additional diurnal cycle case study was selected from the literature.

Two different classes of mesoscale-microscale coupling were assessed, reflecting different approaches for specifying the microscale domain's lateral boundary conditions (LBCs). For regions with nearly flat terrain such as the SWiFT facility, spatially uniform but time-dependent meteorological forcing conditions, such as diurnal cycles, can be simulated with periodic LBCs. In this setup, the use of periodic LBCs provides a means to obtain turbulent inflow and outflow, while the mesoscale coupling is achieved via linking internal forcing parameters, such as the mean horizontal pressure gradients and advections of momentum and temperature, to mesoscale time variability of those fields. Mesoscale time variability can be obtained either from observations, as during one case study examined, or from a separate mesoscale simulation, as exemplified during another case study. Significant work was necessary to run the mesoscale model for the SWiFT site and extract the advective tendencies, pressure-gradient forces, vertical planes of data, and surface conditions/fluxes for driving the mesoscale models. The second method is to couple not only the microscale domain's internal forcing parameters, but also its lateral boundaries, to a mesoscale simulation. The boundary coupled approach therefore removes the restriction of periodicity and spatial homogeneity of the forcing meteorology, providing a general approach applicable to arbitrary terrain and meteorological conditions.

While the boundary coupled approach provides the greatest generality (since the mesoscale flow information providing the lateral boundary information for the microscale domain contains no explicit turbulence information), the approach requires methods to accelerate turbulence production at the microscale domain's inflow boundaries. Various inflow perturbation strategies, including the use of stochastic temperature field perturbations, and TurbSim-generated synthetic turbulence (a model generated by NREL) were therefore tried to initialize turbulence. Both methods demonstrated success at generating turbulence with moderate fetch lengths.

Wind Resource Assessment in the Developing World

Figure 10. Partners deploying a sodar in Bangladesh.

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 RAL's Real Time Four Dimensional Data Assimilation (RTFDDA).

PLANS FOR FY2017

FY2017 will continue to be an exciting time for renewable energy research at RAL. New collaborations with national laboratories, university 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 FY2017 significant efforts will include advancing comprehensive renewable power forecasting capabilities. An emphasis will be on porting the research to other regions of the world. 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:

- Continue work with NREL on 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. During FY17 the emphasis will be on coupled modeling in complex terrain.
  - Collaborate with Vaisala Inc. and DOE laboratories to improve mesoscale simulations of flows in complex terrain as part of the DOE-funded WFIP2 project.

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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 (DICast®) and the GRidded Atmospheric Forecast System (GRAFS) are examples of such technology (Figures 1 and 2). DICast® 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 2016 ACCOMPLISHMENTS

During this year the statistical improvements in DICast's short-term precipitation forecasting have been significant with the addition of high-resolution data from models such as 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. To improve the precipitation

forecasts over the extended forecast period, machine learning techniques have been employed using a dynamic tuning strategy and applied to the probability of precipitation forecasts. These forecasts are improved over the previous baseline and are more agile than the previous method. Near the end of 2016, RAL began a new partnership with a private weather company to provide DICast forecasts focused on aviation activities. This is a new application area for DICast and promises to be an exciting and challenging area of research.

DICast'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 DICast 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-Advective 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 open to the university community for research (Figure 2). This system is modular in nature, allowing choices in base numerical weather prediction models for inclusion, as well as consensus forecasting techniques. This system was first applied to solar energy (Figure 3) allowing utilities to assess production of distributed solar power, but has been extended for use in other applications as well.

RAL systems also continued to push the envelope of advanced weather forecasting in the transportation arena. 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, DICast and a weather-tuned version of GRAFS forms the backend weather engine used in both the FHWA and Colorado Pikalert Hazard Assessment forecast systems.

FY 2017 PLANS

Areas of development for the next fiscal year include:

- Expand DICast forecast modules to include other artificial intelligence techniques
- Expand DICast to produce aviation-related forecast variables and use new model sources
- Expansion of GRAFS to other consensus blending methods and other variables
- Improve road temperature and precipitation forecasts in the MDSS

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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

FY2016 ACCOMPLISHMENTS

A Public-Private-Academic Partnership to Advance Solar Power Forecasting

For this DOE-funded project, primary research was completed with a focus on 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. Xcel Energy undertook analysis using their PCM for the Colorado service area as a contribution to the project. Xcel data was analyzed by NCAR personnel to develop benefits estimates and aggregated to a national benefit estimate of the value of research to improve solar forecasting. This work found that the present value of the socio-economic value of research to improve solar weather forecasts for the utility sector could be over $450 million.

Capacity Assessment and Modernization Plan of National Meteorological and Hydrological Services and Early Warning Systems in Honduras and Nicaragua

The high-level objective of this World Bank funded project is to support climate-resilient development in Nicaragua and Honduras through the improvement of climate, meteorological and hydrological services in the two countries. The project is assessing the current status of climate, meteorological and hydrological services and development of a national Modernization Plan, which will contribute to shift from knowledge-based services to demand-driven activities, and enhance the development of improved and financially sustainable services. SIP staff are undertaking benefit-cost analysis of potential improvements in hydro-met services in Nicaragua and Honduras.

Assessing the Economic Value of Improving Weather, Water, and Climate Information in Bangladesh

Building on work supported by the World Bank, analysis and reporting was initiated on a survey of over 2,400 members of the public in Bangladesh 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. Analysis also was initiated on a sector expert survey of over 120 individuals from industry and government on their industry’s or agency’s sources, perceptions, uses, preferences, and values for current and improved weather, water, and climate information. A report on this work will be 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 FY2016. 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 in evaluating warning processes and systems holistically. Project work led to publication on mental models, risk communication, and societal aspect of flash flood and hurricane warnings in *Risk Analysis*; the *Journal of Hydrology*; *Weather, Climate, and Society*;and *Weather and Forecasting*. Ongoing FY2016 work focused on analysis of a survey of the general public in the Houston-Galveston and Miami areas and identifying factors influencing their stated preferences and economic values for potentially improved hurricane forecast and warning information.

Socioeconomic Benefits of Improved Forecasts on Decision-Making in Public Health and Air Quality(AQ)

For this NASA funded project initiated October 2016 our goal is to identify and assess improvements in AQ authority practices that will maximize the net socioeconomic benefits of the data resulting from the existing grant. To reach this goal, we are following the standard benefit-cost analysis framework (EPA 2010; WMO 2015), which involves comparing baseline conditions in the absence of improved AQ data with the conditions likely to result given better data. The costs and benefits

of alternative approaches to adjusting AQ management practices will then be compared to estimate the net social welfare improvements and identify the preferred approach.

Climate Matters

SIP staff served on the Advisory Board of the NSF-funded Climate Matters project (Ed Maibach, PI) to aid TV weathercasters in presenting science-rooted climate information in clear, concise and relevant ways. SIP staff supported the Climate Matters “Users Conference” in early March in Boulder, CO. This effort was aimed at increasing the competence, confidence, and use of climate materials on-air by the 18 broadcast meteorologists attending the conference from across the U.S. Project work also led to an article “Broadcast meteorologists’ views of climate change appear to be rapidly evolving” accepted for publication in the *Bulletin of the American Meteorological Society.*

HIWeather Project - WMO World Weather Research Programme

SIP staff are participating 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. SIP staff participated in the April 2016 HIWeather Kickoff meeting and led development of a White Paper on using the Weather Information Value Chain concept to develop integrated research projects.

FY2017 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 focus on evaluating factors influencing the economic value of improved forecasts and warnings using responses to a stated preference experiment in the Miami-Galveston survey of the general public.

Analysis and reporting will be completed on the public survey and expert elicitations of the World Bank hydrometeorological improvement program efforts in Bangladesh. Analyses will compare results between the two Bangladesh and Mozambique surveys and begin to develop best practices to facilitate implementation in other developing countries. Related projects are being pursued in several African and Central American countries including the World Bank funded work in Nicaragua and Honduras.

A manuscript will be developed on the Production Cost Modeling results from stakeholder partners will as part of the DOE funded project “A Public-Private-Academic Partnership to Advance Solar Power Forecasting.” This analysis estimates the value to improved solar irradiance forecasts in the day-ahead unit-commitment decision making of Xcel energy who was one of the project partner utilities.

The Societal Impacts Program will continued to support Climate Matter work 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.”

A manuscript will be completed on “*Economic Assessment of Hydro-Met Services and Products: The Weather Information Value Chain*.” This work will present a framework for assessing the socio-economic impacts and benefits of hydro-meteorological information – the Weather Information Value Chain (WIVC). The conceptual model provides a template for efforts in this area and encourages discussion about the structure and complexity of the information process and about theories, methods, and applications for assessing and improving the process. Three cases studies will provide difference

perspectives on developing and implement the WIVC approach.

Additional work includes a manuscript to be completed and submitted in partnership with Betsy Weatherhead from NOAA and co-authors on the optimal length of overlap in satellite data systems needed to identify an offset or a drift in the offsets of data between two sensors. Another manuscript will be completed on the future of sub-seasonal to seasonal (S2S) applications and forecasting with lead-author Chris White of the University of Tasmania. Work will be initiated as well on user-relevant verification as a contribution to the 7th International Verification Methods Workshop to be held in Berlin during of May of 2017

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WILDLAND FIRE MODELING AND PREDICTION

In FY2016 RAL and MMM researchers collaborated on research and development of an operational wildland fire spread prediction system. To safely manage wildland fires, decision makers need, reliable, accurate, frequently updated, easily accessible, geo-referenced current and predicted weather and fire behavior information. Timely information allows decision makers to better assess current conditions and future trends. Reliable information about the potential for rapid rate of fire spread and extreme fire behaviors is essential to saving life and property.

Currently operational wildland fire spread prediction systems are not coupled to numerical weather prediction models. These systems often rely on wind fields coarsely resolved in space and time. However, when flows are rapidly evolving due to storm outflows, density currents, frontal passages, etc., or are spatially variable due to complex terrain effects, highly resolved wind fields in time and space are needed to accurately predict fire spread. Furthermore, large wildfires result in significant surface heat fluxes generating strong updrafts and consequently intensifying local winds which in turn cause more rapid fire

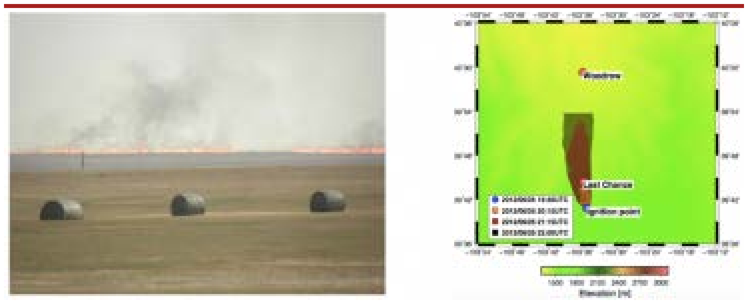

Figure 5. Last Chance Fire. Left panel - grass fire that spread through

Last Chance, Colorado, on June 25, 2012. Right panel – numerical simulation of the Last Chance fire. The fire was ignited south of Last Chance and rapidly spread northward driven by strong southerly winds. Contours represent fire perimeter at different times while orange circles denote satellite observations of fire spread at 20:15 UTC. Observed and predicted fire behavior are in good agreement.

spread rates. Large wildfires also result in significant smoke plumes that can affect radiative transfer, while lofted particulate matter and moisture can result in the formation of pyrocumulus clouds. All these phenomena can be predicted only using coupled models. Therefore, developing an operational coupled wildland fire spread capability – the NWP model is essential for accurate wildland fire spread prediction. To achieve this goal RAL researchers are extending capabilities of the Weather Research and Forecasting NWP model based on the Coupled Atmosphere Wildland Fire Environment (CAWFE) model. The new developments focused on improvements to the fire spread model and the level-set based fire perimeter tracking algorithm. These developments will be included in the community WRF-Fire model.

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NATIONAL SECURITY APPLICATIONS

Significantly advance our understanding of mesoscale and urban-scale weather and climate processes, especially in the boundary layer, and our ability to forecast these atmospheric conditions operationally for the purpose of providing forecasters, decision makers, and emergency managers with accurate information to save lives and property.

- Numerical Weather Prediction
- Data Assimilation
- Dynamical Ensemble Prediction
- Post-Processing
- Air Quality Forecasting

- Statistical and Dynamical Mesoscale Climate Downscaling
- Atmospheric Transport and Dispersion of Hazardous Materials Research and Development

‹ Wildland Fire Modeling and Prediction up Numerical Weather Prediction ›

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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

‹ National Security Applications up Four-Dimensional Weather System (4DWX) ›

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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. RAL upgrades 4DWX software several times per year. 4DWX is used by ATEC meteorologists at seven test ranges across five major climate zones: White Sands Missile Range (WSMR), New Mexico; Electronic Proving Ground (EPG), Arizona; Dugway Proving Ground (DPG), Utah; Aberdeen Test Center (ATC), Maryland; Redstone Test Center (RTC), Alabama; Yuma Proving Ground (YPG), Arizona; and Cold Regions Test Center (CRTC), Alaska.

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

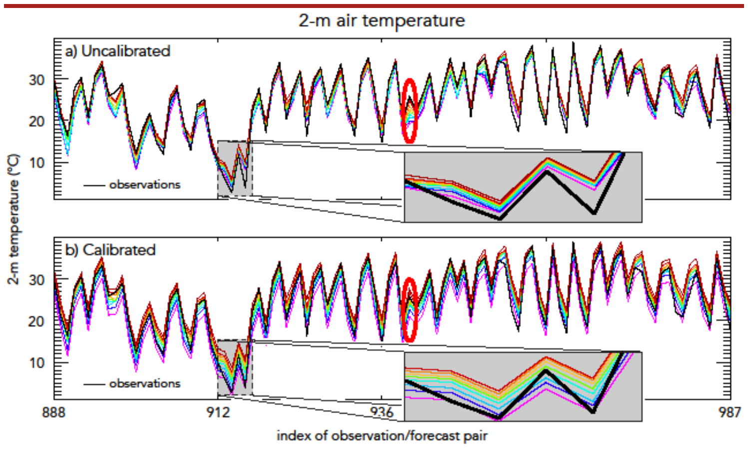
The WRF model is an industry standard for numerical weather prediction in operations and research. The model code is open source. It was developed by a group of partners including NCAR, the National Oceanic and Atmospheric Administration, the Air Force Weather Agency, the Federal Aviation Administration, and the university community. The model is designed for NWP across many scales, from global to microscale. The WRF Model is the predictive core of 4DWX.

Real-Time Four-Dimensional Data Assimilation (RTFDDA)

The project continues to rely on Real-Time Four-Dimensional Data Assimilation (RTFDDA) as one way to ingest observations and define the atmosphere's current state for 4DWX's NWP core, the WRF model. RTFDDA involves modifications to an NWP model's predictive equations so the model can be gently adjusted, or nudged, toward observed conditions during the model's analysis stage, before the forecast stage begins. The scheme is computationally efficient and preserves the precise timing of observations, which gives 4DWX a particularly accurate depiction of the weather at any instant. RTFDDA continues to show itself superior to, or the equal of, many alternative methods of data assimilation in operational systems. RTFDDA 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. RTFDDA 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, which is an under-appreciated problem in applied NWP.

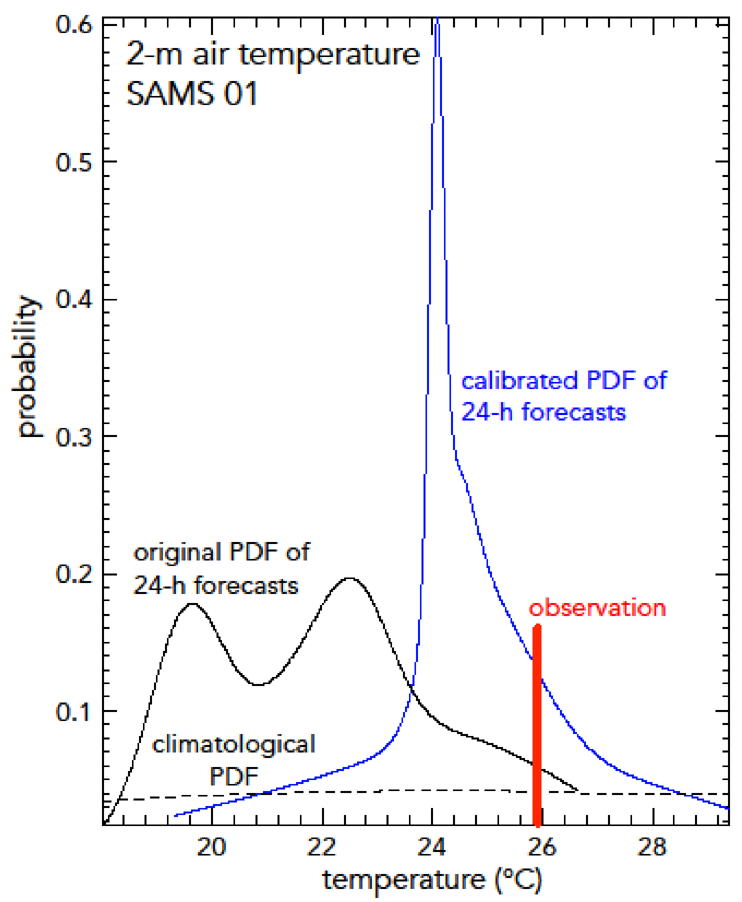
Ensemble 4DWX (E-4DWX)

Since 2007, DPG 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: WSMR, YPG, and EPG.



A subset of output from E-4DWX is calibrated so that the probability of E-4DWX's forecasts being realized matches the observed probability. Benefits of calibration include: 1) reducing forecast error of the ensemble mean, partly by reducing bias; 2) increasing reliability, resolution, and sharpness, including for predicting extreme and potentially devastating weather; and 3) providing a measure of forecast uncertainty through the spread among ensemble members. Calibration is performed on moments of the overall probability density function, no matter the size of the ensemble membership, as opposed to calibrating output from specific ensemble members. This makes E-4DWX particularly robust, even if individual members of the ensemble fail at some point during the forecast. E-4DWX's calibration algorithms combine logistic regression with quantile regression. To ensure the ensemble's reliability, it is pre-processed, then the calibration is explicitly conditioned on the ensemble dispersion. Regressions are always performed with cross-validation to minimize the likelihood of overfitting.

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 employs the dual polarization data newly available from the nation's NEXRAD network as well as terminal Doppler Weather Radar (TDWR). An algorithm called Trident helps to alert forecasters to conditions that could lead to flash flooding in dry washes. Trident 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.

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)

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 accurately 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

Each year, RAL provides to ATEC meteorologists several days of on-site training on 4DWX technology. Not only does 4DWX improve every year, but the test support required of ATEC meteorologists also changes frequently. Close interaction between ATEC and NCAR is critical for maintaining the project's success.

SELECTED ACCOMPLISHMENTS IN FY16

Improvements to 4DWX's NWP core and data assimilation

Even at fine model resolutions, dense observing networks can lead to groups of observations within a single model grid cell. To avoid this wasteful and problematic situation, 4DWX now includes a method to thin spatially dense data while preserving the essential information from all the observing sites that fall within a cell.

Predictions of lightning

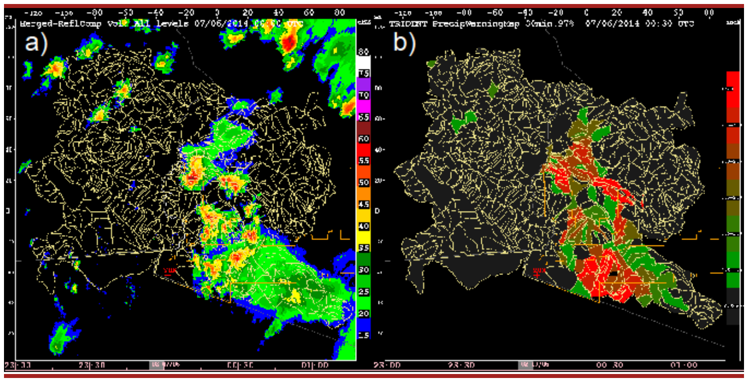
4DWX includes a tool for tactical prediction of lightning (lead times of minutes to tens of minutes) and a tool for strategic prediction of lightning (lead times of hours to days). The former is based on WSR-88D radar data that are used to monitor reflectivity above the melting level. The latter is based on numerical output from 4DWX's predictive core. Recent improvements in 4DWX's lightning predictions now capture earlier initiation of lightning and are better at predicting lightning in regions of lower probability, such as in anvil cirrus.

Predictions of flood-inducing rainfall

Since Trident was installed at YPG in 2014, RAL has improved the algorithm in several ways. We have modified the range of altitudes over which composite reflectivity is used to estimate rainfall, have increased the resolution of the drainage basins used in calculations, and have tuned warning criteria based on several cases of flooded dry washes at YPG. Trident

uses two methods of calculating warning criteria, one based on maximum rainfall in a drainage basin, another based on the percentage of a basin covered by rainfall of various thresholds. Testing suggests the second of these produces better results for YPG.

Very large-eddy-simulation (VLES) version of 4DWX



Much of ATEC's testing is sensitive to microscale weather, so RAL continues to work on extending 4DWX into the range of very-large-eddy simulation (VLES) resolutions (grid intervals of 100s of meters). At these scales, developers need to revisit not only many traditional approaches to weather forecasting, but also traditional approaches to data assimilation and model verification. For example, RAL is using wavelet-based scale filtering as a step toward ensuring that there are not extreme discrepancies between the scales of information in model output and in observations.

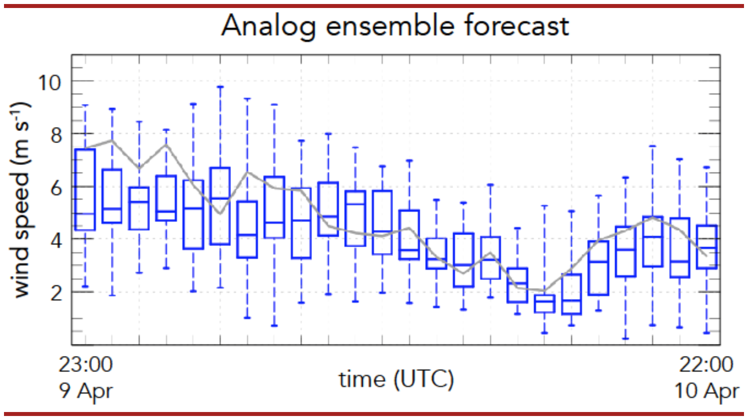
Advanced quality-control of range observations

4DWX now includes set of algorithms to evaluate the quality (often called quality-control or quality-assurance) of observations collected by high-resolution instrument arrays at the ATEC ranges. These observations are used in 4DWX's assimilation cycle. Among the tests being applied in real time are: general validity, climatic validity, and temporal consistency. The original design for the spatial consistency test was too computationally demanding to be run in real time on the computers that ATEC uses, so that test is being redesigned.

Analog ensemble

4DWX's Analog Ensemble (AnEn) is now being used operationally by three test ranges: ATC, RTC, and CRTC. 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



Some fraction of ATEC testing is conducted at remote locations away from the seven Army ranges with whom RAL works most closely. Despite what can be unfamiliar surroundings and logistical challenges, ATEC meteorologists still need access to 4DWX products even when away from their home ranges. Recently RAL has made this much easier by upgrading the 4DWX Portal to include display of products for those special missions.

SELECTED KEY PLANS FOR FY2017

Migration away from dedicated hardware

Traditionally ATEC has relied on dedicated computer clusters to run 4DWX for operational support at the ranges. NCAR and ATEC are now exploring whether large, shared clusters owned and operated by the DOD could be used to run 4DWX operationally. If this proves feasible, it would translate to lower hardware costs for the government and would allow computing resources to expand or shrink on demand as 4DWX technology evolves. RAL is currently redesigning key elements of 4DWX to be more platform-independent, and we are working with the Army and Navy to demonstrate that shared computing resources in the DOD can be extended to accommodate the demands of real-time weather modeling.

E-4DWX

RAL plans to integrate grid-point statistical interpolation (GSI) as one of the methods of data assimilation in the ensemble.

Analog Ensemble (AnEn)

AnEn will be extended to all seven supported ATEC 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.

Trident

An upgrade under development will allow dual-polarization data to be used for flood alerts.

Stream-flow prediction

Trident's recent successes in alerting range meteorologists about the potential for flooding in dry washes at YPG has motivated RAL to begin developing a plan for incorporating stream-flow prediction into 4DWX. The system's numerical weather prediction will be linked to watershed hydrologic models.

Observing and modeling the Chesapeake Bay breeze

A tool will be added to the 4DWX Portal that displays observations and model predictions of the Chesapeake Bay breeze. ATC's weather is often influenced by the breeze, so for testing there it would be useful to have explicit predictions of the breeze's onset, duration, and extension inland.

‹ Numerical Weather Prediction   up   Real-Time Four-Dimensional Data Assimilation (RTFDDA) and Forecasting Advances ›

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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, power grid weather safety, weather-related emergency response etc., desire rapid-update precision weather information for areas of interest. RTFDDA (Real-time Four-Dimensional Data Assimilation and forecasting system) is a mesoscale numerical weather modeling system that has been developed to meet the needs of these 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 WRF and provide the best possible weather information service for a target 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 50 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, energy, water resource and flood prediction, etc.

To take advantage of the availability of new data and meet new requirements for applications, RTFDDA is continuously improved with respect to its data assimilation schemes, dynamical configuration and physical parameterizations to advance the RTFDDA system itself and improve its accuracy and capabilities. In the last seven years, RTFDDA has evolved from a single mesoscale deterministic analysis and forecasting system to a modeling capability suite that integrates ensemble prediction technology (Ensemble-RTFDDA), 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 (RTFDDA-LES) (Fig. 1). As a result, RTFDDA 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 RTFDDA for forecasting sand and dust storms.

RTFDDA currently integrates the following data assimilation technologies: 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. The technologies are configured to create a hybrid data assimilation scheme that provides optimal modeling for specific application requirements.

FY 2016 ACCOMPLISHMENTS

Advances in WRF-FDDA

In order to assimilate increasing number and types of diverse observations and support the 4 dimensional relaxation ensemble Kalman filter data assimilation scheme, the WRF model has been modified to

Real-Time Four-Dimensional Data Assimilation (RTFDDA) and Forecasting Advances

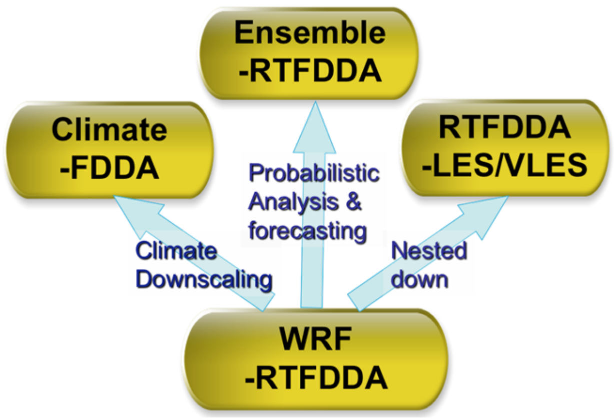

Figure 1. RTFDDA and its extension for regional microclimatology dynamical downscaling, ensemble prediction and LES/VLES NWP of local microscale flows.

refactor the observation-nudging data structures. The new data structure significantly improves the computing efficiency and memory usage of the FDDA scheme and avoids the long-existing data-handling bottleneck of the legacy FDDA data structure. In addition, the new data structure is more compatible with those employed by the other NCAR data assimilation tools such as DART and GSI, which eases the hybrid deployment of different data assimilation schemes. This new data structure is critical for conducting Doppler radar radial velocity data assimilation with the advanced 4D-REKF technologies.

Quality control of observations continues to be a vital component of the RTFDDA model system. In FDDA observations are ingested into the full physics WRF and interact directly with the model dynamics and physics, making it critical to ensure that bad observations are not assimilated. Inadequate quality control may seriously affect the model's reliability and performance. The RTFDDA online QC scheme was further refined to correct problems due to the differences between model terrain heights and observation station elevations. The consideration of terrain height differences allows assimilation of more surface observations into RTFDDA. Work has also focused on addressing a model performance problem caused by excessively dense observations in a specific location. A data-thinning module has been developed to thin observation density according to given model grid sizes. Finally, work has focused on aligning RTFDDA research and development with WRF advances being made by the research community. An effective version-control tool has been developed to track and merge the two system development efforts.

Sand and dust forecasting with WRF-Chem

Improved sand and dust forecasting capabilities are being developed using RTFDDA and the fully coupled WRF-Chem model. Data assimilation of weather data is improving the modeling of dust emission and transport within WRF-Chem and significantly improving the model's dust spin-up processes and thus forecast accuracy. RTFDDA-dust forecasting systems have been deployed in Saudi Arabia (Fig.2) and Israel.

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 (μg kg^{-1}) during the period of 03 LST March 9 through 03 LST March 12, 2009.

PLANS FOR FY 2017

RTFDDA is an evolving modeling system. Research and development efforts are conducted continuously to improve all major system components. In particular, the community WRF achievements, and the nudging-based FDDA scheme will be merged and integrated for new deployments. All operational RTFDDA systems will be upgraded to WRF Version 3.8.1 in early FY2017, and work will begin to upgrade the system for Version 3.9.x by the middle of FY2017.

Real-Time Four-Dimensional Data Assimilation (RTFDDA) and Forecasting Advances

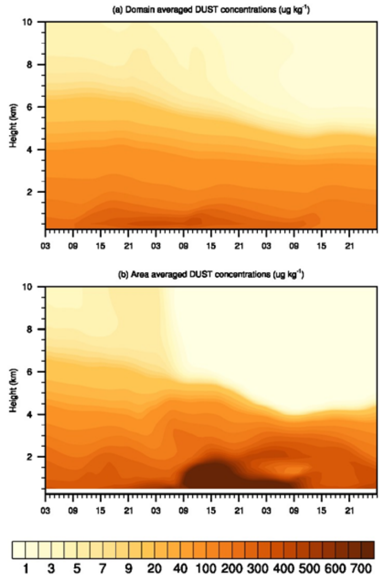

Figure 2. Height-time cross section of the WRF-Chem simulated (a) Domain 2 averaged and (b) an area centered around Solar Village averaged dust concentrations (μg kg^{-1}) during the period of 03 LST March 9 through 03 LST March 12, 2009.

RTFDDA core research will focus on the RTFDDA-GSI-HLHN hybrid radar data assimilation system, 4D-REKF four-dimensional data assimilation scheme for radar data assimilation, 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 compared 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. Work will also focus on improving 4D-REKF, an advanced FDDA capability that combines the advantages of Newtonian relaxation-based “observation nudging” and the advanced ensemble Kalman filter, by using flow-dependent data assimilation weights generated with dynamical ensemble forecasts.

‹ Four-Dimensional Weather System (4DWX) up Operational RTFDDA ›

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OPERATIONAL RTFDDA

BACKGROUND

Real-Time Four-Dimensional Data Assimilation (RTFDDA) and forecasting technology has been developed to meet the need for high-resolution, accurate, and rapidly updated weather information for weather-critical applications. directed at national defense and security, energy, emergency response and health. It has been deployed for real-time operational weather support in over 50 applications areas (e.g., national defense and security, energy, emergency response, and health) by US government agencies, international organizations, and commercial entities. This section reviews the following operational RTFDDA NWP projects:

1. US Army Test and Evaluation Commands (ATEC) test ranges
2. Advanced NWP for State Grid Corporation of China (SGCC)
3. MAGEN for the Government of Israel
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

FY2016 ACCOMPLISHMENTS

US Army Test and Evaluation Commands (ATEC)

RTFDDA system serves eight Army test ranges located in the US and also supports on-demand test missions of ATEC in other regions aroundthe globe. Both an ensemble-RTFDDA system and a deterministic RTFDDA-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 in the 4DWX section of this report.

Advanced NWP for the State Grid Corporation of China (SGCC)

Weather affects every aspect of electric power production from power generation, grid integration and transmission through dispatch and load. With recent tremendous growth in renewable energy and the deployment of ultra-high-voltage, large capacity electric power transmission systems, the State Grid Corporation of China (SGCC) has critical needs for better weather information. RAL is working in collaboration with the SGCC's Chinese Electric Power Research Institute (CEPRI) to meet these needs by applying and improving the WRF-RTFDDA technology to support weather modeling capabilities and to develop new advanced weather/climate tools. Fig. 1 summarizes major NWP systems developed for real-time operational use in China.

MAGEN for Israeli Government

MAGEN (Model for Advanced GENeration of 4D Weather) developed by RAL for the Israeli Ministry of Defense employs RTFDDA and WRFDA-3DVAR hybrid data assimilation technologies to provide high-resolution weather guidance over the eastern Mediterranean region. RTFDDA data assimilation has been coupled with WRF-Chem online dust modeling to

Operational RTFDDA

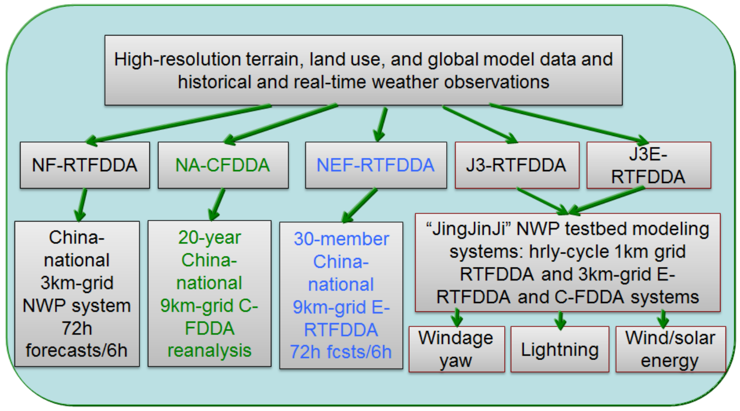

Figure 1. Summary of RTFDDA, Climate-FDDA and Ensemble-RTFDDA systems developed for SGCC

provide real-time sand and dust prediction capabilities. A large single-domain RTFDDA-Dust model at a grid size of 9km has been set up to cover the main dust emission and transport areas over the Middle East and northern Africa region that affects Israel. In addition, a new 3.3km grid high-resolution MAGEN forecasting capability has been developed to optimally take advantage of the high-resolution ECMWF global model forecasts working as the initial and lateral boundary conditions. Case studies have been conducted and the results have demonstrated the superior performance of the dust storm prediction and lower stratus simulation of the new modeling systems.

WRF-RTFDDA for Xcel Energy Wind-Power Prediction

The NCAR-Xcel wind power prediction collaboration has moved into its third phase in which enhancements are being made to the WRF-RTFDDA system. The goal is to further improve WRF-RTFDDA'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 RTFDDA data assimilation technology called Four-Dimensional Relaxation Ensemble Kalman Filter (4D-REKF), recently developed at NCAR, will be applied in the Xcel WRF-RTFDDA 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. This is an important area of research as turbine blade icing can impede power production of turbines and/or potentially damage the turbines themselves.

PWS CONUS-scale RTFDDA Operation

Operational RTFDDA

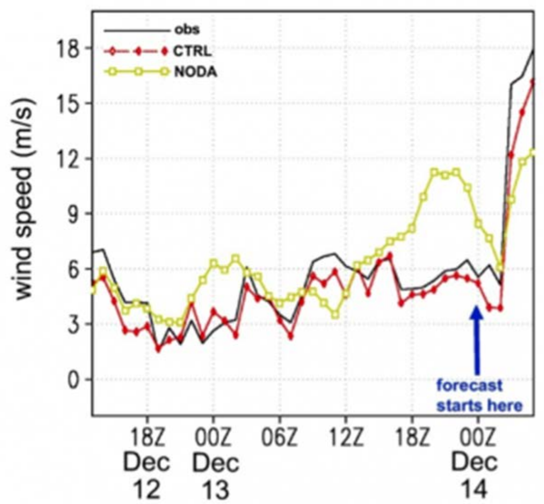

Figure 2. Time series of farm-averaged hub-height wind speed for a

NCAR and PWS (Panasonic Weather Solutions; formerly AirDat LLC) have been long-term partners in developing RTFDDA technology for TAMDAR (Tropospheric Airborne Meteorological Data Reporting). This work has focused on data quality-control, optimization of TAMDAR impact in regional NWP, and development of operational RTFDDA forecasting systems. A CONUS-scale operational WRF-based RTFDDA 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 RTFDDA system with radar data assimilation. More recent land cover data are used to better specify the RTFDDA 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. Peudo-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.

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.

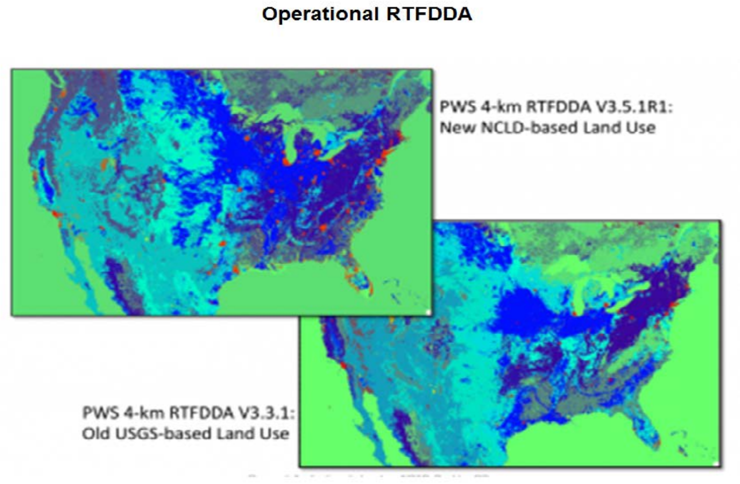

Figure 3. Update of land uses for the PWS-NCAR CONUS 4-km grid RTFDDA using the new land cover-based datasets. Many differences can be seen, especially the improved representation of urbanization in recent decades (red areas).

RTFDDA 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 RTFDDA 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 RTFDDA 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 FY2016 include: 1) installation of RTFDDA 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 RTFDDA microscale weather analysis and nowcasting system.

PLANS FOR FY2017

Research and development efforts will focus on continuous deployment and improvements of the RTFDDA 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 RTFDDA systems for UAE, Thailand and other countries. Plans for several other on-going RTFDDA projects include:

Israel MAGEN Systems

New research proposals will be initiated to significantly augment the capabilities of the existing MAGEN hybrid system to assimilate data from dust models to improve the 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.

Joint Research Program with the China Electric Power Research Institute

RAL is working with CEPRI, a major electric power research institute within the State Grid Corporation of China, to establish a CEPRI-NCAR joint program for electrical power meteorological research and ensure a long-term, stable collaborative research program with multi-discipline electric power and meteorological sciences. CEPRI and NCAR will jointly develop advanced numerical weather prediction and data assimilation systems using technologies such as the Weather Research and Forecasting (WRF) model, Four-Dimensional Data Assimilation (FDDA), Ensemble-Kalman-Filter FDDA, Gridpoint Statistical Interpolation (GSI), Climate-FDDA, data quality control, advanced model output statistical bias correction, and ensemble calibration technologies.

Because of the diverse weather regimes across the country, the joint research program will conduct a number of weather forecasting experiments to advance electric power weather simulation and forecasting capabilities. High-resolution weather reanalyses for generating a multi-year electric power weather/climate reanalysis historical database will be performed, and fine-scale weather modeling and forecasting systems toward renewable energy resource assessment and power forecasting applications and effectively support large-scale integration of renewable energy on to the power grids will be carried out. Electric-power meteorological disasters are the key research foci. NCAR and CEPRI will jointly research and develop analysis and forecasting technologies and develop weather safety forecasting and early warning systems for electrical power grids.

Panasonic Weather Solutions

Work will continue to focus on development and optimization of the NCAR-PWS CONUS-scale 2.5-km operational RTFDDA system with assimilation of radar reflectivity. Case study and statistical verification of real-time operation will be conducted.

Shenzhen Meteorological Bureau

RAL will continue to optimize the WRF-RTFDDA 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.

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FINE-SCALE PRECISION NWP: WRF-RTFDDA-LES

BACKGROUND

Demands for 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 is 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 is currently being adapted for research and operational use in weather-critical applications.

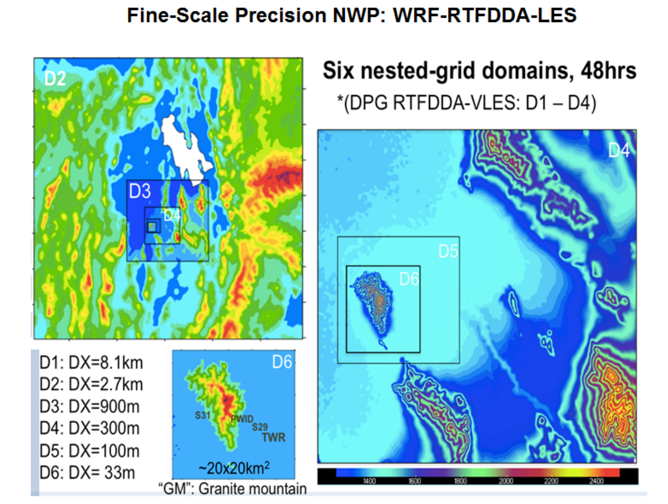

Figure 1. Simultaneous multi-scale WRF-RTFDDA-LES simulations with six-nested-grid domains with model grid intervals varying from 33m to 8.1km.

FY2016 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 (ATC) in Maryland. A WRF-RTFDDA-LES model has also been set up to simulate fine-scale weather flows and mountain convections over the White Sands Missile Range in New Mexico.

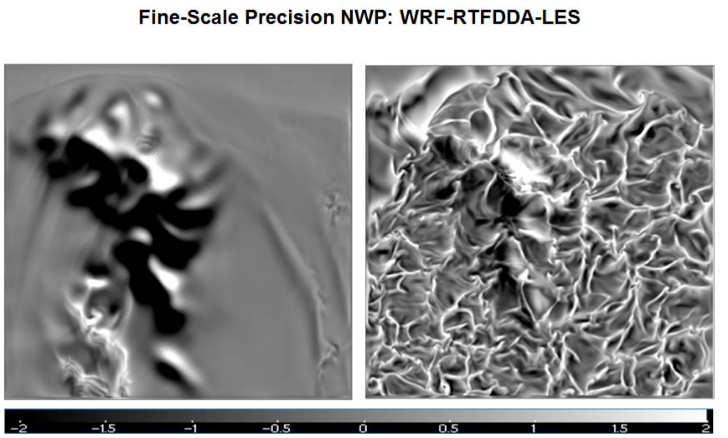

Figure 2. Snapshots of WRF-RTFDDA-LES simulation of early morning (left panel; valid at 11:00 UTC, May 4, 2012 with stable boundary layer) and around-noon (right; valid at 17:32 UTC, May 4, 2012 with convective boundary layer) at 33m grid intervals. The field shown is the model vertical velocity at 200m Above Ground Level (m/s).

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 assimilated 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. Modeling studies were conducted with six nested-grid domains (two extra nested domains with grid sizes of 100m and 33m, respectively [Fig. 1])

to study microscale flows associated with the Granite Mountain (~60 km^2) at DPG and complex coastal flow over ATC. 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).

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.

RTFDDA-VLES/LES bas been employed to study the orographic convection over the mountain ranges surrounding the White Sands Missile Range as well. Simulation experiments with seven cases show that with 300m and 100m grid VLES fine mesh grid, RTFDDA-VLES displayed a dramatic ability to forecast convective initiation over the complex mountain ranges.

FY2017 PLANS

Although demonstration of WRF-RTFDDA-LES/VLES has shown a good deal of promise for real-world microscale weather forecasting, many challenges remain in order to practically realize the value of the LES/VLES NWP technology. We propose the following plan to address those challenges: First, each LES/VLES NWP system should be formulated to address the specific needs of an application and tools should be developed to improve the use and visualization of VLES forecast outputs for those end users. Second, VLES/LES forecast verification strategies and special observations contain microscale weather information that should be studied to help understand when LES/VLES NWP is valuable and when it is not. This will help modelers to improve the modeling technology and provides guidance for end users. Third, LES-scale data assimilation, which is critical for operational forecasting of VLES/LES NWP models, must be improved. And finally, modeling studies need to be carried out to understand small and microscale severe weather processes including strong winds, icing, thunderstorms and extreme temperatures over small-scale complex terrain. RTFDDA-LES/VLES will be further assessed for modeling these high-impact local weather phenomena at different army test ranges.

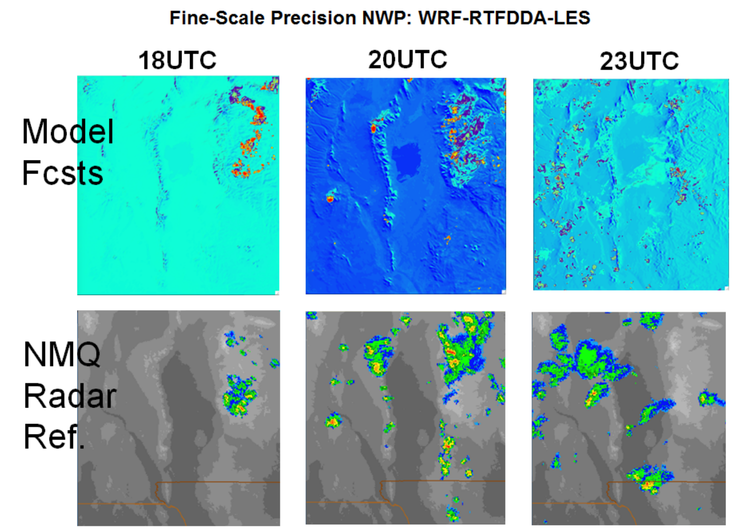

Figure 3. A snapshot view of RTFDDA-VLES simulation of summer monsoon convection initiation, on August 6, 2015, over mountain ranges around the army White Sam Missile Range.

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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 (WRF) as well as serial based post-processing, various software layers have been under examination to improve performance across differing job sizes. During FY16 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 FY16 NSAP had approximately 228TB of highly fault-tolerant, parallel, network attached object-based storage,

with the capability to increase by 100s of TB in FY17 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 continue with the 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.

Hosted HPC and Cloud Computing

RAL continues to review and leverage access to (remote) hosted HPC services for the purposes of testing various software models on emerging hardware such as GPUs, newer CPU and networking technologies as well as Cloud platforms in order to gain efficiencies as well as reduce potential costs to sponsors or developing projects. The use of hybrid computing architectures where "right-sized" compute resources can execute job tasks in tandem by optimizing on-premise hardware as well as dynamic and scalable cloud based compute services is another area RAL is exploring from a design, workflow and cost model perspective. Leveraging cloud technology to produce more efficient, as well as higher quality scientific results, will depend on careful consideration of such factors as data locality, software model optimizations and workflow tool design.

‹ Fine-Scale Precision NWP: WRF-RTFDDA-LES up Data Assimilation ›

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DATA ASSIMILATION

- Satellite Precipitation Data Assimilation
- Mesoscale Ensemble Data Assimilation and Prediction System
- RTFDDA-3DVAR Hybrid System

‹ High Performance Computing for Operational Modeling up Satellite Precipitation Data Assimilation ›

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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 are strategic with regard to national 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 FY2016

Satellite Precipitation Data Assimilation

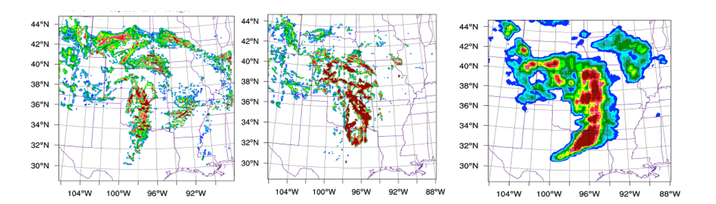

Figure 1: 3-hour accumulated precipitation: WRF without assimilation (left), WRF with assimilation (center) and NOAA CMORPH analysis (right), valid at 00z on May 25, 2011 (7pm local time). The WRF grid increment is 9km. The CMORPH grid increment is 0.25°.

Our approach builds on Fillion and Belair (2004, MWR) work, in which precipitation is assimilated within a variational framework using the Kain-Fritsch cumulus parameterization. Practically, it acts as a one-dimensional variational data assimilation of precipitation estimates through the KF scheme and its Jacobian to produce increments to the model temperature and moisture profiles, including those within the boundary layer. This method was ported to the WRF model and an initial WRF integration was performed with assimilation of conventional observations and the 1D-VAR is performed grid point by grid point using precipitation estimates from the Climate Prediction Center MORPHing (CMORPH) as observations and the WRF integration as first guess. CMORPH blends precipitation estimates that have been derived from low orbiter satellite microwave observations exclusively. A second integration was then conducted in which the WRF model was nudged toward the gridded solutions of the 1D-VAR precipitation assimilation. Figure 1 shows WRF precipitations with (middle) and without (left) assimilation of precipitation for an event that occurred over the Southern Great Plains (SGP) the evening of May 24, 2011, compared to the precipitation estimate from the CMORPH analysis (right).

PLANS FOR FY2017

We intend to validate the method described above on the comprehensive observational data set collected during the Midlatitude Continental Convective Cloud Experiment (M3CE) over the Atmospheric Radiation Measurement (ARM) Southern Great Plains (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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Zou X. and Y.-H. Kuo, 1996: Rainfall assimilation through an optimal control of initial and boundary conditions in a limited-area mesoscale mode. *Mon. Wea. Rev*., **124**, 2859-2882.

Fillion, L., and S. Belair, 2004: Tangent linear aspects of the Kain–Fritsch moist convective parameterization scheme. *Mon. Wea. Rev*., **132**, 2477–2494

Fillion, L., and R. M. Errico, 1997: Variational assimilation of precipitation data using moist convective parameterization schemes: A 1D-Var study. *Mon. Wea. Rev*., **125**, 2917–2942

Prediction System ›

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MESOSCALE ENSEMBLE DATA ASSIMILATION AND PREDICTION SYSTEM

BACKGROUND

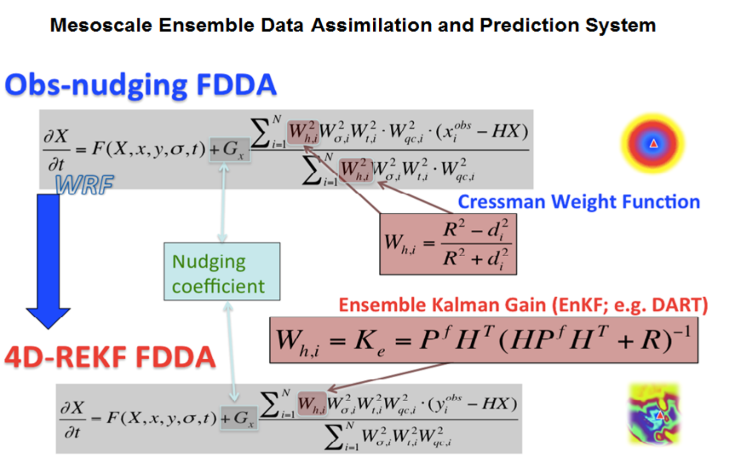

Figure 1. A description of Obs-nudging and 4D-REKF FDDA formulations.

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-RTFDDA (Ensemble Real-Time Four-Dimensional Data Assimilation and forecasting system). E-RTFDDA 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-RTFDDA model members employ Newtonian-relaxation 4D data assimilation algorithms to achieve rapid cycling of continuous 4D analysis and forecasting. To take advantage of E-RTFDDA ensemble prediction, 4D-REKF uses Kalman gains that can be computed using the multi-model E-RTFDDA forecasts. The Kalman gains are ingested into E-RTFDDA 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. It also 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.

FY2016 ACCOMPLISHMENTS

4D-REKF was enhanced for assimilation of Doppler radar radial velocity measurements. This work involves a major change of the data structures that can handle the radar observation data and Kalman gains effectively. Unlike the radial velocity assimilation, radar reflectivity measurements are assimilated with hydrometeor and latent heat nudging (HLHN) scheme. A convective weather case from the PECAN-2015 field campaign containing a supercell severe convection storm and three mesoscale convective systems was selected to performing the radar data assimilation experiments. Numerical experiments were designed to test the validity of the scheme and its implementation. Preliminary results show welcome potential for using the scheme to improve short-range forecasting of convection systems.

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 ongoing, 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 have thus been formulated.

FY2017 PLANS

4D-REKF is still at an early stage of initial operating capability. Further evaluation and enhancement are necessary to fully exploit the power of the technology. The limited representativeness of Kalman gains computed from mesoscale ensemble forecasts of excessively small number of ensemble members is still the main challenge for effectively taking advantage of 4D-REKF. Empirical algorithms will be explored to 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. Refinement of 4D-REKF with cross-variable (covariance) "observation-nudging" capabilities for assimilating Doppler radar radial velocities will be studied. Finally, performance of 4D-REKF for real-time semi-operational runs at the US Army Dugway Proving Ground will be assessed and refined. The scheme will also be deployed for other applications.

‹ Satellite Precipitation Data Assimilation up RTFDDA-3DVAR Hybrid System ›

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RTFDDA-3DVAR HYBRID SYSTEM

BACKGROUND

RTFDDA (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 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.

RTFDDA 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 RTFDDA and 3DVAR (WRFDA and GSI) hybrid data assimilation approach has been developed, with RTFDDA 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 2016 ACCOMPLISHMENTS

RTFDDA-GSI-HLHN Hybrid Data Assimilation

One of the challenges for numerical weather prediction in the regions in which conventional weather data are excessively sparse (e.g., oceanic regions, 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 approach is also employed to assimilate Doppler radar radial velocity observations in RTFDDA. A major benefit of the RTFDDA-GSI hybrid data assimilation technology over the typical GSI-only model initialization scheme is that it retains the advantage of the RTFDDA in generating 4-D dynamically consistent and physically spun-up analysis and forecasts.

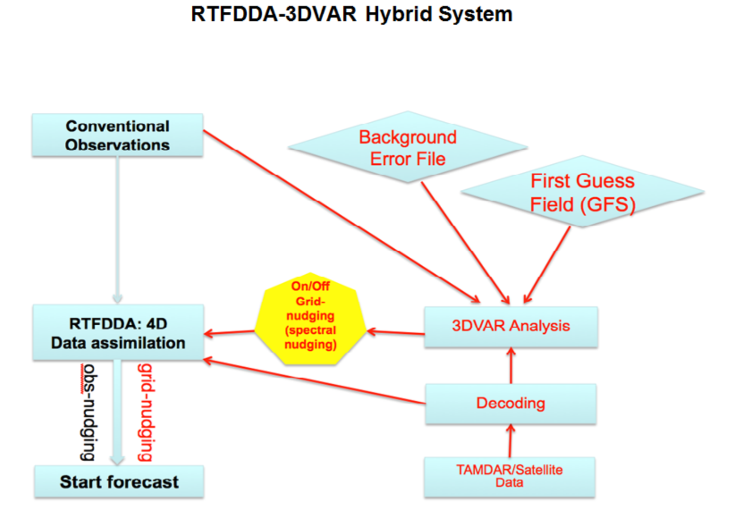

Figure 1. Schematic diagram of the RTFDDA-GSI hybrid data assimilation system.

Incorporating radar data 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 WRF-RTFDDA system, a hybrid approach that couples RTFDDA and GSI with a hydrometeor and latent heat nudging (HLHN) technique has been developed. This scheme allows us to use radar reflectivity to retrieve precipitation particles (e.g., snow, rain drops and graupel) which are then nudged into WRF along with adjustments of latent heat releases. 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, Redstone Test Command (RTC) range and Shenzhen metropolitan regions in China. A prototype RTFDDA-GSI-HLHN hybrid system was also run in real-time for the ATC domain. During FY2016, a sensitivity study was conducted with the assimilation of radar reflectivity measurements with HLHN to study the impact of data frequencies between six minutes and one hour, relaxation strength. Figure 2 shows a diagram of the RTFDDA-GSI-HLHN radar data assimilation (RDA) capability

PLANS FOR FY 2017

Research on RTFDDA-GSI-HLHN will continue to focus 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. Strategies for nudging hydrometeors (rain, snow, and graupel mixing ratios) and the corresponding latent heat derivation from radar reflectivity observations will be studied. The HLHN-based radar reflectivity data assimilation scheme will be employed in a development of a high-resolution (2.5km grid) RTFDDA system for use over the contiguous US (CONUS) domain. In addition, work to assimilate polarimetric radar products and lightning data into the hybrid RDA system will begin.

RTFDDA-3DVAR Hybrid System

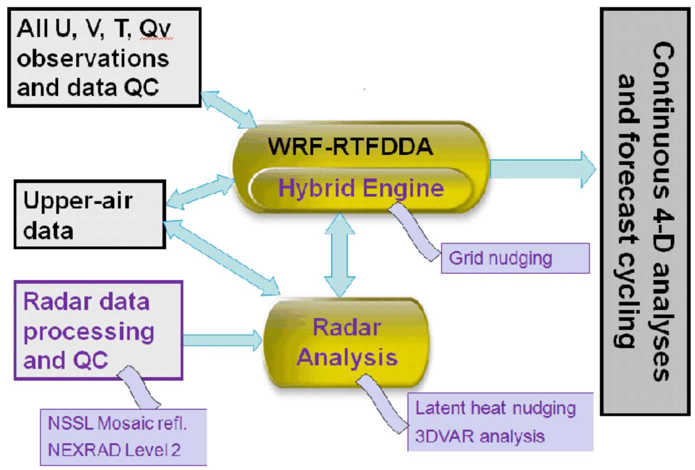

Figure 2. Schematics of the RTFDDA, GSI and HLHN hybrid for radar data assimilation.

‹ Mesoscale Ensemble Data Assimilation and Prediction System up Dynamical Ensemble Prediction ›

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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 developed an Ensemble Real-Time Four-Dimensional Data Assimilation (E-RTFDDA) and forecasting system. The system is built upon WRF. The first E-RTFDDA system was deployed to support the US Army Dugway Proving Ground in 2007 and is known as E-4DWX. Since then the WRF core, data assimilation scheme, ensemble perturbation approaches, and ensemble output post-processing have been continuously improved. A second system was developed to support Xcel Energy for real-time wind energy prediction. And most recently, in working with the Chinese Electric Power Research Institute (CEPRI), the third system, a 30-member 9km-

grid E-RTFDDA model that covers the China-national domain, has been developed.

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.

FY2016 ACCOMPLISHMENTS

Achievements in E-RTFDDA development include further enhancement of the four-dimensional relaxation ensemble Kalman filter (4D-REKF) algorithms, the WRF version upgrades that involve evaluating and adopting the community WRF advances, implementation of an analog-based bias correction algorithm and a quantile-regression-based probability calibration scheme for statistical processing of the Army E-4DWX system, and a deployment of an E-RTFDDA system to support the power grid operation of the State Grid Corporation of China. The SGCC E-RTFDDA system contains 30 WRF members and its domain cover the whole China region at grid intervals of 9km. The system downscales ECMWF/IFS, NCEP/GFS, Canada/GEM and JMA/JSM global model forecasts to the WRF grids in combination of WRF physics and data assimilation perturbations. (Fig. 1). The system runs four forecast cycles per day and each cycle produces 72hour forecasts.

FY2017 PLANS

Development of E-RTFDDA will continue with efforts focused in the areas of ensemble-based 4D-REKF FDDA data assimilation, the model output statistical post-processing using the analog bias-correction and quantile regression calibration approach, including joint probability of specific variables and indices desired by end-users. The WRF SKEP scheme for dynamical ensemble perturbation and DART-EnKF for WRF initial condition perturbation strategies will be further evaluated and integrated for real-time E-RTFDDA operation. And finally, E-RTFDDA technology will be an essential element in new proposals U.S. and international sponsors.

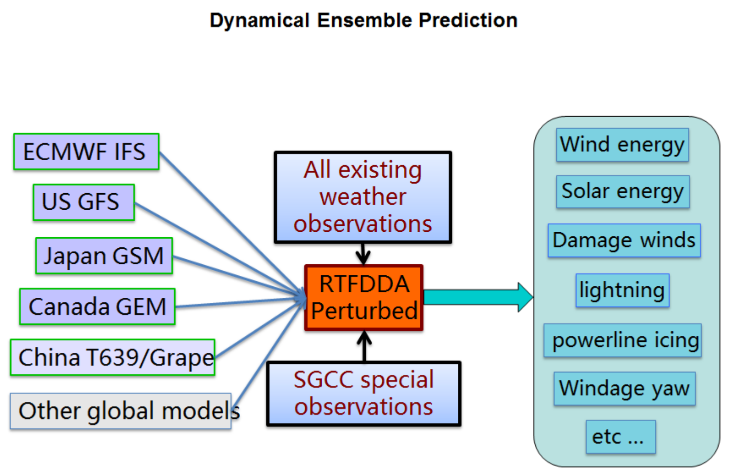

Figure 1. Design of the NCAR-SGCC China-national E-RTFDDA ensemble forecasting system.

‹ RTFDDA-3DVAR Hybrid System
up
Post-Processing ›

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POST-PROCESSING

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

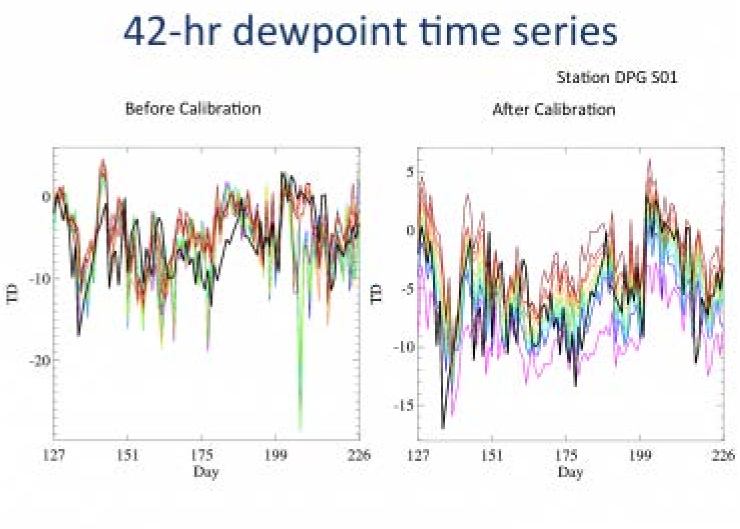

Figure 1: Quantile regression applied to dewpoint temperature at one station at the Army Test and Evaluation Command at the Dugway Testing Range in Utah, providing a probabilistic range that the dew point may fall within at a lead-time of 42-hr.

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.

QR is also a powerful approach for combining different forecast model outputs to generate one coherent and reliable probability distribution function of what the future weather will be. RAL scientists have merged medium-range ensemble rainfall forecasts from five global weather centers (Canada, China, ECMWF, US, Brazil) to calibrate and enhance the accuracy of rainfall forecasts over both East Africa and the Indian subcontinent, gaining 2- to 3-days in additional forecasting skill in the process.

ACCOMPLISHMENTS IN FY2016

- 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
- QR was used to generate ensemble predictions of river flow at hydrologic gauging stations in the Ganges and Brahmaputra river basins within India
- QR was applied to medium-, monthly-, and seasonal-range ensemble prediction of rainfall falling within select river basins in East Africa for water resource planning purposes

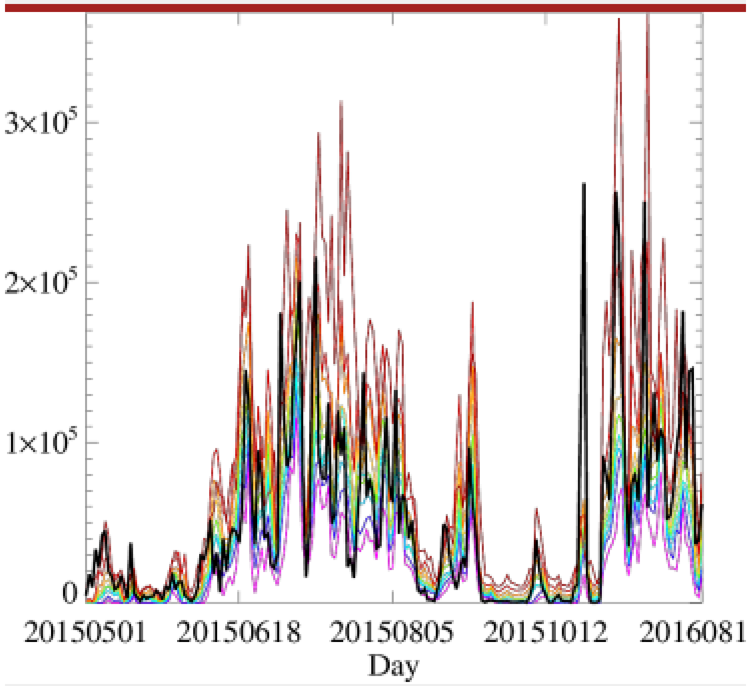

Figure 2: Quantile regression applied to Kosi river (India) basin-wide rainfall forecasts during 2015-6, blending forecasts from five global weather centers into one “grand global ensemble” for this particular basin, enhancing forecast skill out 2 to 3 additional days longer.

PLANS FOR FY2017

- 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.

‹ Dynamical Ensemble Prediction up Air Quality Forecasting ›

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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.

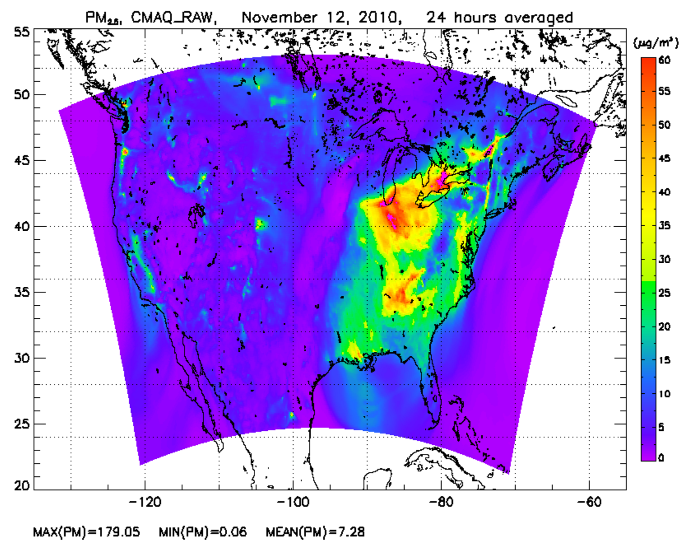
Air pollution across the world.

The National Center for Atmospheric Research (NCAR) works in collaboration with other agencies to develop new technologies that allow us 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.

RECENT ACCOMPLISHMENTS

In an effort funded by NASA, NCAR 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 the decision making activity in air quality management. The system is being set up over the USA but can be easily applied to any part of the world.



Fine particulate matter predictions over the US.

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). We will use GSI 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 $PM_{2.5}$ (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. The proposed effort will lead by NCAR, in collaboration with NOAA, CU

Boulder, and the University of Maryland.

PLANS

A first prototype of the GSI/CMAQ system, analog ensemble probabilistic predictions of ground-level zone and surface $PM_{2.5}$, and the corresponding gridded predictions will be 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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STATISTICAL AND DYNAMICAL MESOSCALE CLIMATE DOWNSCALING

- Analog Ensemble for Wind Resource Assessment

- Fine-Scale Seasonal Climate Prediction
- Global Climatological Analysis Toolkit

‹ Air Quality Forecasting up Analog Ensemble for Wind Resource Assessment ›

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ANALOG ENSEMBLE FOR WIND RESOURCE ASSESSMENT

BACKGROUND

As part of NASA and NREL funded projects, a new method has been proposed and demonstrated for the long-term estimate of the wind speeds at a target site, a key step in wind resource assessments (Vavyve et al. 2013, Zhang et al. 2015). Analog ensemble (AnEn) techniques have been used with success 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).

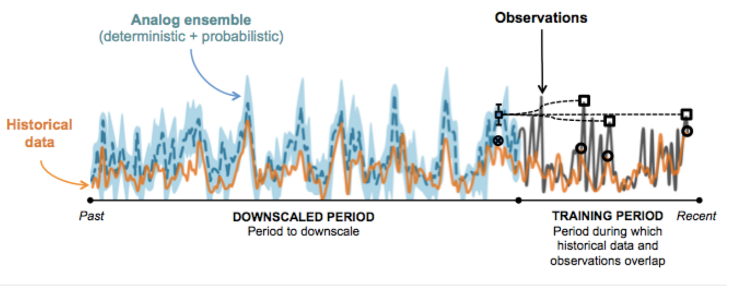

Figure 1 Sketch of the functioning of the analog ensemble method for one analog predictor, the analog trend reduced to one time step, and when retaining the best three analogs.

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*) 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 *analogs*) 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. Analogs 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):

- The AnEn can be used effectively for wind resource applications;
- The AnEn provides an accurate long-term wind resource estimate at target sites;
- The AnEn reliably quantifies the uncertainty allowing for cost-effective decision making;
- The AnEn is a computationally inexpensive method.

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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FINE-SCALE SEASONAL CLIMATE PREDICTION

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 of the fine scale details that are critical to regional and local climate-sensitive business and decision-makers. To fill that need, we are developing a fine-scale seasonal climate prediction capability through dynamical downscaling. A framework for fine-scale seasonal climate prediction has been set up. In this framework, the global large-scale seasonal forecasts issued by the Weather Service's Climate Forecast System (CFS) are applied to force the Weather Research and Forecasting (WRF) model. The version of the WRF model we use has been specially customized and configured for climate purpose. 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.

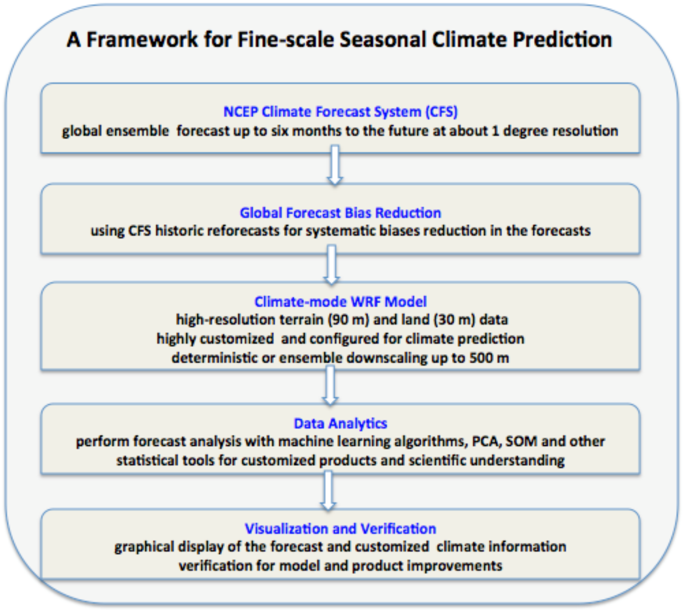

Figure 1. The framework for fine-scale seasonal climate prediction

RECENT ACCOMPLISHMENTS

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 the kilometer and subsequently verified with the local observations collected during the field campaign. The verification results show some predictive skills in the method.

PLANS

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.

‹ Analog Ensemble for Wind Resource Assessment up Global Climatological Analysis Toolkit ›

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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 climatography 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 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 has been implemented for execution for each dynamical downscaling simulation upon user request. This allows SOMs to 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.

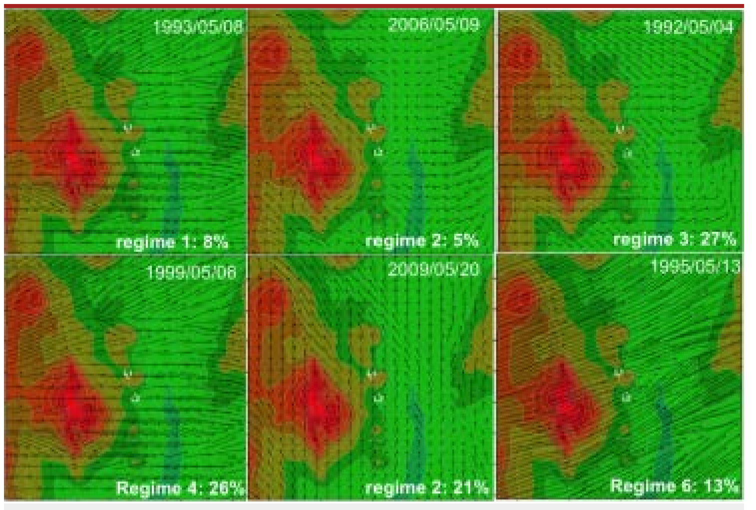

Figure 1. Typical days based on SOM classifications for downscaled historical flow during May over Socorro, NM.

FY2016 ACCOMPLISHMENTS

Updates to GCAT have been released in a new version. These include:

- Case Study capability: This functionality generates 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) data 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.
- SOM Classifier extension to 3D winds and stability parameters: Additional meteorological variables can now be chosen 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.
- Migration to HPCMP super computers: Transition of GCAT system to the DoD HPCMP system has been almost accomplished. A prototypal version of GCAT allowing only the "climo" capability has been developed.

FY2017 PLANS

Complete the migration to HPCMP super computers by transitioning the GCAT system to the DoD HPCMP system.

Additional tests to assess the potential value of using the Climate Forecast System (CFS) to classify the typical days as an alternative to the Climate Forecast System Reanalysis (CFSR) will be performed. Also, alternative WRF input name lists will be tested for specific applications involving simulations of the urban environment.

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ATMOSPHERIC TRANSPORT AND DISPERSION OF HAZARDOUS MATERIALS RESEARCH AND DEVELOPMENT

‹ Global Climatological Analysis Toolkit up Hazardous Material Source Term Estimation ›

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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.

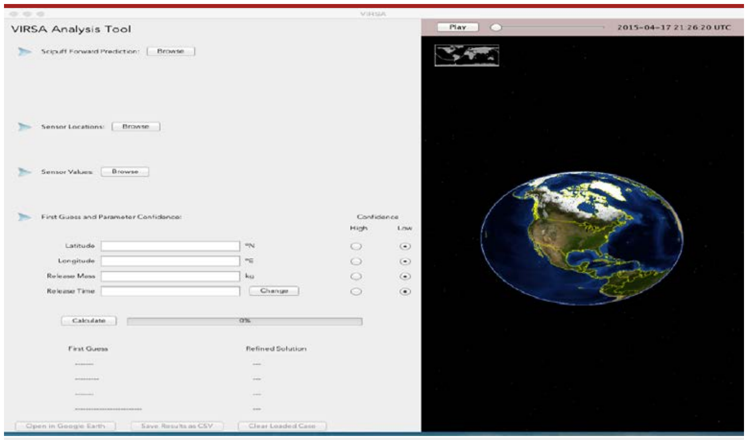

Fig. 1 illustrates an example of the graphical interface

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 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 FY201

Specific accomplishments since the last reporting period:

- Verified and validated VIRSA after Institute of Defense Analysis DTRA report delivery and concluded that the performance IDA observed was due to the concentration information degradation from the NBC messaging system.
- Added visualization to VIRSA standalone and delivered the standalone version of VIRSA v.2 to DTRA Reachback.
- Began testing the background error covariance methodology described in Fig. 2.

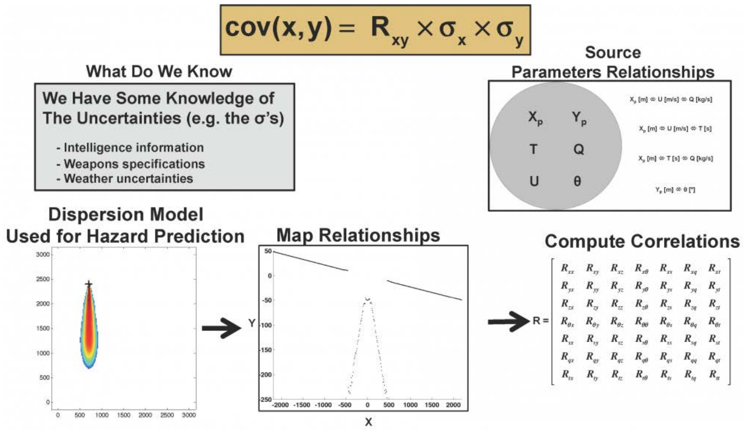

Figure 2 Background error covariance methodology

Plans for the coming year:

- 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 we plan on delivering VIRSA v.3 to DTRA Reachback.
- Add urban capability to VIRSA. We plan on using the Urban Dispersion Model (UDM) and the reverse UDM developed at the Defence Science and Technology Laboratory (Dstl) to upgrade our current VIRSA capabilities.
- 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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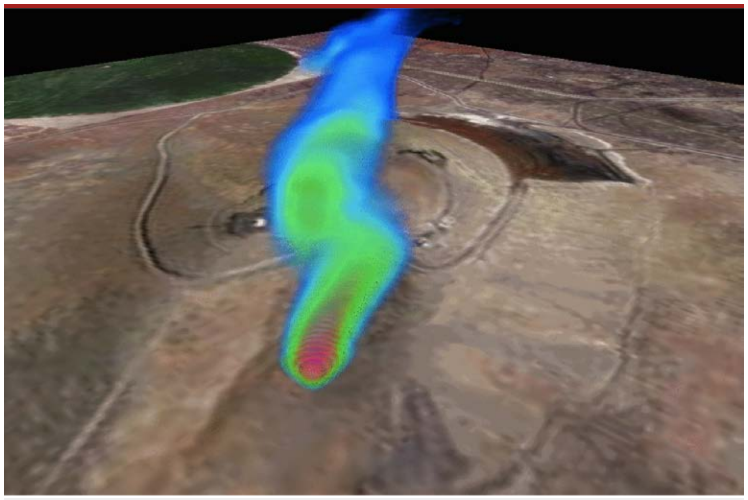
VIRTUAL ATMOSPHERIC DISPERSION FIELD TESTING



Virtual Threat Response Emulation and Analysis Testbed (VTHREAT)

In order to more robustly test and evaluate the evolving 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 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.

Plans for future work:

- Continue validation of the WRF LES capability.
- Utilize the VTHREAT display capability within a physical sandtable 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.

‹ Hazardous Material Source Term Estimation up Dense Gas Modeling ›

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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 (Cl_2) release and the downstream concentration field. The experiments were intended to assess the dispersion model formulations, assumptions, and predictions using the Cl_2 measurements. The JRI experiment was conducted in 2010 with 1- or 2-ton chlorine releases and JRII in 2015 with 5- to 9-ton releases, both experiments being conducted at the Dugway Proving Ground. A third experiment was planned for 2016.

In support of the DTRA activity, RAL/NSAP initiated a dense gas modeling effort in 2015 aimed at predicting Cl_2 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_2 concentrations.

ACCOMPLISHMENTS

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 200^3 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 concentration 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_i), and the source strength (Q) as a function of the scaled downstream distance X based on the friction velocity, distance x, U, and z_i . 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 fair to good.

PLANS

Work will continue 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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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 map high-dimensional data into a two-dimensional space. Using this, recurring patterns can be distinguished and the frequency of which those patterns occur 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, where 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 SOMs over the past few years and continues to improve and refine the analysis tools to produce increasingly better results.

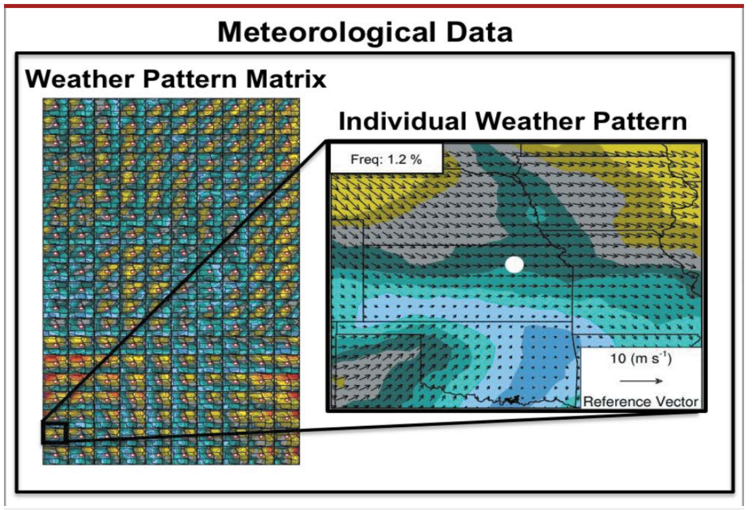

Fig. 1: Each node of the SOM map represent a single representative weather pattern and its frequency of occurrence within the entire training dataset.

FY2016 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.

FY2017 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 up
Numerical Systems Testing and Evaluation ›

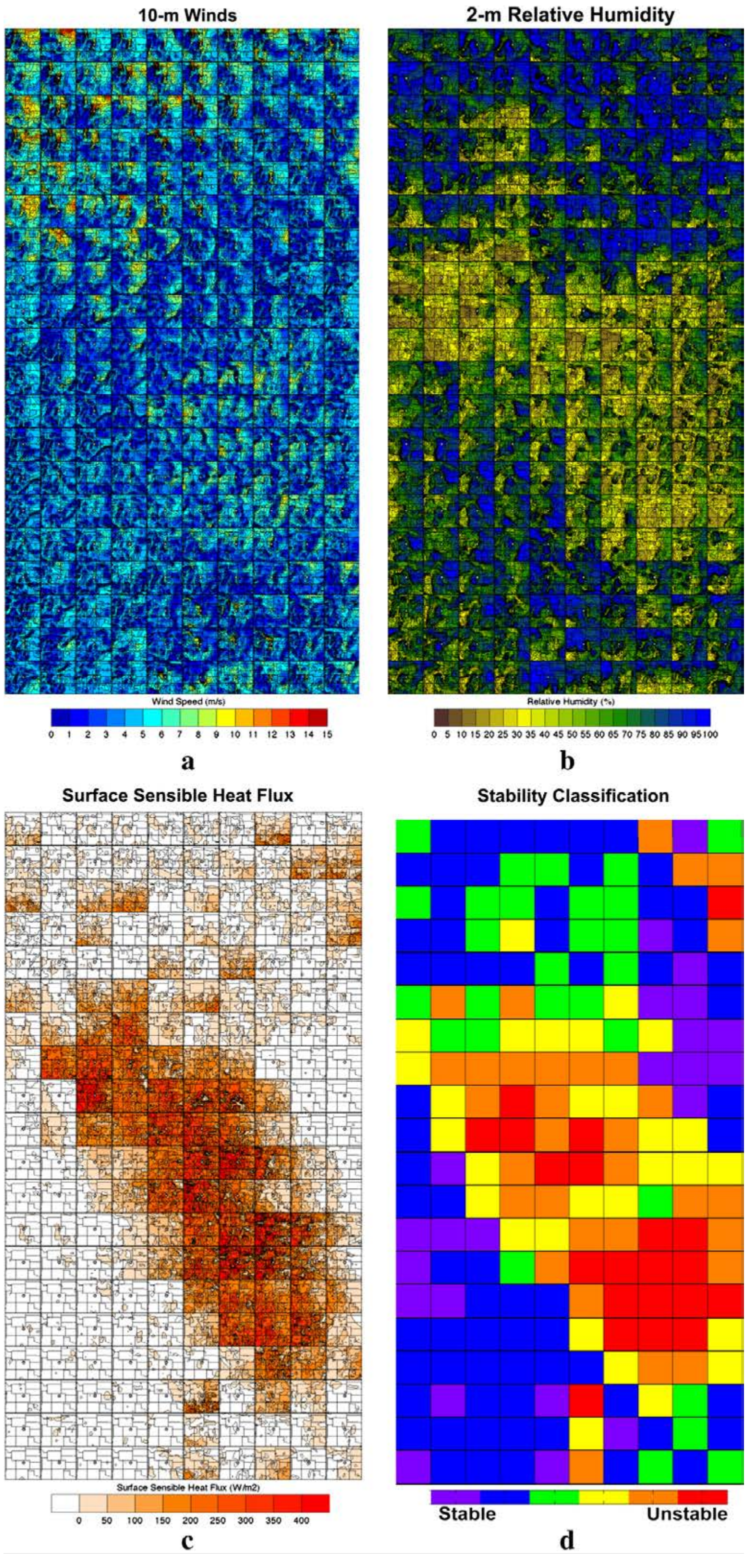

Fig. 2: The SOM matrix maps for relative humidity (a), wind speed (b), surface sensible heat flux (c), Pasquill stability categories (d).

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NUMERICAL SYSTEMS TESTING AND EVALUATION

Maintain and expand a central collaborative function within NCAR and a distributive network of collaborators for developing, testing, and validating numerical forecast systems important to operational decision makers and the international research community.

- Regional Modeling Systems
- Advanced Verification Techniques and Tools
- Data Assimilation
- Global Modeling
- Tropical Cyclone

‹ Climatological Dispersion Patterns with Self-Organizing Maps up Regional Modeling Systems ›

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REGIONAL MODELING SYSTEMS

BACKGROUND

Regional modeling activities in the Joint Numerical Testbed (JNT; http://www.ral.ucar.edu/jnt)) are focused primarily on the Developmental Testbed Center (DTC; http://www.dtcenter.org) activities, and real-time systems. The DTC is a distributed facility with components in the JNT at NCAR's Research Applications Laboratory (RAL), and the Global Systems Division (GSD) of NOAA's Earth System Research Laboratory (ESRL). It 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 regional forecasting systems, with a goal of accelerating the rate at which new 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

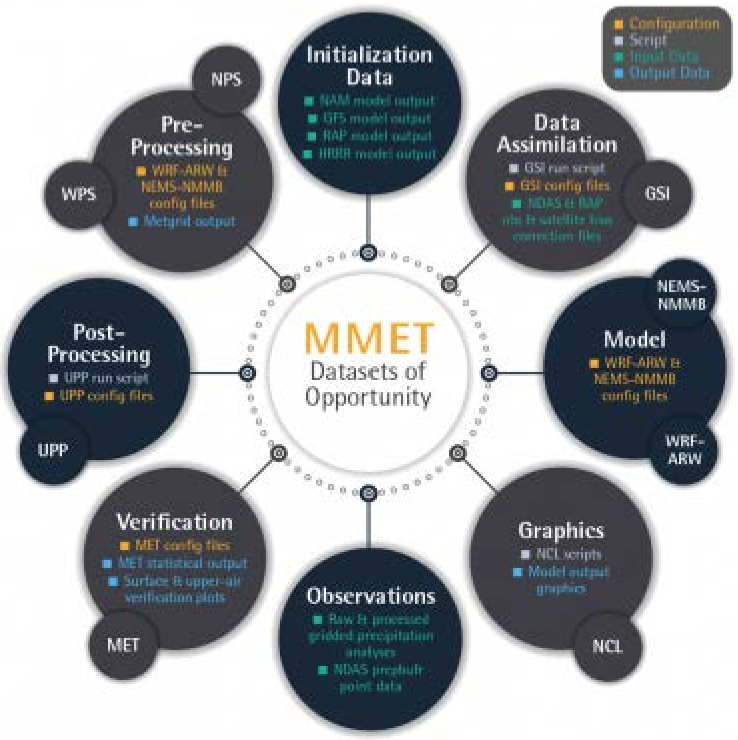

Figure 1: Diagram illustrating the MMET datasets of opportunity available to the user community from each step of the end-to-end process, including configuration files (orange), scripts (gray), input datasets (green), and output datasets (blue).

NWP technology, maintaining a state-of-the-art verification package, and connecting the NWP research and operational communities through its visitor program. In addition to DTC activities, JNT staff have been working on technology transfer in support of mesoscale weather prediction for the Colombian Civil Aviation Authority.

FY2016 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 (GFDL), National Aeronautics and Space Administration's (NASA) Global Modeling and Assimilation Office (GMAO), National Environmental Satellite, Data and Information Service (NESDIS), the University of Rhode Island (URI), and NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division (HRD). During 2016, 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-nmmb/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 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 (T&E)

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.

During 2016, the focus within the regional modeling group was on ensemble systems. In most existing regional ensemble systems, model-related uncertainty is addressed by using multiple dynamic cores, multiple physics suites, or a combination of these two approaches. While these approaches have demonstrated potential, it is time-consuming and costly to maintain such systems, especially in operations. In order to move toward a more sustainable and unified system, stochastic parameter perturbations within the High-resolution Rapid Refresh (HRRR) physics suite are being investigated with a current focus on planetary boundary layer (PBL) and land surface model (LSM) processes.

DTC staff members have worked to establish a test harness using the Rocoto Workflow Management System to conduct functionally similar end-to-end testing of the HRRR model in both a deterministic and ensemble mode. Model Evaluation Tools (MET) verification tasks to evaluate the deterministic and probabilistic forecast output have also been incorporated into the workflow. The inclusion of MET provides the opportunity to not only verify the final products, but to also iteratively adjust the ensemble design while examining how probabilistic statistics change when different approaches are utilized.

This T&E task has a high level of complexity given the need to run a frequently updating (hourly), high spatial resolution (3 km), large domain (CONUS) ensemble system. The work requires extensive high performance computing (HPC) resources which have been provided through the NCAR Strategic Capability (NSC) project. This has allowed for a more extensive set of tests to be conducted leading to more robust results than would otherwise be possible. This effort is on-going.

Mesoscale Model Evaluation Testbed

The Mesoscale Model Evaluation Testbed (MMET; http://www.dtcenter.org/eval/meso_mod/mmet) provides the opportunity for the research community to conduct their own T&E of a new technique. Datasets for a number of cases deemed to be of high interest by EMC are distributed via RAMADDA, a Repository for Archiving, Managing and Accessing Diverse DAta (http://ramadda.org/). The MMET datasets of opportunity (Fig.) include a variety of initialization and observation datasets as well as baselines for select operational configurations that were established by the DTC.

This year, a new aspect is being added to MMET. Operational model output for several NWP systems (both deterministic and probabilistic) are being evaluated and the objective verification scores will be provided to the research community through MMET as baseline results for comparison with the forecast performance of their innovation. Operational systems of initial focus include North American Mesoscale (NAM), Rapid Refresh (RAP), High-Resolution Rapid Refresh (HRRR), and Hurricane WRF (HWRF) models for deterministic forecasts and the Storm Scale Ensemble of Opportunity (SSEO) for probabilistic forecasts. For each deterministic model, MMET cases of high relevance are being determined (select MMET cases are being aged off and new, relevant cases are being identified) and operational data have been obtained. For the probabilistic forecasts, a multi-week period of SSEO data collected during the 2016 Hazardous Weather Testbed (HWT) Spring Experiment was gathered, and staged for distribution through RAMADDA.

Many times the biggest hurdle when running a new software system is getting it set up and compiled on the intended computer platform. Building complex systems that require a number of external libraries can be a prohibitive hurdle for users to overcome. In order to reduce some of this difficulty, software containers are being exploited to ship complete software systems to users. The containers have everything that is needed to run a software application, including the necessary operating system components (tools and libraries) and compiled executable (or code and compiler), thus, allowing for the user to quickly produce output without being delayed by technical issues. Currently, DTC staff members are creating UPP and MET containers to supplement those containers that had already been established by others in the community (including, WPS, WRF, and NCL) so that an end-to-end NWP system can be fully employed through containers. Along with the software containers, datasets that make up two Mesoscale Model Evaluation Testbed (MMET) cases are also being bundled in a container. By establishing these additional containers, the DTC will be assisting the user community (especially students) with efficiently running NWP components and making connections with future collaborators.

Real-time modeling systems

JNT has also participated in technology transfer in support of the Colombian Civil Aviation Authority's weather prediction needs. A prediction system based on the WRF model and GSI was developed and deployed in collaboration with Sutron/Meteostar, who is responsible for operational support and visualization. The work has leveraged JNT capability developed under DTC funding. Workflows based on Rocoto provide a stable and modular deployment environment. The high-elevation tropical weather of Colombia provides unique prediction challenges associated with deep convection and fog, and allow for evaluation in an environment not commonly studied. Retrospective testing and evaluation provide the basis for optimizing system configuration, and for measuring improvements from upgrades.

FY2017 PLANS

In the coming year, the JNT through the DTC will continue to support various community codes, including NWP systems, GSI and MET. The DTC will also help organize and support tutorials on the community codes that it supports, as well as on 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. In addition, efforts will continue related to evaluating deterministic and ensemble-based probabilistic model output.

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ADVANCED VERIFICATION TECHNIQUES AND TOOLS

BACKGROUND

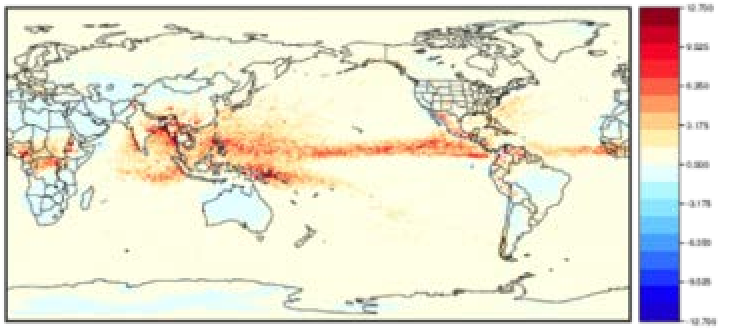

Figure 1: 90th percentile of differences between two operational models.

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.

FY2016 ACCOMPLISHMENTS

Spatial verification methods and the spatial method inter–comparison project

The initial forecast verification methods intercomparison project focused on comparing the capabilities of newly developed spatial forecast verification methods. That project was completed in 2011 and resulted in a special collection of articles in the journal *Weather and Forecasting.* A second intercomparison 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 meetings in September 2013, October 2014 (Vienna, Austria), September 2015 (Sofia Bulgaria) and most recently in September 2016 (Bologna Italy). The meeting was well attended by key researchers and operational forecasts from various centers/institutions in Europe, as well as Russia and China. 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 TN-505+STR (Dorninger et al., 2013).

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. Many improvements to SpatialVx were made based on feedback from MesoVICT participants, who have been using the software, at the MesoVICT workshop in Bologna. Initial results for the MesoVICT cases have been made in part because of the availablitiy of SpatialVx. One paper is now in press in the journal *Weather and Forecasting* (Gilleland, 2016, DOI: 10.1175/WAF-D-16-0134.1) that provides an initial analysis of MesoVICT Tier I cases.

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 MTD, was designed to track objects through time. Objects could range from proxies for convections (e.g. updraft helicity) to climate 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). During this year, MTD has been applied to several fields including probability of precipitation and probability of exceeding a given snowrate threshold. Figure 2 shows an example of MTD objects for probability of snowfall rate exceeding 0.5 inch per hour. Additionally, MTD objects were used for an investigation of forecast consistency using time series revisions.

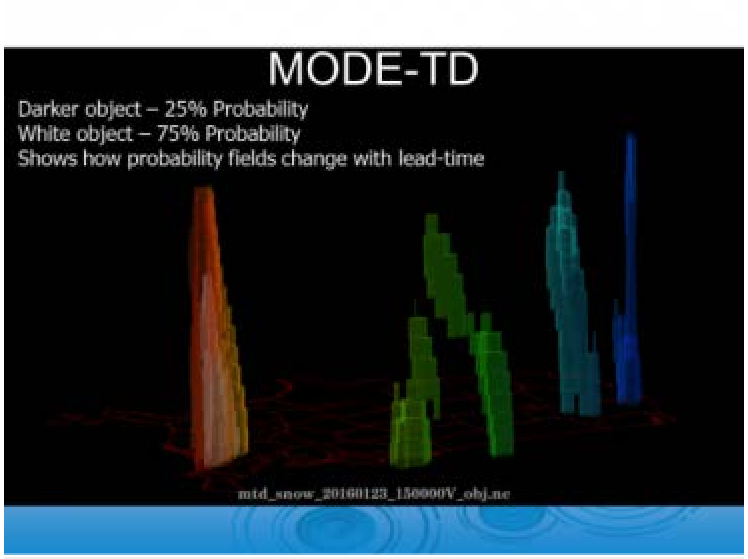

Figure 2. Example three-dimensional objects of ensemble derived probability of snowfall rate fields identified by MODE-TD. Lead time is decreasing with height. Colors range from blue for western objects and red for eastern ones.

MTD functions equally well on a series of forecasts with the same valid time from different model runs and thus, with decreasing lead times. The change in the forecast attribute from each time to the prior is the 'revision'. Thus, increases in the forecast are positive revisions and decreases in the forecast are negative revisions. Initially areal coverage of the probability of snowfall. Use of other object attributes is possible, depending on the forecast type.

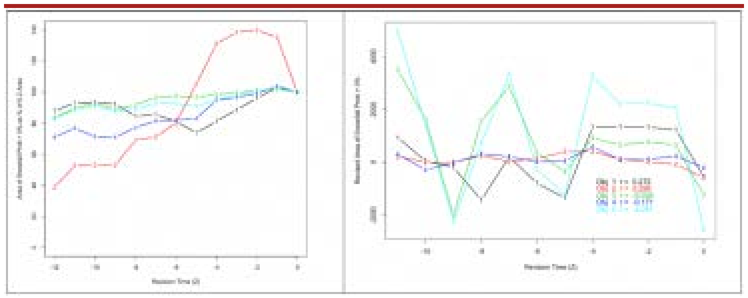

Figure 3: Left: Line plot showing area of each object as a percent of final object area for each individual object plus the entire domain (object 5). Right: Line plot showing area revisions for each individual object plus the entire domain. The autocorrelation value of each revisions series is shown in the legend. None are statistically significant, possibly due to the sample size typical of a single case study.

Figure 3 below shows the area of each object with decreasing lead time as a percent of the object area at the valid time (left). Object 2 stands out as having a distinct increasing trend. The right panel of Figure 3 shows the revisions in the area of each object from as the forecast updated. Visually, object 3 stands out as having some large, oscillating revisions. The autocorrelation and Wald Wolfowitz tests may be applied to identify significant trends in the revisions as well as measure the degree of randomness in the updating forecasts.

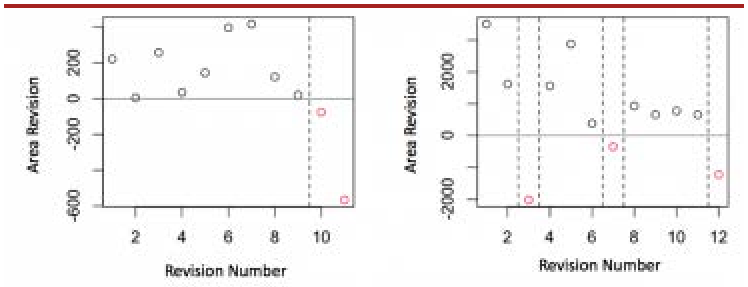

Figure 4 below shows how the direction of the change can be quantified into positives (+) and negatives (-) based on the revision series for an individual object. The examples here are from a single case study, for ease of interpretation. However, these metrics are easily extended to larger sets of cases. In this example, we grouped the four individual objects into object 5, covering the whole domain. This accumulation can also be accomplished across a set of forecasts to determine overall consistency and guide the forecaster on interpretation of forecast

Figure 4: Runs test graphic showing increases and decreases in

revisions. Additionally, forecasters are encouraged to provide consistent forecasts to the public unless large changes are warranted. Therefore, guidance with optimal consistency measures are more likely to be adopted by the forecast community.

forecast area revision series for objects 2 (left) and object 3 (right). Dashed lines delineate each run. Object 2 has only 2 runs and a p-value = 0.036, indicating a trend in the revisions. Object 3 has 6 runs with a p-value = 0.75, indicating randomness.

Evaluating solar forecasts

All components of the NCAR SunCast solar prediction system were evaluated routinely and thorough in-depth analysis for the final time in FY16. Evaluation of point forecasts for approximately 50 locations were performed for both Global Horizontal Irradiance and power. Traditional continuous statistics, such as the industry standard RMSE and MAE, were computed as well as categorical statistics for ramp events and statistics for probability forecasts coming from the Analog Ensemble method developed in RAL. Two NCAR Technical Notes were published from this project, including one on the metrics definition work performed earlier in the project (NCAR Technical Note TN-527+STR; Jensen et al., 2016) and the other on the entire project, including a lengthy section on the evaluation (NCAR Technical Note TN-526+STR; Haupt et al., 2016). Figure 5 shows the performance of the blended forecast at three different lead-time ranges (0-1hr, 1-3hr and 3-6hr) for several ramp event intensities (100-350 Wm^{-2} over 30 minutes). This shows the blended forecast was able to capture larger ramps at longer lead times.

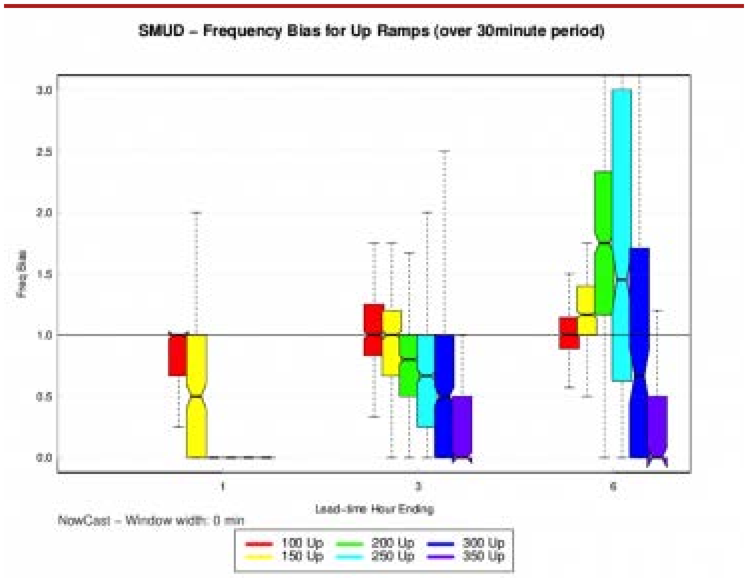

Figure 5. Frequency Bias for blended forecast at lead-time ranges of 0-1hr, 1-3hr and 3-6hr for several ramp event intensities from 100 (red) -350 (purple) Wm^{-2} over 30 minutes.

Cyclone-relative verification

New methods for evaluation of extratropical cyclones were developed in collaboration with Stony Brook University. The method uses the latitude and longitude of the center of an extra-tropical cyclone to identify and extract a user-defined tile around the cyclone. For extra-tropical cyclones, this may be as large as 30 degrees by 30 degrees. The centers of the cyclones may be found using cyclone tracking software. Statistics are then computed over numerous cases at every grid-point on tile while the exact location of the tiles is ignored. For example, the errors related to over-deepening and under-deepening storms may be computed to assess where there are systematic biases in the forecasts. Figure 6 shows an example of Bias, or Mean Error (ME), and RMSE in the Global Forecasts System (GFS) mean sea level pressure field at 60hr for cyclones traversing the continental United States (CONUS). Visual comparison between the forecast mean and observed mean indicate they are similar but computing the ME and RMSE show systematic biases on the northern and south-eastern portions of the storms.

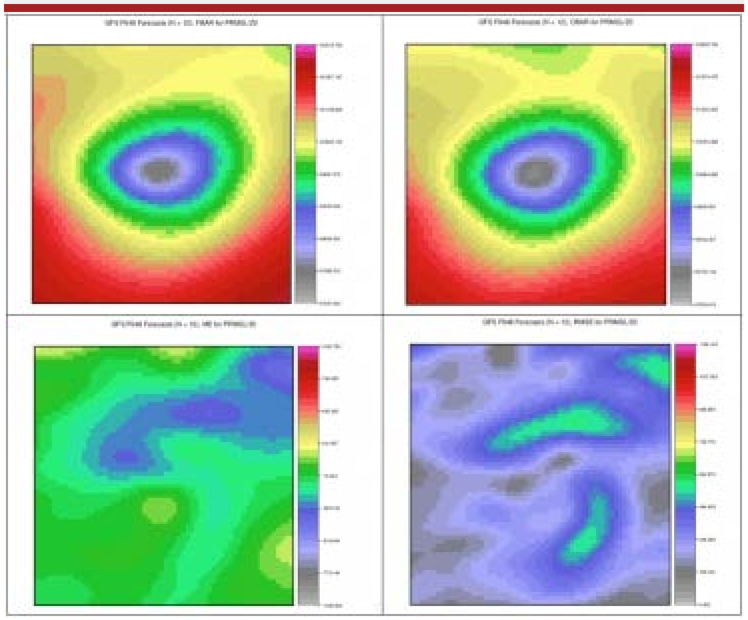

Figure 6. Example of mean forecast (top left) and observed (upper right) fields that were used to compute the mean error (Bias – lower left) and RMSE (lower right) computed from 30deg by 30deg tiles around the center of extra-tropical cyclones found in the GFS forecast and analysis fields.

Verification of Total Cloud Fraction

This year, NCAR worked with the Air Force 557th Weather Wing on exploring verification approaches for clouds. The primary focus of this study was total cloud amount (TCA) predicted by several forecast

systems and depicted in the Air Force World Wide Merged Cloud Analysis (WWMCA). The methods considered for evaluation of TCA include traditional continuous and categorical verification methods as well as the spatial verification methods, such as Method for Object-based Diagnostic Evaluation (MODE) and measures based on binary images (Figure 7). The spatial methods can provide more meaningful information about forecast performance, which would not be subject to the double-penalty problem associated with traditional grid-matching approaches. Results of the analyses indicate that both the traditional approaches and the spatial methods provide useful information and should be included in a standard verification toolbox for clouds.

Among the traditional approaches, the categorical methods – which consider important events (e.g., clear conditions, cloudy conditions) defined by examining situations where a threshold is crossed – can provide more meaningful performance information (in general) than the continuous approaches. Displays such as performance diagrams (see Figure 8) were used to simultaneously consider multiple related measures.

Among the binary images and distance metrics it was found that the Baddeley's Δ metric (Baddeley 1992a,b) gives a useful overall summary of how well, in the present context, two cloud-amount products compare in terms of size, shape, orientation and location of clouds. Mean error distance (MED) gives useful information but is sensitive to small changes in the field and also violates the symmetry requirement in order to be a true mathematical metric. The asymmetry of MED can be capitalized upon in order to glean information about false alarms and misses (Gilleland 2016). AghaKouchak et al. (2010) introduced three useful geometric indices for spatial verification purposes: (i) area, (ii) connectivity, and (iii) shape. Where MED informs about false alarms and misses, it does not inform about the patterns of these errors. The geometric indices, on the other hand, do inform about such patterns, and therefore provide complementary information.

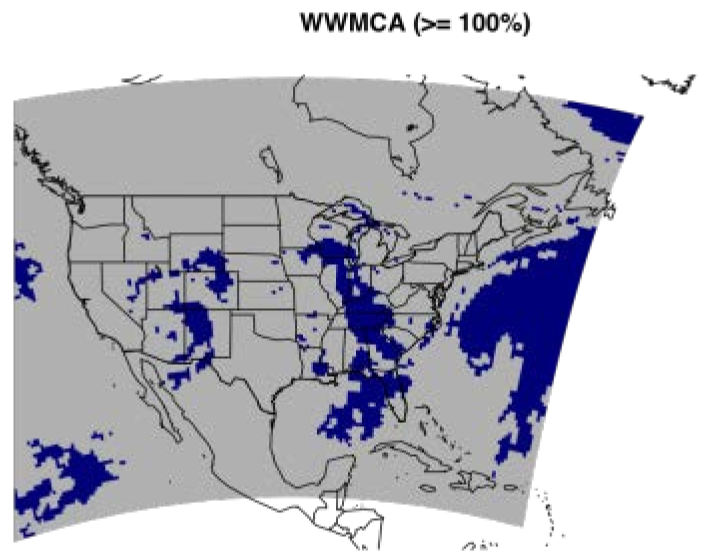

Figure 7. WWMCA areas of cloud amounts of 100% on 8 January 2016 at 0300 UTC.

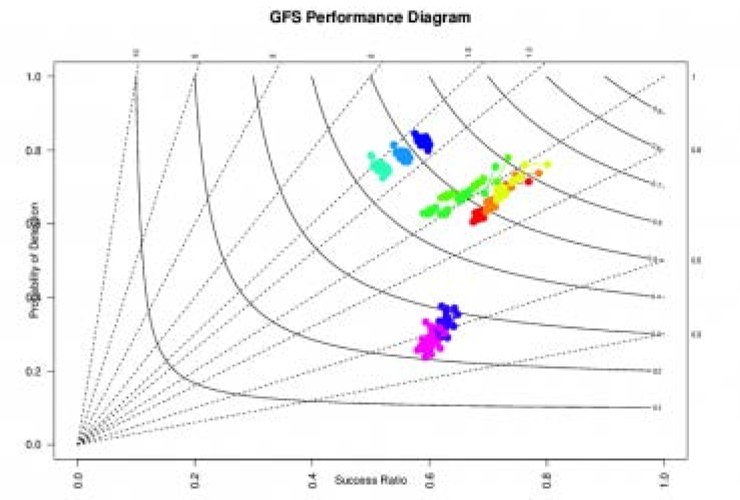

Figure 8. Performance diagrams for GFS raw (purples and blues) and bias-corrected forecasts (red, yellow and green) for several thresholds. Individual points represent different lead times.

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/JNT staff. METv5.2 was released to the community in August of this year. It includes a multitude of enhancements to the already extensive capability. Nearly 250 additional users registered to download MET in FY16 placing the total registered users at approximately 3150. The user base is predominantly university researchers, both international and US-based. The METViewer database and user interface software were updated to accommodate additional capabilities released in METv5.2 as well as to continue to provide a more streamlined and intuitive interface. The METv5.2 release includes better handling of GRIB files and the World Wide Merged Cloud Analysis product from the Air Force. Grid-area and cosine latitude weighting was added for evaluation of global or large domain datasets. It also has new capabilities to help with event-relative verification and enhancement to MODE to run multiple thresholds in one call. METv5.2 is available for download at

http://www.dtcenter.org/met/users/downloads/index.php.

MET+

RAL staff have started working with National Center for Environmental Prediction (NCEP)/Environmental Modeling Center (EMC) on unifying the verification system between the two organizations through MET and METViewer. NCAR staff visited with EMC for a week during early May. They conducted 18 meetings with approximately 50 EMC staff to discuss their current verification practices and immediate needs. The results of the meetings were summarized in a requirements document that was released to all participant as well as the EMC Director in September 2016. The RAL verification team is using this information to develop a unified verification system, called MET+, through NGGPS funding outside of the DTC. Briefly, MET+ is a set of python wrappers to simplify set-up and running of MET, allow researchers to leverage their own unique algorithms, and systematically plot the fields and results.

FY2017 PLANS

There will be a major release of MET (v6.0) in Q2 of FY2017 and a minor release (6.1) in Q3. METv6.0 will include support of NetCDF data model 4, many new statistics to support the unified verification effort. There will also be support for evaluating forecast consistency and new spatial methods based on distance maps. Additional support of calculating scores using reference or climatological fields will also be explored. METv6.1 will include additional enhancements necessary for the unification. Also, the database within METViewer will undergo refinements to optimize for “big data” and many users. Additional spatial verification methods will be explored through the MesoVICT project and added to SpatialVx and, if applicable, MET.

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DATA ASSIMILATION

BACKGROUND

The goal of the Data Assimilation Team (DAT) is to provide a pathway between data assimilation research and operational communities to help accelerate transitions from research to operations. Working closely with research and operational centers, 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).

FY2016 ACCOMPLISHMENTS

Code Management and Community Support

The DAT currently maintains the code management framework for and provides centralized community support of the following data assimilation systems:

- Gridpoint Statistical Interpolation (GSI) system
- Ensemble Kalman Filter (EnKF) system

The GSI system was originally developed by the National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC), designed as a traditional three-dimensional variational (3DVar) data assimilation system. Under the community framework maintained by the DAT (under the auspices of the DTC) and EMC since 2009, GSI has evolved into a community data assimilation system with various data assimilation techniques, including 2DVar, 3DVar, the (hybrid) Ensemble-Variational (EnVar) technique, and 4DVar (if coupled with the ***National Aeronautics and Space Administration (NASA) global model)***. The EnKF system is a Monte-Carlo algorithm for data assimilation that uses an ensemble of short-term forecasts to estimate the background-error covariance in the Kalman Filter. It was originally developed by the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL). The DAT started supporting the EnKF system to the research community in 2015. The GSI and ENKF are currently the operational data assimilation systems for the NCEP Global Forecast System (GFS). GSI is also used by other operational systems/models, e.g., the North American Mesoscale (NAM) forecast system, the Hurricane Weather Research and Forecasting (HWRF) system, the Rapid Refresh (RAP) system, the Goddard Earth Observing System (GEOS), etc.

In FY16, the DAT continued to maintain the community code repository for GSI and EnKF, and performed code reviews for each proposed code update. Through this repository, the DTC released GSI version (v)3.5 and EnKF v1.1 to the public in August 2016. In addition to the regular maintenance, the DAT initiated efforts to work with the DTC NOAA partners and EMC developers to improve user interfaces, including efforts to unify the code build tool for GSI, EnKF, and NCEP input/output (I/O) libraries.

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. In the past fiscal year, the DAT took various measures to enhance community user support. The helpdesk service was enhanced by transitioning to a Request Tracker (RT) ticketing system with better tracking of users' requests and questions. The DAT also provided new online tutorials for both GSI and EnKF in FY16. Testing cases were carefully selected with new testing periods and domains, covering updated and additional configurations with alternative data assimilation techniques (3DVar, 3D hybrid, 4D hybrid EnVar), data types (conventional and satellite radiance data), and forecast models (ARW, HWRF, NMMB, WRF_chem, GFS).

The DAT continued to coordinate the GSI/EnKF development among distributed developers, and hosted a DA review committee meeting on 26 April, 2016. In this meeting, the Joint Center for Satellite Data Assimilation (JCSDA) was accepted as the new member of the committee, joining NCEP/EMC, NOAA/ESRL, the NASA Global Modeling and Assimilation Office (GMAO), NCAR, the National Environmental Satellite, Data and Information Service (NESDIS), the University of Maryland, the Air Force, and the DTC.

Development and Testing and Evaluation

Testing 4D EnVar For Regional Applications

One focus of the DAT FY16 efforts was testing the state-of-art data assimilation technique, 4D EnVar, for Advanced Research WRF (ARW) based regional applications. The goal of this task is to examine the readiness of the GSI EnVar system for regional forecast systems, and provide an assessment of potential working areas for further improvement. Currently, all NOAA regional operational forecast systems use the GSI 3D hybrid EnVar technique for atmospheric data assimilation. In this effort, the DAT built an experimental GSI 4D hybrid EnVar data assimilation system, performed various experiments to

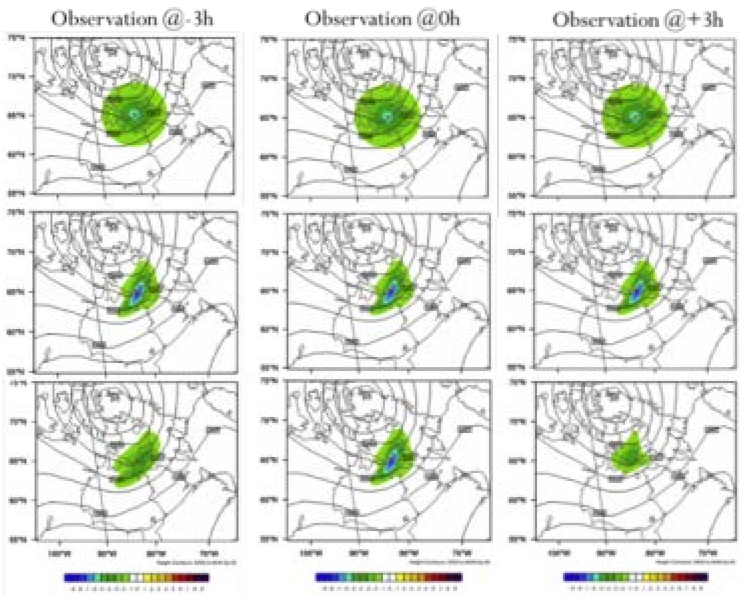

Figure 1. Temperature analysis increments from the pseudo-single observation tests for 3DVar (upper panels), 3D hybrid EnVar (middle panels), and 4D hybrid EnVar (lower panels). One single temperature observation was set at -3h (left column), 0 (middle column) and +3h (right column) within a 6h time window.

investigate the EnVar capability, and evaluated its impacts on analyses and forecasts.

Tests include executing single observation tests, tuning the observation and ensemble/static error contributions for hybrid data assimilation, and evaluating the merits of using regional ensembles for EnVar instead of using global ensembles (the default for the NCEP operational systems). Figure 1 shows the temperature analysis increments from pseudo single observation tests performed using the GSI EnVar system with the 3DVar, 3D hybrid EnVar, and 4D hybrid EnVar techniques, respectively. One single temperature observation was set at -3 h, 0 and +3 h within a 6 h time window. The results show that the analysis increments of the 4D EnVar experiments vary with the observation time, while the 3DVar and 3D hybrid experiments do not present any time-variant information. Both 3D and 4D EnVar experiments capture the flow-dependent features for the analysis fields due to the incorporation of ensemble-based background errors.

The DAT coupled the experimental GSI 4D EnVar system with ARW and performed three sets of experiments for a two-week period to evaluate analyses and forecasts:

- 3DVar
- 3D hybrid EnVar
- 4D hybrid EnVar

GFS observations and ensembles were used for these experiments. Figure 2 shows the root mean square errors (RMSEs) of analyses and 6 h forecasts for humidity and wind fields. The 4D hybrid EnVar results show reduction of RMSEs for most of layers. It was also found the 4D hybrid technique helps the convergence of the cost function, with smaller cost function values achieved at the end of the minimization loops. The DAT also investigated computational costs of these three experiments. One 4D hybrid EnVar run presents a 40% increase of the computational wall-clock time over a single 3D hybrid EnVar run (using 384 processors on NCAR's Yellowstone computer).

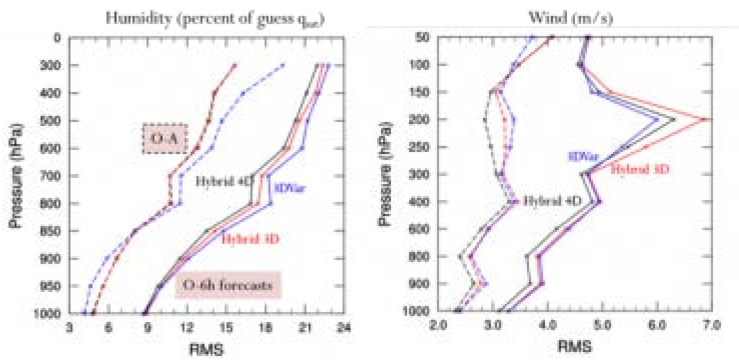

Figure 2. Vertical profiles of the RMSEs of humidity (left) and wind (right) analyses (dashed lines) and 6h forecasts (solid) from three experiments: 3DVar (blue), 3D hybrid EnVar (red), and 4D hybrid EnVar (blue).

The DAT applied the 4D hybrid EnVar technique to an operational system, the hourly RAP system, in order to provide a reality check for implementing this technique, since many operational systems have application dependent configurations not generally used by a research model, e.g., RAP using 2-m temperature/10-m wind for near-surface data assimilation. The DAT examined the results and

provided a summary. All these experiments and results are described in a final report, which can be found at http://www.dtcenter.org/eval/data_assim/4denvar/rap_15km/.

All-sky radiance assimilation research and development

The DAT has also been testing proposed methods to assimilate cloud-affected infrared and microwave radiance measurements. Those measurements are often not assimilated because of the large errors in both the observations and the model background field, and the potential for strongly nonlinear forward operators. With the overall goal of improving cloud analyses and very short term forecasting, the team has been evaluating the following: (1) observation error models and an outer loop to allow more observations to affect the analysis, (2) tradeoffs between ensemble and static background error covariances in the hybrid, and (3) strengths and weaknesses of different instruments such as the Global Precipitation Measurement (GPM) Microwave Imager (GMI) and the Cross-track Infrared Sounder (CrIS). Promising developments are being merged with the GSI trunk.

FY2017 PLANS

The DAT, in collaboration with developers, will continue its GSI and EnKF code management and community support efforts to facilitate the transitions from research to operations. The DAT plans to organize a tutorial for these two systems in the summer of 2017. The DAT will continue its 4D EnVar tests in a high-resolution hourly cycling forecast system. Working with university collaborators, the DAT will extend the GSI system to include capabilities to assimilate ionospheric observations from the *Global Navigation Satellite System* (GNSS). The DAT also plans to evaluate the quality of the commercially provided GNSS radio occultation data and its impact on the skill of NCEP weather forecast models.

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GLOBAL MODELING

BACKGROUND

A research to operations (R2O) initiative has been established by NOAA to upgrade the current operational Global Forecast System (GFS) to run as a unified and fully coupled Next Generation Global Prediction System (NGGPS). NOAA's long term plan seeks to integrate the capabilities of its short-term (GFS), ensemble (GEFS), and sub-seasonal (CFS) NWP applications under the infrastructure of NGGPS. A key challenge during this process is to develop a common physics infrastructure that works across all temporal and spatial scales as well as to accommodate an efficient R2O pipeline that effectively uses the expertise in both the research and operational communities. As part of this effort, the Global Model Testbed (GMTB) team was established within the Developmental Testbed Center (DTC) to facilitate community involvement in the development of NGGPS through several avenues: contributing to select aspects of code management and infrastructure for the community to

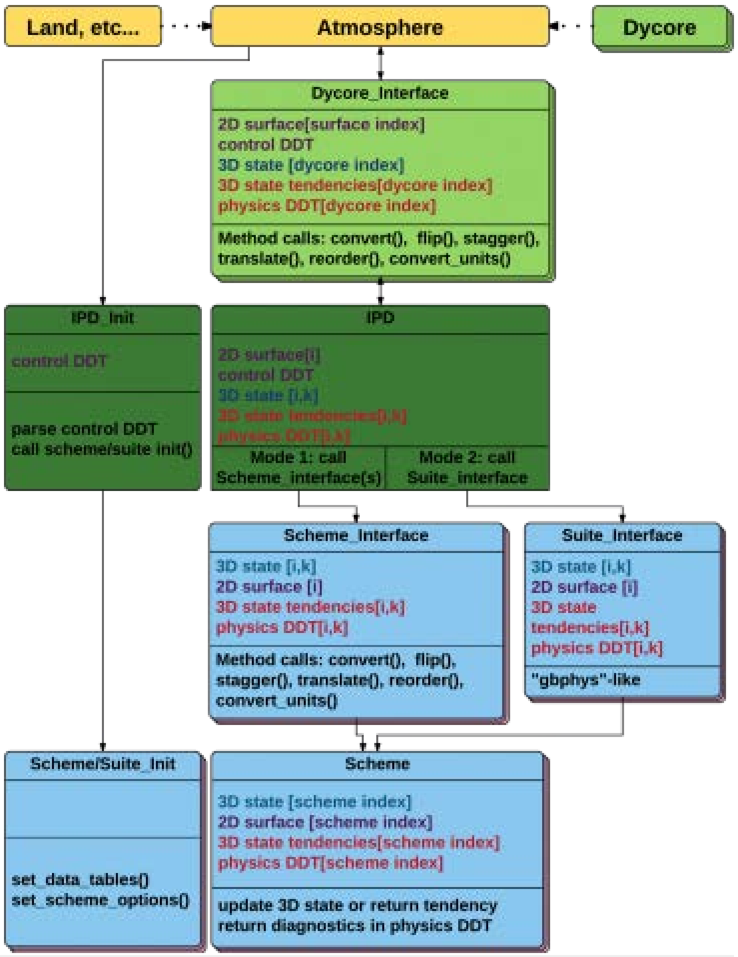

Figure 1: Design of a generalized IPD capable of interfacing with multiple dycores and multiple physics suites together with a representation of how it interacts with schemes and suites within the CCPP.

interact with the code system, supporting a hierarchical testing framework to NGGPS developers, and facilitating and performing testing and evaluation of innovations for the operational system. The GMTB consists of scientists and software engineers within RAL's Joint Numerical Testbed Program (JNTP) who take active roles in supporting R2O for global numerical weather prediction (NWP) by closely collaborating with NOAA's Environmental Modeling Center (EMC) and the research community to develop an Interoperable Physics Driver (IPD), a Common Community Physics Package (CCPP), and a physics testbed.

FY2016 ACCOMPLISHMENTS

Interoperable Physics Driver (IPD) and Common Community Physics Package (CCPP)

A modular physics suite accessible both in-line as part of a prediction model, and off-line for isolated testing, will enable physics innovation and contribution from the broader community. In response to this need, the DTC and NGGPS put forth the concept of a Common Community Physics Package (CCPP) coupled with an Interoperable Physics Driver (IPD) that would be setup and maintained by GMTB to facilitate efficient and effective collaborative development of next generation physics suites. Although a one-way IPD was developed by EMC and used for the NGGPS Dynamical core Test Group (DTG), an IPD with two-way interoperability that can be easily used with all schemes and suites of the CCPP needs to be developed for the vision of the CCPP to be realized. Significant progress was made during FY2016 toward this goal. In the spring of 2016, the GMTB worked with EMC and the NUOPC Physics Interoperability group to assemble a document that lays out requirements for the IPD beyond the first version's capabilities, and by the end of FY2016, a software design (visualized as figure 1) that meets those requirements was created and disseminated to working partners for further collaboration.

Progress toward the realization of a CCPP included the delivery of a document describing its goals and requirements, comprehensive documentation of the GFS physics suite (the foundational member of the CCPP) and the one-way IPD developed by the DTC in partnership with EMC, and an initial attempt at defining the process for physics development to be considered for inclusion into the CCPP as shown in Figure 2.

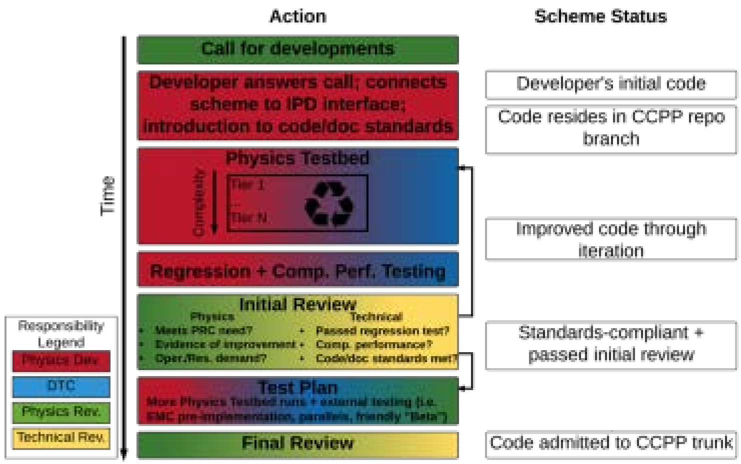

Figure 2: Proposed workflow for CCPP inclusion.

Hierarchical Testing

To facilitate the development of an advanced physics suite for NGGPS, the JNTP, working through the DTC, is developing a uniform 'test harness' to enable in-depth investigation of various physical parameterizations. The principal purpose of this physics testbed is to assist the research and operational communities in streamlining the testing process to accelerate the transfer of worthy improvements into operations. The testbed should see use as both a tool for physics developers to display merit and further improve upon their schemes and as an addition to EMC's physics development decision-making arsenal. The test harness represents the logical progression for testing newly developed parameterizations that typically takes place within the scientific community. Components and complexity are gradually added and iterated upon as one moves through the hierarchy until the full forecast model complexity is reached. The hierarchy is designed to complement both the existing testing protocol at operational centers and independent testing typically performed by parameterization developers. The natural sequence of testing new physics schemes tends to follow tiers of progressively difficult and computationally intensive model runs as merit warrants, and the GMTB testbed mimics this progression. Figure 1 illustrates the different hierarchical tiers and represents how the GMTB envisions the division of responsibility. Initial efforts of the GMTB have been placed on developing a Single Column Model (SCM) and establishing the capability to run the Global Spectral Model (GSM) within a contained workflow.

A primary focus of GMTB is to create information that can be used for an evidence-based decision making process at EMC. To demonstrate the hierarchical testing capability of GMTB, a testing and evaluation effort is underway to compare a control configuration [using the GFS operational convective scheme, Simplified Arakawa Schubert, which is based on the work of Arakawa and Schubert (1974) and Han and Pan (2011)] against an experimental configuration using a more advanced scale-aware convective parametrization, the Grell-Freitas scheme (GF; Grell and Freitas 2014). While this demonstration is still underway, it will be executed using the SCM and the workflow for global forecast tiers of the testing hierarchy, both described in more detail below.

Single Column Model (SCM)

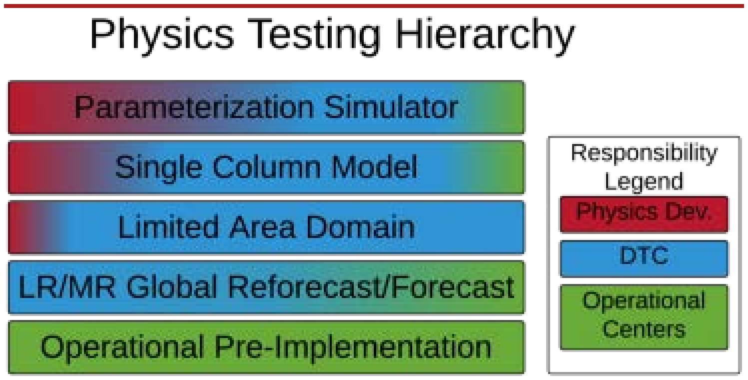

Figure 3: Diagram representing the structure of the physics testbed,

As part of the GMTB Physics Test Harness, a SCM that makes use of the IPD has been developed and lightly tested using two GEWEX GASS cases. The code base resides on NOAA's VLab for easy dissemination to testing partners. Design of the model focused on community-friendliness by minimizing external dependencies and using community-sanctioned coding practices. Using the SCM only requires the cmake utility for building (utilizes automatic dependencies) and the fortran netCDF library (I/O) to be installed and accessible. Python and some of its standard scientific libraries are required for the plotting/analysis routines. The operational GFS physics source code is bundled with the SCM source code, but managed as a separate repository. This structure allows for

starting with simple methods and progressing to more complex and resource-intensive methods. Colors denote the proposed division of labor among the interested parties.

swapping of various modified versions of the GFS physics suite as appropriate for testing purposes. The code is updated occasionally to work with the top-of-trunk GFS physics code, although it will likely only support specific, tagged versions of this code in the future. Testing of the code has been successful on two machines -- a late model Macintosh and NOAA's Theia HPC R&D machine. In addition, a GMTB SCM User's Guide and technical documentation was developed with Doxygen and is available to access on DTC's website.

The "catalog" of cases to use with the SCM is a work-in-progress, with one shallow convective case based on the transition from stratocumulus-to-cumulus as observed during the ASTEX field campaign and one deep convective case as observed during the TWP-ICE field campaign. Both cases are initialized and forced based on observations made during their respective field campaigns. Although both cases use horizontal advective tendencies with prescribed vertical motion, it is possible to configure the SCM to use total advective tendencies and relaxation forcing as described in Randall and Cripe (1999). Basic plotting routines are available to compare SCM output to observations for some basic fields (u, v, T, q, precipitation, surface fluxes) as well as to plot profiles of tendencies due to individual physical parameterizations. Evaluation and analysis tool development is ongoing and will remain responsive to the needs of operational and research users.

Workflow for Low-Resolution/Medium-Resolution Global Forecast Mode

To facilitate three-dimensional testing that provides information about the interaction between the physics packages and feedback on the large-scale flow, the GMTB assembled an end-to-end workflow for the atmospheric component of the GFS [Global Spectral Model (GSM)] which also includes post-processing, comprehensive verification, and production of graphics. Running the global model at medium-to-coarse resolutions will allow the researchers and developers to ensure their contributed physical parameterization are able to appropriately connect to the global model producing realistic solutions. The GMTB heavily leveraged the scripts, configuration files, and source codes provided by EMC to establish an initial capability of running free forecasts of the GSM, including post-processing, within an automated workflow.

To visualize and analyze the model output, a flexible and portable graphics suite is being actively developed using Python to plot a number of basic meteorological fields. The current framework includes making it straightforward to add diagnostics as they become available as well as providing users the ability to specify different forecast times, regions, and grids to plot. The verification portion of the workflow is being configured to replicate key functionality of EMC's verification package (e.g., near-surface, upper-air, and precipitation verification) as well as provide additional, more advanced verification metrics (e.g., fractions skill score). Forecast verification statistics are calculated using the DTC's Model Evaluation Tools (MET) and METViewer (a GUI used to aggregate and visualize output from MET). The use of MET is relevant because it has been selected by NGGPS as the framework under which the current EMC, DTC, and NOAA's Earth System Research Laboratory (ESRL) verification tools will be unified. In addition to graphics and verification, additional diagnostic tools are being made available. Through a number of avenues, the GMTB solicited input from model physics experts to better understand the spectrum of diagnostic and verification tools that would be most beneficial to include in the testbed. The solicitation provided GMTB with a variety of ideas as well as highlighted the usefulness of having a centrally-located area with tools for physics developers to assess strengths and weaknesses of new physics innovations. This capability will include basic diagnostics to show the global-scale impacts of a new physics scheme.

Documentation for the global workflow, including diagrams of the workflow, description of the setup, configuration options, and I/O, is actively being written and maintained. In addition, similar to the SCM, a Git repository has been set-up to reside on NOAA's VLab to manage the diagnostic and verification workflow and scripts that are currently being developed and used by the GMTB.

FY2017 PLANS

The IPD design will be used to develop an incremental implementation plan for evolving the current IPD and GFS physics into an IPD/CCPP package that will minimize the impact of the IPD development on the on-going operational physics development and the two-way IPD software engineering will begin. The scientific and technical review bodies for guiding the CCPP will be created and the process for physics evaluation for inclusion into the CCPP will be finalized.

Continued work is currently underway to expand the capabilities in the physics testbed in order to equip physics developers with a wide spectrum of tools to assess strengths and deficiencies of physics parameterizations. Work will begin on fleshing out the parameterization simulator and limited-area domain tiers of the testbed with the inclusion of EMC's surface layer simulator, the capability to run FV3's set of idealized test cases, and perhaps the inclusion of an LES to generate synthetic data with which to evaluate SCM results. Capabilities will be added to the SCM including a broadened case catalog and the ability to be forced from GFS model output. With respect to the global workflow, the GMTB is looking to include the calculation of time-integrated tendencies, sub-grid fluxes, cloud properties, conservation of select fields, and using synthetic satellite output to evaluate the model's ability to accurately simulate clouds. The GMTB intends on being responsive to user needs and will be amenable to community input regarding additional tools to add to the testbed as well as include community contributions.

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TROPICAL CYCLONE

BACKGROUND

RAL's Joint Numerical Testbed Program has several activities related to tropical cyclones (TC). These will be described below as they relate to the Developmental Testbed Center (DTC); the Tropical Cyclone Modeling Team (TCMT); the Tropical Cyclone Guidance Project (TCGP); and the Tropical Cyclone Data Project (TCDP).

The Developmental Testbed Center works closely with 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.

The focus of RAL's Tropical Cyclone Modeling Team is testing and evaluation of experimental models for tropical cyclone forecasting. Currently, the primary sponsor of the TCMT is NOAA's Hurricane Forecast Improvement Project (HFIP). In coordination with the HFIP teams, the TCMT collects, evaluates, and provides results of tropical cyclone track forecasts to the broader HFIP community. Statistical approaches and new graphical displays are developed by the TCMT. Current efforts

are focused on methods of evaluation for ensemble tropical cyclone forecasts of rapid intensity change and development of a specialized display and diagnostic evaluation system for use at the National Hurricane Center.

TCGP provides real-time visualizations of TC track and intensity guidance through an outward-facing web page that receives millions of hits each year. TCGP also collects real-time tropical cyclone guidance data from numerical prediction centers around the world and collates these data into a publicly-available global repository of TC forecast aids. The site is widely used by forecasters, emergency managers, government agencies (e.g., NOAA, FEMA, DHS), private-sector firms (e.g., ship-routing, transportation and logistics, energy producers, energy and risk trading, media), weather enthusiasts, and the general public. The overarching goal of TCGP is to foster increased development of forecast aids for global basins by engaging the wider community of operational centers, academic researchers, and commercial interests, ultimately moving the community’s focus beyond track and intensity to a more expansive focus on TC structure.

The goal of TCDP is to provide and maintain a new historical database of TC wind structure parameters that is based on high quality observational sources such as high resolution flight level data. This new database uses objective methods to optimally estimate the various database parameters, as well as to provide time-dependent error bounds on the estimated parameters. It is intended to provide the highest quality database possible for parametric wind modeling applications and model evaluation activities (e.g., verification), and to support basic and applied research on TC intensity and structure change.

FY2016 ACCOMPLISHMENTS

Developmental Testbed Center

Advancing the Connections between Radiation and Clouds in HWRF

During FY2016, the DTC’s Hurricane team investigated 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). Given the significant upgrades to the 2015 operational HWRF system, performance when using the Thompson microphysics scheme was evaluated. Tests were designed in close collaboration with the EMC HWRF team to inform 2016 pre-implementation testing, where the Thompson microphysics scheme was a candidate for replacement of the Ferrier-Aligo microphysics scheme, which supports advection of only total condensate and not individual species. The tests included five storms from the Atlantic (AL) basin and eleven storms in the Eastern Pacific (EP) basin that occurred during the 2014 and 2015 seasons. Particular emphasis was placed on EP basin storms in response to the FY2014 results. Prior to conducting the retrospective test, the Thompson scheme was modified in an effort to understand the cause and alleviate the increased track error in the EP basin. These modifications included a bug fix to the partial cloudiness scheme within the radiation parameterization, particle fall-speed changes within the Thompson microphysics scheme, and alterations to the RRTMG partial cloudiness scheme to change the lower limit of the snow and ice particle size.

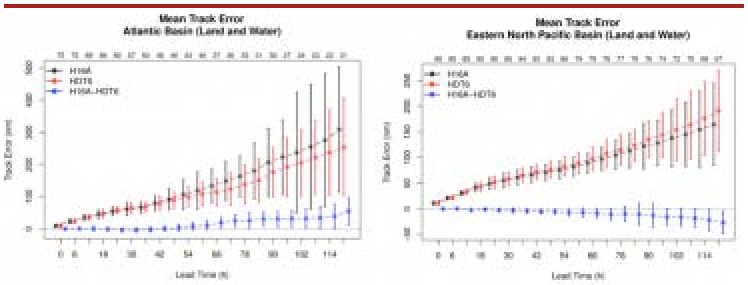

Figure 1. Mean track errors in the AL basin (left) and EP basin (right) with respect to lead time. Ferrier-Aligo microphysics is shown in black, Thompson microphysics in red, and mean pairwise differences (blue) with 95% confidence intervals.

Track and intensity error statistics indicated the Thompson configuration produced smaller track errors than the Ferrier-Aligo configuration in the AL basin beyond 60 hours (Figure 1), and had no statistically significant intensity differences (not shown). Despite the modifications, the

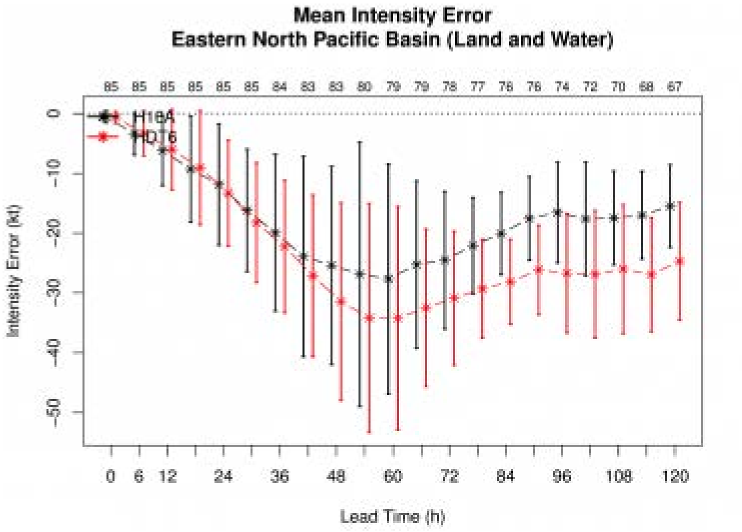

Figure 2. Same as 1, except mean intensity errors in the EP basin.

Thompson configuration still produced larger track errors than the Ferrier-Aligo configuration beyond 96 hours in the EP basin (Figure 1). These errors are dominated by along-track errors indicating the Thompson microphysics configuration moved storms too quickly. Although the sample for the current test is vastly different from that for the FY2014 test, the magnitude of the track error differences between the Thompson configuration and the operational baseline, beyond 72 hours forecast time, are noticeably reduced from the FY2014 results.

Intensity errors in the EP basin showed a large negative intensity bias for both configurations, with larger errors present in the Thompson microphysics configuration, beyond 36 hours (Figure 2). The large intensity errors present in both configurations result from the sample containing challenging intensity forecasts, including multiple rapid intensification (RI) cases.

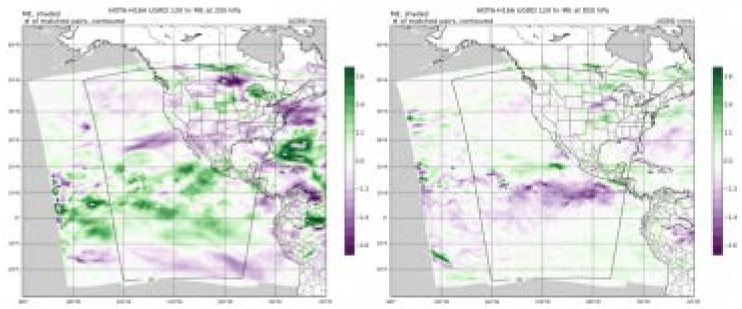

Figure 3. Large-scale verification of the u-component of the wind for aggregated 120 hour forecast lead times at 250 hPa (left) and 850 hPa (right). Shading indicates the difference of the mean errors of the Thompson configuration minus the operational Ferrier-Aligo configuration. Green shading indicates more westerly flow and purple shading indicates less westerly flow.

In addition to looking at track and intensity errors, the DTC evaluated the large-scale flow of the two configurations, with a focus on the EP basin, to better understand the differences in performance. GFS analyses were used to represent truth for this portion of the evaluation. For longer lead times, both configurations exhibit a positive westerly wind bias between 15°N and 0°, relative to the GFS analyses. The configuration using Thompson microphysics produced an environment with too much shear relative to the GFS analyses, whereas the operational version using Ferrier-Aligo microphysics created an environment similar to that of the GFS (not shown). This difference is evident from comparisons between the configurations, where results indicate the configuration using Thompson microphysics produced a more sheared environment compared to the operational version using Ferrier-Aligo microphysics, shown by stronger westerly flow aloft (250 hPa) and less westerly flow at lower levels (850 hPa) (Figure 3). The increased shear in the Thompson microphysics configuration is consistent with producing weaker storms than the operational configuration, although the explanation for why the Thompson configuration produced more shear is under investigation. Both configurations had a warm and moist bias compared to GFS analyses. The large-scale differences reveal the Thompson configuration produced cooler temperatures and lower relative humidity in the middle levels relative to the operational configuration, indicating an improvement relative to the Thompson scheme. This is particularly evident in areas coincident with regions typically associated with stratus in the EP basin.

The full report for the evaluation is available on the DTC webpage: http://www.dtcenter.org/eval/hwrf_thomp2016/.

Tropical Cyclone Modeling Team

Development of a Tropical Cyclone Display and Diagnostic System

A next-generation display and diagnostic system is being developed to support evaluation needs of the U.S. National Hurricane Center (NHC) and broader tropical cyclone (TC) research community. The new hurricane display and diagnostic capabilities allow forecasters and research scientists to more deeply examine the performance of operational and experimental models. The system is built upon modern and flexible technology, including OpenLayers Mapping tools, that are platform independent. The forecast track and intensity along with associated observed track information are stored in an efficient MySQL database. The system provides an easy-to-use interactive display system, and provides diagnostic tools to examine forecast track stratified by intensity. Consensus forecasts can be computed and displayed interactively. The system is designed to display information for both real-time and historical TC cyclones. Display configurations are easily adaptable to meet the needs of the end-user preferences.

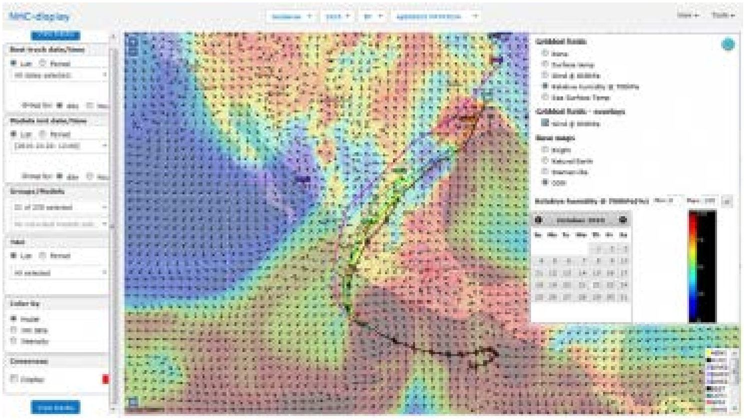

Fig 4: Example snapshot of the NHC Display and Diagnostic software system. Example for Hurricane Patricia in the Eastern Pacific Basin. Map shows observation and forecast of TC track, model forecast wind field at 850 hPa, and relative humidity field at 700 hPa.

Ongoing enhancements include improving capabilities for stratification and evaluation of historical best tracks, development and implementation of additional methods to stratify and compute consensus hurricane track and intensity forecasts, and improved graphical display tools. The display is also being enhanced to incorporate gridded forecast, satellite, and sea-surface temperature fields.

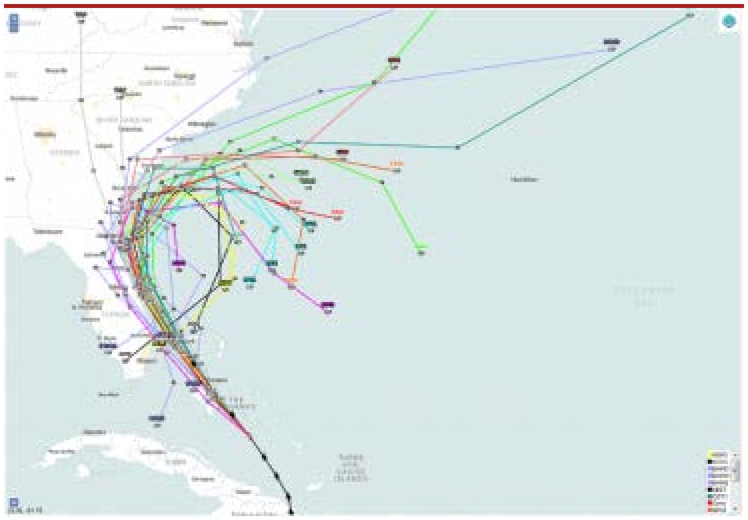

Fig 5: Example mapping tool showing forecast and observation of TC track for Hurricane Matthew.

Website: http://www.hfip.org/nhc-display

Ensemble Rapid Intensification Products

Additionally, the RI probability for all available model configurations were computed and displayed for each initialization time. Relative Operating Characteristic (ROC) diagrams for the 2013-2015 retrospective EP basin cases for all model configurations during the 24 hr forecast lead time and RI threshold of 30 knots are shown in Figure 8, including ROC area, reliability, and Brier scores for each model configuration.

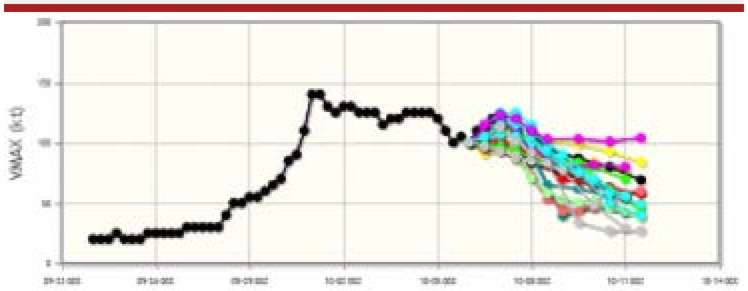

Fig 6: Example plotting tool showing forecast and observation of TC intensity for Hurricane Matthew.

Ensemble RI products were generated and posted online for distribution to the community. Website: https://www.ral.ucar.edu/projects/hfip/d2016/ensRI/

Tropical Cyclone Guidance Project

New TCGP Data and Visualization

During FY2016, the TCGP has continued to provide reliable visualizations of the publicly-available TC guidance product. Many companies and other sites rely on TCGP's open data repository, as web logs show on the order of 10-15 GB of automatic data downloads per day. Several improvements were made to increase the reliability of the data feeds, including the addition of ingest of NCEP/EMC's HWRF forecasts for the

other global TC basins. A new visualization was developed and added to TCGP's real-time products to provide an overview of the various track predictions of three different global ensemble prediction schemes (EPS). Figure 9 shows an example early in the life of Hurricane Matthew. This visualization has become quite popular and was featured in Nate Silver's Five-Thirty-Eight blog.

Tropical Cyclone Data Project

Public Release of New TC Datasets of Aircraft and Satellite Observations

To support the ultimate goal of providing a new database of historical database of TC wind structure parameters, TCDP released three major source datasets to the public in FY2016. Each dataset is a high quality research-grade dataset of TC-focused wind data, from aircraft or satellite observations. Each dataset uses modern standards and formats, and serves as source data input for the new historical database. These include the:

- Enhanced Vortex Data Message Dataset (VDM+, released 25 Nov 2015), the
- QuikSCAT Tropical Cyclone Radial Structure Dataset (QSCAT-R, released 23 Dec 2015), and the
- Extended Flight Level Dataset for Tropical Cyclones (FLIGHT+, released 20 April 2016).

The VDM+ and FLIGHT+ datasets have a registration process to track basic user metrics (including intended use), and mailing lists to notify users in the event that bugs are found or new versions become available. VDM+ currently has 26 registered users and FLIGHT+ has 12 registered users. Many of the users are Masters or PhD students who are using the datasets in their thesis or doctoral research. Two journal articles that use these datasets have already been published (Vigh et al. 2012; Stern et al. 2015). Several others are in preparation.

The Tropical Cyclone Observations-Based Structure Database (TC-OBS)

TCDP's ultimate goal is to develop and maintain a new historical database of TC wind structure parameters to supplement existing databases such as the National Hurricane Center's Hurricane Database (HURDAT2). While HURDAT2 is created through a subjective labor-intensive process by NHC's hurricane specialists, TC-OBS relies on automation and objective methods to build its dataset. TC-OBS provides the parameter estimates at full precision, improving on the HURDAT2 that uses rounded parameter values to the nearest tenth of a degree (for TC position) and nearest 5 knots (for TC intensity). HURDAT2, which generally includes data every 6 h, effectively smooths out fluctuations

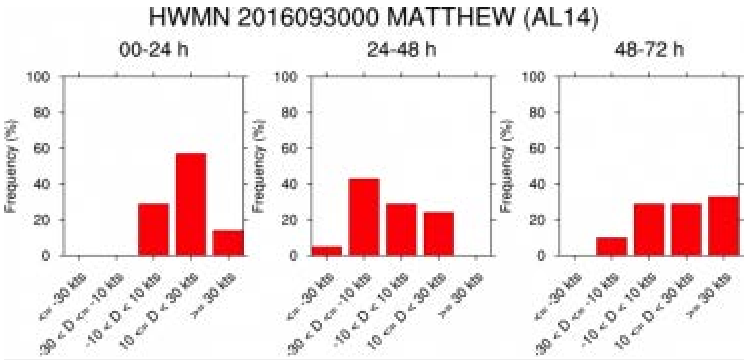

Fig 7. HWRF ensemble frequency distributions for the RI/RW bins during 0-24 (left), 24-48 (center), and 48-72 (right) time periods.Each hurricane season, the Hurricane Forecast Improvement Project (HFIP) conducts an experiment, referred to as the Demonstration System, where the program attempts to demonstrate model capability including high resolution ensembles using both regional and global models for the prediction of hurricanes. The demonstration is conducted over the AL and EP basins. The goal of the experimental models is to test various configurations to determine if they meet HFIP goals of improving track and intensity forecasts. The TCMT FY2016 Demonstration activities included product generation and evaluation for probability of intensity change during 0-24 hr, 24-48 hr, and 48-72 hr time periods. The focus was on intensity changes indicating the occurrence of rapid intensification (RI) and rapid weakening (RW). Retrospective ensemble forecasts from the 2013-2015 hurricane seasons, as well as near real-time 2016 hurricane season forecasts were verified from six participating modeling groups. Ensemble RI products were generated to show the ensemble frequency distributions of each model configuration for RI/RW during the three time periods (Figure 7) for a single initialization of hurricane Matthew.

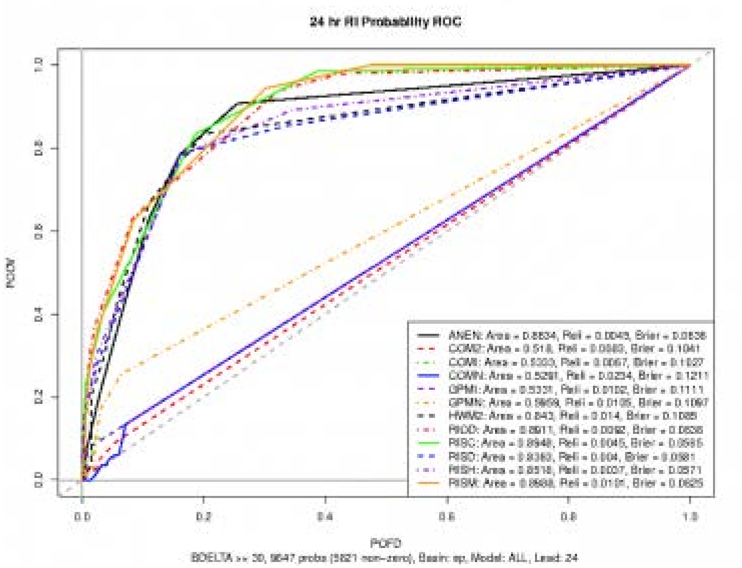

Figure 8. ROC diagram for the 2013-2015 retrospective EP basin cases for all model configurations during the 24 hour lead time and RI

shorter than a day, but TC-OBS provides its parameter estimates for each hour. TC-OBS also provides observations-based estimates of the radius of maximum wind, and the wind radii for the 34-, 50-, 64-, 83-, 96-, 113-, and 137-kt wind-speed thresholds (HURDAT2 only provides 34-, 50-, and 64-kt). TC-OBS also includes alternative metrics that are not provided by HURDAT, such as an estimate of the azimuthal mean wind and the coherence of the location of the maximum wind in the TC.

An initial version of TC-OBS (v0.4) has been released to the private companies that provided the initial funding to this project. Figure 10 shows a visualization of the TC-OBS track parameter for Hurricane Isaac (2012). This is a case in which flight-level observations were present at regular intervals prior to Isaac's landfall in Louisiana. While the Best Track/HURDAT provide a smoothed track, the TC-OBS objective methods are able to capture the trochoidal looping of the storm center as it approached the coast. These wobbles in the wind center can be of particular importance for assessing which locations may have experienced the extreme winds of the TC core.

FY2017 PLANS

Developmental Testbed Center

For FY2017, the DTC will continue its work toward improvement of the HWRF physics through partnerships with physics developers. The performance of alternate physics schemes and innovations to the current parameterizations within the HWRF physics suite will be investigated. Enhancements to the RRTMG radiation and partial cloudiness scheme will be evaluated and alternate scale-aware cumulus parameterizations will be tested. Retrospective forecasts using the most recent HWRF model version will be conducted to evaluate the performance of each configuration. Upgrades to the atmospheric component of HWRF will be passed to EMC to be included in its pre-implementation testing for the HWRF 2017 implementation.

Tropical Cyclone Modeling Team

For FY2017, the TCMT will continue to enhance graphical display diagnostic tools through additional stratifications and inclusion of gridded forecast, satellite, and sea surface temperature fields. New diagnostic tools that provide information on tropical cyclone wind radii structure and impact observed (aircraft, satellite, etc.) fixes on track and intensity forecasts will be added to the display system. Additionally, ensemble RI forecasts for the 2016 hurricane season will be evaluated and made available through the TCMT website. The TCMT will also start evaluating other ensemble-based forecasts such as tropical cyclone genesis.

Tropical Cyclone Guidance Project

For FY2017, TCGP plans to develop advanced visualizations for global

threshold of 30 knots.

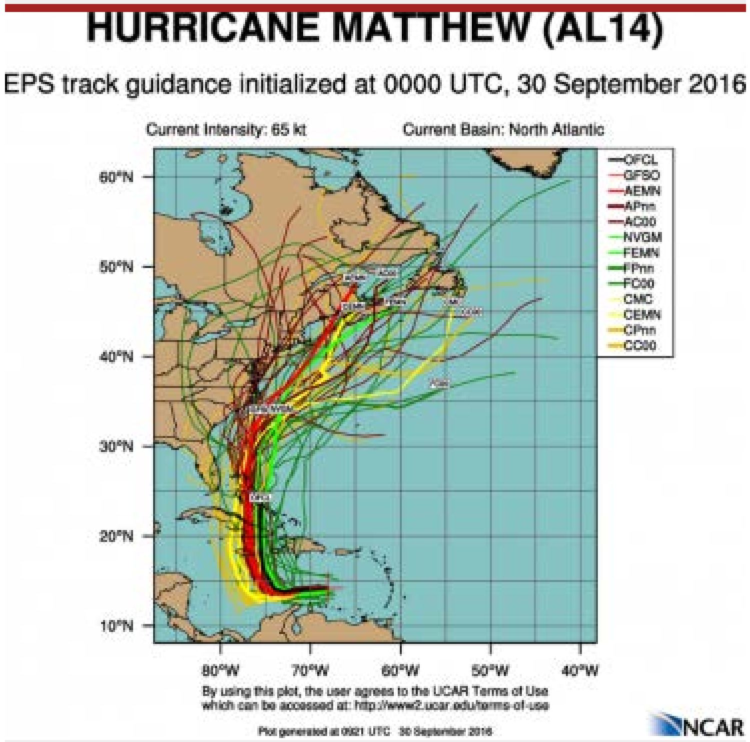

Figure 9. Example of TCGP's new overview visualization of forecast trajectories from three different ensemble prediction systems (EPS) through 240 hours. Tracks from the NCEP Global Ensemble Forecast System (GEFS) are shown in red, tracks from the U.S. Navy's NAVGEM ensemble are shown in green, and tracks from the Canadian Meteorological Center's global ensemble are shown in yellow. The NHC Official forecast (OFCL) is shown in black (through 120-h). Individual ensemble members are shown in thin lines (xPnn), while the control member (xC00) and deterministic forecasts (xxxO) are shown with thicker lines. The thickest lines show the mean track forecast of each EPS (xEMN).

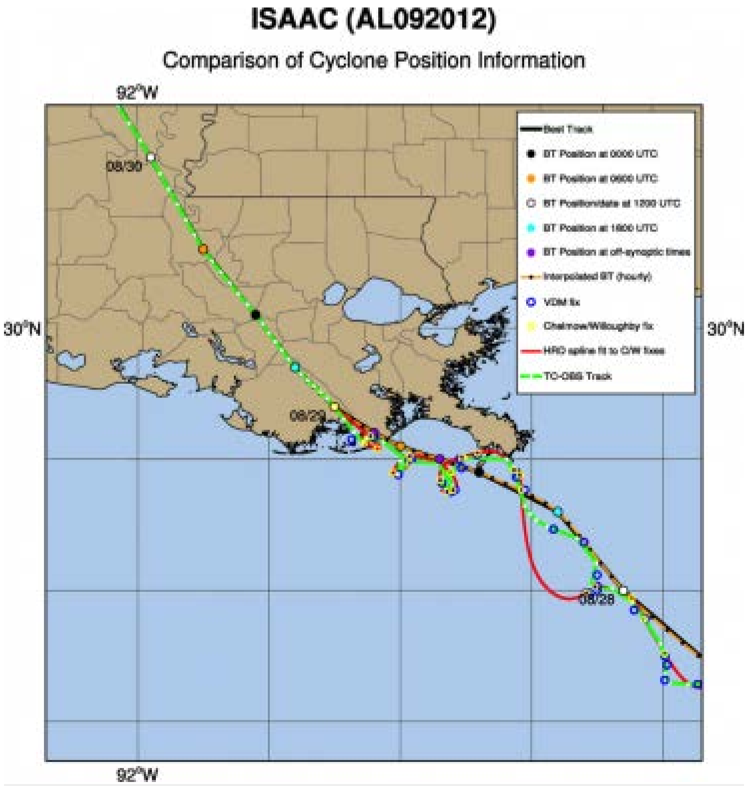

Figure 10: Comparison of the Best Track (HURDAT) track (black), an interpolated version of the best track (orange), a spline analysis of flight-level wind centers from the Hurricane Research Division (red), and the TC-OBS track (green).

EPS through a collaborative effort with the University of Miami. Additionally, TCGP will release the TC-OBS Database to the public in late 2016.

Tropical Cyclone Data Project

A public release of TC-OBS (v0.4) is planned in FY2017. Pending funding support, TCDP will also continue to provide yearly updates and improvements to the FLIGHT+ and VDM+ datasets during FY2017.

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WATER SYSTEM PROGRAM

BACKGROUND

The Water System Program is an NSF base-funded effort involving scientists from RAL, CGD, MMM, and EOL. Since 2001 the program has conducted research aimed at improving the representation of the water cycle in regional and global climate models. Using the diurnal cycle of precipitation as a focus, research has shown that current climate models do not accurately simulate the frequency, intensity, and timing of summer time convection over much of the globe, including continental regions, despite reasonable simulations of precipitation amount (see figure). This model deficiency greatly hampers climate models' ability to predict future changes in intense storms, flash floods, tornados, hurricanes, and other severe weather events that likely have the largest impact on the society under global warming. Water System funding at RAL supports a number of research efforts; several are described below and links provided to projects described more fully elsewhere in this report.

COLORADO HEADWATERS

The Colorado Headwaters high-resolution climate modeling effort was expanded to consider most of North America. The primary goal of the “CONUS project” is to examine how key physical processes such as precipitation, snowfall, snowpack, runoff and evapotranspiration are impacted by climate change over a significant part of North America using a model with sufficient resolution to capture them (4 km horizontal grid size). This effort was made possible through the award of 27.5 M core hours on the NCAR Yellowstone computer from the CISL Advanced Science Discovery grant process. The first year of the project tested and evaluated the model configuration and parameterizations necessary to produce a faithful simulation of the current climate. During the second year of the project nine years of the current climate simulation at 4 km resolution (Oct. 2000 – March 2010) were completed. During this past year the full thirteen years of both current and future climate were completed (April 2016). The simulations for the future climate 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.

A paper describing the simulation and verification as well as some preliminary results was published in September 2016 in the journal *Climate Dynamics* (Liu et al. 2016). The dataset is available to the community. Since publication of the *Climate Dynamics* paper numerous requests for the dataset have been received. A data portal to access the data will be available through CISL in a few months to more efficiently respond to these requests.

The output of the model runs is being 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. One paper has been accepted examining extreme hourly precipitation in a future climate (Prein et al, *Nature Climate Change*), and another submitted to *Nature Climate Change* on “Slower melt rates in a warmer climate”, Musselman et al. 2016.

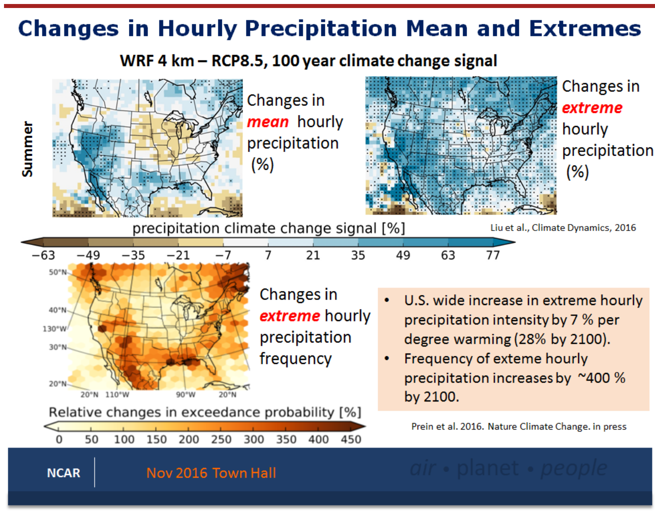

Figure 1: Changes in hourly precip mean and extremes.

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 significant warm and moist bias occurs in the simulation in the central U.S. in the summertime. Stan Trier at MMML has been investigating whether this problem is due to issues with the Planetary Boundary Layer schemes used in WRF. This is a well-known problem with many weather and climate models and is an active research area for the Water System program and for the community.

The team is preparing for a second set of current and future simulations at high-resolution that will be forced by the CMIP5 ensemble mean using a novel way to force the future climate simulations using output of the NCAR CESM model 6 hourly output of one of the ensemble members from the CMIP5 archive. This effort is being led by Professor Aiguo Dai from the State University of New York, Albany.

A two-day Water System retreat was held on March 15-16 2016 with approximately 40 NCAR scientists participating. The goal of this workshop was to provide a forum in which NCAR water related science can be discussed and new collaborations formed. The next Water System retreat will be held on January 17-18th, 2017.

A major highlight of the Water System program this year was sponsoring and conducting an international workshop in September at NCAR entitled: "Convective Permitting Climate Modeling Workshop". This workshop was co-sponsored by GEWEX and over 75 scientists from around the world attended. A summary of the workshop was published in *BAMS* and the GEWEX news. The workshop talks are available at the following web site: https://ral.ucar.edu/events/2016/cpcm. Roy Rasmussen, Andreas Prein and Graeme Stephens (GEWEX co-chair) organized the workshop. A second workshop is being planned at NCAR in two years. This scientific area is growing rapidly and the participants appreciated the opportunity to come together and discuss the successes and challenges related to this new scientific endeavor. In addition, the NCAR Water System program has been hosting AGU sessions on this topic the past two years and will have another session this year.

Plans for FY2017

In FY2017, the Water System program will support a second major current and future CONUS simulation at 4 km resolution based on CMIP5 forcing. The primary difference from the previous simulation will be the use of transient current and future weather from one select Global Climate Model instead of the weather from current re-analysis. The team is currently working on reducing the central U.S. dry and warm bias before proceeding with this simulation.

GLOBAL WATER CYCLE AND DROUGHT

Global water cycle studies conducted by Aiguo Dai focused on historical and future changes in precipitation, drought, streamflow and continental discharge by analysing of WRF-based downscaling of future climate projections on 4km grids over the contiguous U.S.(CONUS). One particular area is how precipitation frequency for light, moderate and heavy precipitation events may respond to future GHG changes. Another focus area is the separation of natural variations associated with the Pacific Decadal Oscillation (PDO) or the Inter-decadal Pacific Oscillation (IPO) on decadal to multi-decadal time scales from GHG-forced long-term changes in observational records and model simulations for precipitation and other fields.

Julio Bacmeister of CGD is examining a global water cycle issue through a detailed examination of a serious orographic precipitation biases in the Community Atmospheric Model (CAM). Roughly speaking, two broad categories of these biases appear to be present: 1) Cold season (or large-scale driven) biases; and 2) Warm season (convergence driven) biases. An example of the first category occurs over Greenland where large positive precipitation biases hinder coupling to interactive ice-sheet models. An example of the second occurs over the Andes, where a very large positive precipitation bias may have both local effects, as well as an important remote effect – *reducing* precipitation over the Amazon basin.

These biases are being analyzed by Julio using model sensitivity experiments (e.g., Fig 2 below) and by developing in depth diagnostics of moisture and tracer transport in the spectral element dynamical core.

Accomplishments in FY2016 and Plans for FY2017:

The major accomplishment in FY2016 was the completion of the high resolution PGW CONUS simulations, including publication of 5 papers describing the simulations and the key results. The plans for FY2017 include continued analysis of the PGW CONUS simulations, performance of the new transient climate high resolution CONUS simulation, upgrading WRF-Hydro and SUMMA, further enhancement to NOAH-MP, and progress on the new Community Terrestrial Systems Model (CTSM).

WRF-HYDRO

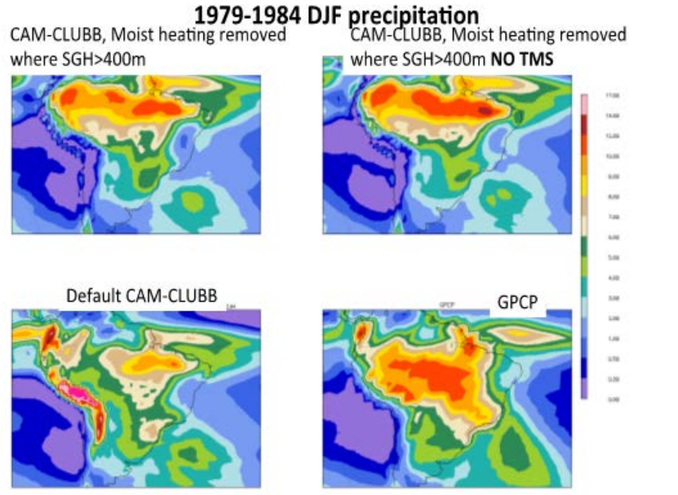

Figure 2: Sensitivity experiments using CAM6-beta AMIP simulations in which moist heating is removed wherever the subgrid orographic standard deviation SGH>400. Condensation is not modified. Disappearance of bias over Andes suggests feedback between moist heating and moisture convergence. Not improved precipitation over Amazon basin in sensitivity runs.

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.

FY2016 accomplishments and FY2017 plans are described in the "WRF-Hydro Community Modeling" section of this report.

WRF-URBAN

Global population has become increasingly urbanized: Currently 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 (UCM) have been developed and implemented into the WRF model to capture urban land-surface processes, but those UCMs were coupled to the simple Noah land surface model (LSM). We recently coupled the more advanced Noah-MP LSM to WRF-Urban as well as to the urbanized high-resolution land data assimilation system (u-HRLDAS). This new modeling capability was tested over Phoenix and Beijing metro areas and will be released in WRF in 2017. It is also being used to assess the degree to which a detailed urban modeling approach can improve real-time weather prediction for cities.

FY2016 accomplishments and FY2017 plans are described in the "Land Atmosphere Interactions" section of this report.

WRF-CROP

This project aims to improve the representation of cropland-atmosphere interactions in the community Noah-MP LSM with the ultimate goal to integrate it in a coupled model to improve seasonal weather forecasts and regional climate simulations for the NCAR Water System Program. 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.

FY2016 accomplishments and FY2017 plans are described in the “Land Atmosphere Interactions” section of this report.

SUMMA

The Structure for Unifying Multiple Modeling Alternatives (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.

FY2016 accomplishments and FY2017 plans are described in the “Computational Hydrology” section of this report.

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.

FY2016 accomplishments and FY2017 plans are described in the “Computational Hydrology” section of this report.

‹ Hydrometeorological Applications | up | Short-Term Explicit Prediction ›

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SHORT-TERM EXPLICIT PREDICTION

The Short-Term Explicit Prediction (STEP) Program is a multi-NCAR laboratory activity aimed at improving the short-term (0-36 hours) forecasting of high-impact weather events such as severe thunderstorms (heavy rain, tornados, downburst, flash flood, lightning and hail), winter storms (snow, freezing rain and drizzle), and hurricanes. The STEP program conducts research in areas that are crucial for advancing the science and application of the short-term prediction of high-impact weather. It is highly collaborative involving national and international scientists, engineers, and operational personnel from universities, government institutions and the private sector. Most of the forecasting/nowcasting systems and analysis tools developed under STEP are available to the research and operational for use in their work.

In FY16, RAL efforts continued to focus on research and real-time demonstration of the integrated Hydromet Prediction System (STEP-Hydromet hereafter; see Fig 1 below). The overarching objective of this work is 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. The major objectives this year were to conduct the analysis and evaluation of the real-time data collected during the 2015 STEP Hydroment Experiment and the real-time Hydromet Experiment, conducted from 1 June – 15 August 2016 summer along the Colorado Front Range. Additionally, RAL continued to lead the STEP research effort aimed at improving WRF microphysics parameterization scheme, and participated in preliminary analyses of the NSF-sponsored Plains Elevated Convection at Night (PECAN) program (see http://pecan15.org) experiment datasets and predictability of nocturnal, elevated convection initiation.

1. DEVELOPMENT AND DEMONSTRATION OF STEP-HYDROMET

STEP-Hydromet provides 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 continued research activities that support the development of the hydromet system, RAL staff have demonstrated the integrated system in real-time using the Colorado Front Range as a testbed since 2014. Components of the system include: 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 hydrology model; and 5) near-real time performance evaluation of the QPE and QPF fields using a set of statistical metrics and techniques.

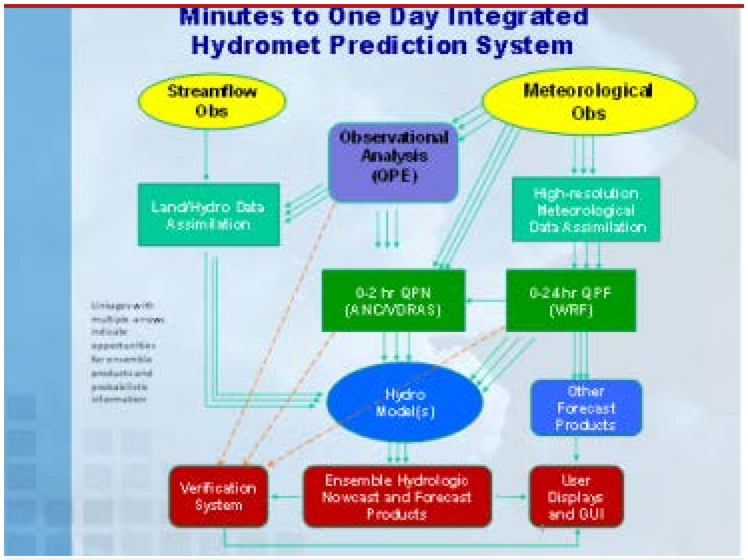

Figure 1.   Flowchart for the STEP Hydromet Prediction System.

The Numerical Weather Prediction (NWP) forecast models and the WRF-Hydro model were run on NCAR's Yellowstone supercomputer, while the AutoNowcaster, Trident and VDRAS nowcasting systems, and the EOL QPE mosaics ran on workstations located in RAL and EOL. A dedicated web page (https://ral.ucar.edu/projects/step_hydromet) was set up for real-time viewing of precipitation accumulation fields, forecast and nowcast products, and streamflow prediction. The JAZZ interactive java-based display system was also 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. Real-time streamflow, soil moisture and overland flow depth information was displayed on a dynamic web mapping service called HydroInspector, also developed as part of the STEP project. Upgrades and enhancements were made to the components of the Hydromet system prior to the start of the demonstration based on research conducted throughout the year. Ongoing research efforts aimed at improving the different components of this system are discussed below.

Quantitative Precipitation Estimation (QPE)

Compared to the previous years, there were not as many heavy rainfall events in the Denver metropolitan corridor, but a larger number of events occurred in Weld, El Paso and Elbert Counties. Heavy rainfall (> 1 in h^{-1}) occurred on 25 days during the demonstration. Flash flooding occurred on a subset of these days in association with the heavy rainfall. Eleven events have been identified for studying in detail regarding QPE, QPN, QPF performance and the impact of these on streamflow predictability.

While the national MRMS QPE product was run again in the Hydromet system, the EOL dual-polarization hybrid QPE field was used as the primary field for estimation of precipitation in the AutoNowcaster/Trident system and WRF-Hydro. The polarimetric methods (NOAA Dual Pol, EOL hybrid) used 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. Analysis of last year's QPE fields showed similar accuracies in the MRMS and EOL hybrid QPE algorithms but both showed a tendency for overestimation of rain amount within the cores of heavy rain areas, especially in hailstorms. An adjustment was made to the $R(K_{dp})$ relationship in the EOL Hybrid algorithm to improve representation rainfall estimation in storms containing hail. An example of 3 h rainfall accumulations from the EOL hybrid QPE algorithm that was re-run with the new $R(K_{dp})$ relationship is shown in Figure 2 for a hail storm from 2015. Most of the rainfall, up to 2 inches (~50 mm), fell over Denver within one hour causing flash floods. During 2016, the EOL hybrid QPE algorithm did a better job of rainfall estimation in hailstorms using the modified rainfall relationship.

Quantitative Precipitation Nowcasting (QPN)

Based on years of experience in monitoring and studying storms over the Colorado Front Range, we understand that a large percentage of storms that form over the Rockies quickly dissipate as they move off the mountains onto the plains. However, no quantitative study had ever been done to document the dissipation of these storms. Using the radar data and TITAN storm tracks produced in real-time during the 2015 demonstration, it was finally possible to determine the frequency of occurrence. Figure 3 shows all the TITAN storm tracks on 1 July overlaid onto the Colorado terrain (color-coded, in 400 m increments). On this day, it can be seen that the majority of storms that formed over the mountains dissipated as they moved to the lower terrain of the plains. Examination of all of the tracks from 1 June – 15 August showed that 91% of the storms that initiated above an elevation of 2600 m dissipated before reaching 1400 m. Using this information, a predictor field and membership function was added to the Autonowcaster/Trident fuzzy nowcasts and run during the 2016 demonstration.

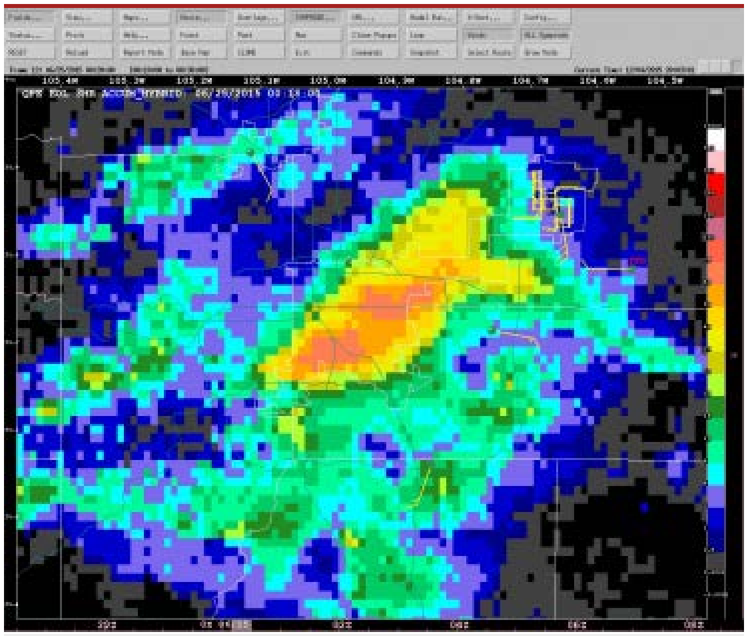

Figure 2. Three hour rainfall accumulation on 25 June 2015 from the updated EOL Hybrid QPE algorithm.

Along with the Autonowcaster, VDRAS was run over the same domain using the same configuration as in 2015 with an improved surface data assimilation scheme. Our research effort on VDRAS focused on PECAN data analysis and development of model-based nowcast techniques. Figure 4 shows an example of VDRAS analysis (left) and 1h nowcast (right).

Qualitative Precipitation Forecasting (QPF)

The model-based QPF effort had three focus areas in FY16. First was the evaluation and verification of the real-time results from the 2015 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 2016.

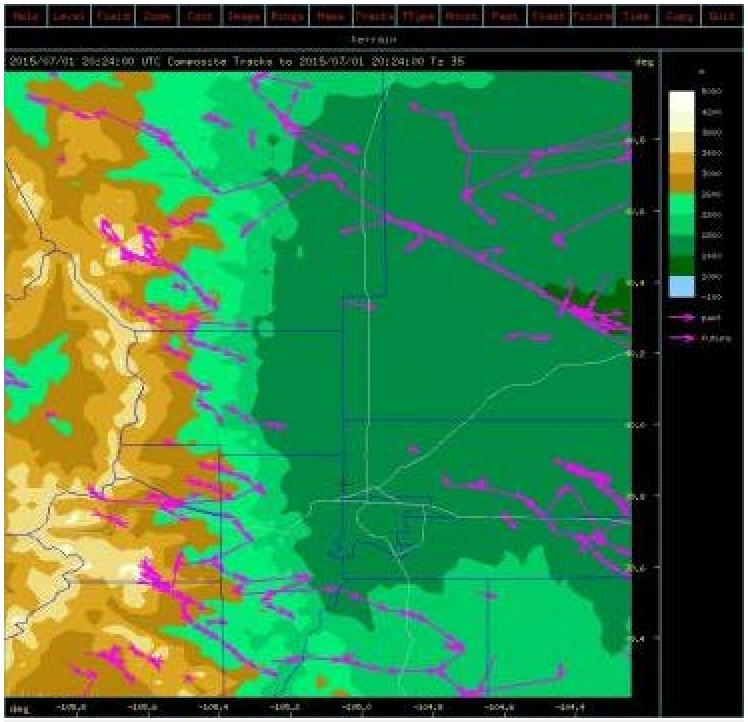

Figure 3. Colorado terrain field with TITAN storm tracks (magenta) from 1 July 2015 overlaid.

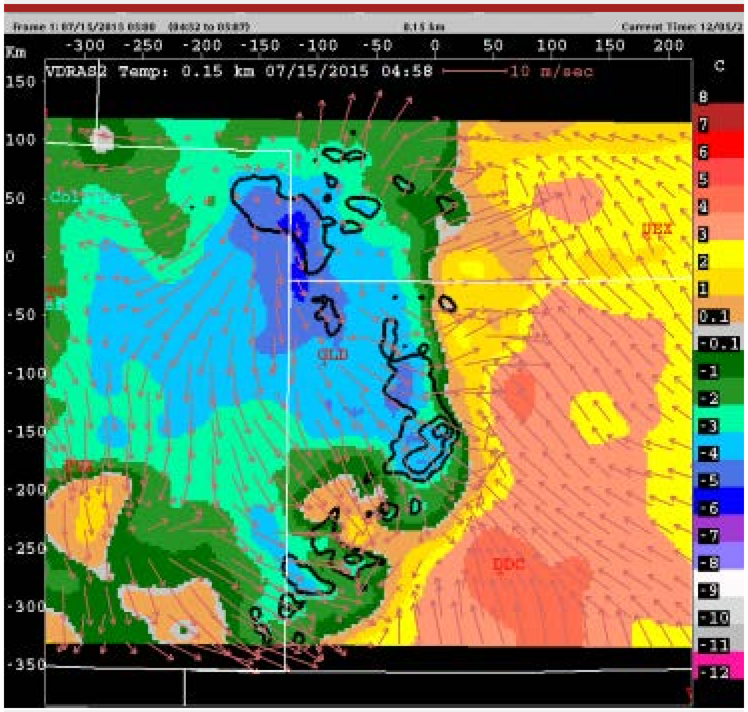

Figure 4. VDRAS analyses of perturbation temperature (color fill), wind vectors, and rain water mixing ratio at the height 150m above ground valid at 2015071505 UTC (left) and 1h nowcast.

The evaluation and verification of QPF was also performed over the entire 3km model domain (see Figure 7 for the domain size) and for the nowcast domain (Figure 3). The verification for the whole 3km domain was done for eight convective days in 2015 summer by comparing three WRF 0-12h QPF systems/configurations against MRMS gauge-corrected precipitation analysis. The Fraction Skill Scores for 1mm and 2.5mm are shown in Figure 5; each compares skills for the following QPF runs:

CYCLE: initialized by WRFDA 3DVar analysis with continuous 3-hourly update cycles, assimilating only conventional observations;

RADAR: partial cycled hourly radar data assimilation with CYCLE as the first guess at the multiples of 3 hour;

HRRR: operational HRRR mapped to the same domain as the other runs.

The results in Figure 5 indicate that the runs with radar data assimilation (HRRR and RADAR) improve the skill over CYCLE for the entire 12 hour forecast period. WRFDA 3DVar-based radar data assimilation run RADAR has higher skill than HRRR at the most forecast hours. Figure 6 compares the skills between HRRR and RADAR for each of the eight cases. HRRR has superior skill only for two of the eight cases. These two cases were chosen for in-depth study to find the issues in the WRFDA data assimilation scheme for future improvement. Figure 7 compares the three 5h forecasts from HRRR, CYCLE, and RADAR against the MRMS analysis for one of the failure cases. It is shown that the precipitation forecasts both by CYCLE and RADAR is contaminated by the false prediction near the corner of Colorado, New Mexico, and Oklahoma, resulting in lower skill score than that of HRRR. Several research efforts are being initiated to tackle the issues discovered from our evaluation of the 2015 QPF.

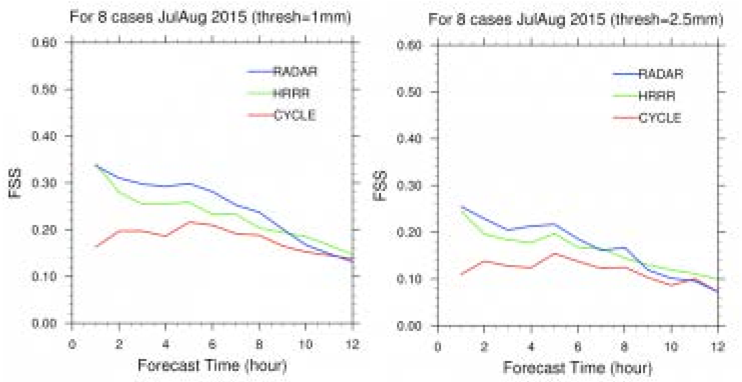

Figure 5. Fractions Skill Score (FSS) of hourly-accumulated rainfall for the thresholds of 1mm (left) and 2.5mm (right) over the WRF 3km domain. The radius of influence used in the FSS computation is 10km. Skills from 3 experiments (explained in the text) are compared.

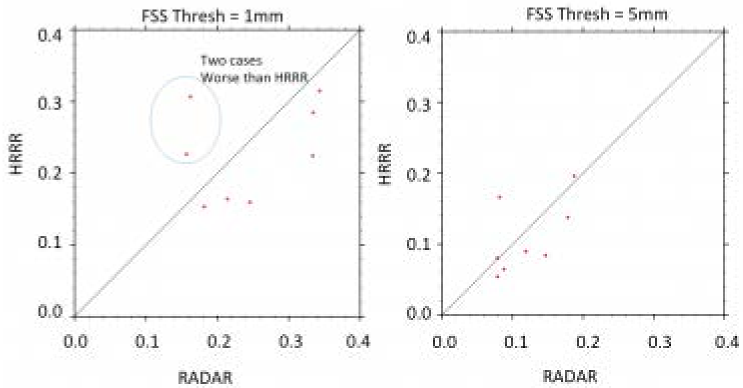

Figure 6. Scattered plot of HRRR vs RADAR FSSs for the hourly precipitation threshold of 1mm (left) and 5mm (right).

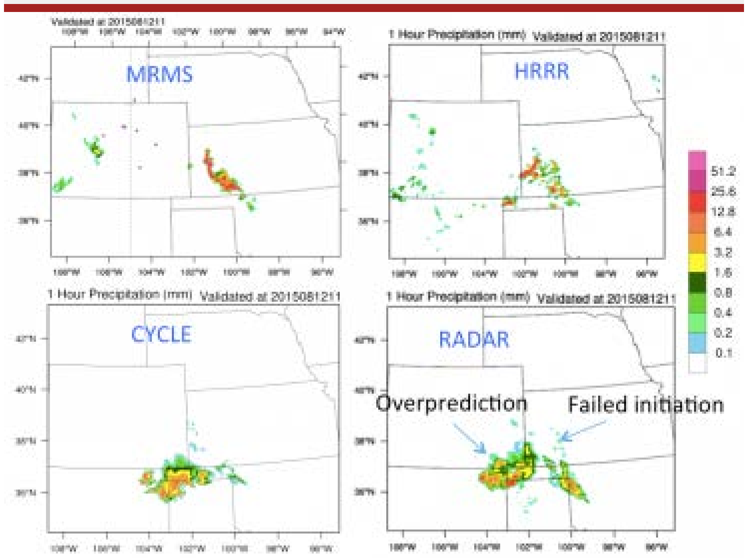

Figure 7. WRF hourly precipitation forecasts (t=5h) from the experiments HRRR, CYCLE, and RADAR, valid at 2015081211 UTC and initialized at 2015081206 UTC. MRMS precipitation analysis is shown in the upper-left panel for verification.

The evaluation and verification of the performance of WRF 3DVAR forecasts with and without data assimilation (DA) and the HRRR model was also conducted for a set of days from June, July and August 2015 over the smaller Front Range nowcast domain. These results have been compared to 2014 QPF verification statistics for the same models. Two verification regions were specified in this study: one domain within 60km of the KFTG Denver radar, the second centered over the eastern Denver region, where a high density of surface rain gauges were used as truth. The verification over the KFTG region used the MRMS gauge-corrected precipitation analysis as the truth dataset. The 3DVar with DA has shown some apparent improvement over 3DVAR without DA from 2014 to 2015. This is cautiously suggested by comparing of the performance in Figure 8 with Figure 9. Note that in these Figures, the experiment 3DVAR are the same as CYCLE in Figure 7 and DA the same as RADAR.

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 funding from the Central Weather Bureau of Taiwan.

During the STEP Hydromet Experiment conducted in the summer of 2016, the QPF systems were run on the same 3km domain (Figure 7) as in 2015. Instead of running one deterministic forecast with radar data assimilation, 15 ensemble runs were conducted in real-time by varying physics and large-scale analysis background (for cold start initial conditions and boundary conditions). Results of the ensemble forecasts are being evaluated.

Streamflow prediction from WRF-Hydro

Real-time, high resolution hydrologic prediction was performed during STEP-2016 using the community WRF-Hydro modeling system. The system was configured somewhat differently than in previous years in order to better align STEP hydrologic prediction research with ongoing hydrologic system forecast development being done at the national scale by the WRF-Hydro modeling team in collaboration with the NOAA National Water Center. These changes included the following:

1. Using s similar model physics configuration of WRF-Hydro as is used in the NOAA National Water Model
2. Implementation of a real-time streamflow data assimilation system

which ingests real-time streamflow data from the USGS and Colorado Division of Water Resources
3. Ingest of the EOL mosaic QPE product instead of the operational NOAA MRMS product.
4. Implementing the HydroInspector web-mapping display tool for visualization of real-time hydrologic forecasts
5. Implementating a comprehensive hydrometeorological model evaluation system using the open-source Rwrfhydro model evaluation software

Example outputs of heavy rainfall and streamflow forecast displays from the HydroInspector tool are shown in Figure 11.

The event shown occurred on July 19, 2016 in a fairly remote, mountainous region southwest of Denver. The map display shows a basin-average re-mapping of the EOL QPE product in order to highlight the tributary watersheds where heavy rainfall fell. The two time series plots on the right hand side show the time series of EOL QPE precipitation within the basin colored in dark red and the resulting streamflow predicted by the WRF-Hydro system. This particular event was not well measured by existing streamflow observations making validation problematic. As noted above, 2016 witnessed very few heavy to extreme rainfall events. Correspondingly, there were not many significant flood or flash flood events to study from the hydrologic model. Analysis is currently underway of the continuous streamflow prediction performance throughout the summer and the STEP team is collectively analyzing a selection of heavy rainfall events that did occur during 2016.

Real-time data assimilation of streamflow was implemented in 2016 which had a significant impact on streamflow initial state characterization, particularly below reservoirs which exert significant control on streamflow behavior in the Colorado Front Range region. Figure 12 provides an example of entire summer streamflow analyses from observations (black), an open-loop (no data assimilation) version of the WRF-Hydro model (yellow) and the analyses from the assimilation system (blue). It can easily be seen how the streamflow data assimilation keeps the model analyzed streamflow state close to the observations while without the data assimilation a background model bias emanating from a poorly described reservoir in the model is not able to keep track of the actual streamflow behavior below the reservoir.

Improvement upon the data assimilation methods used in the WRF-Hydro modeling system will be a major focus of research and development work leading to real-time forecasting activities in 2017.

FY17 plans

The STEP Hydromet Experiment will be conducted during the summer of

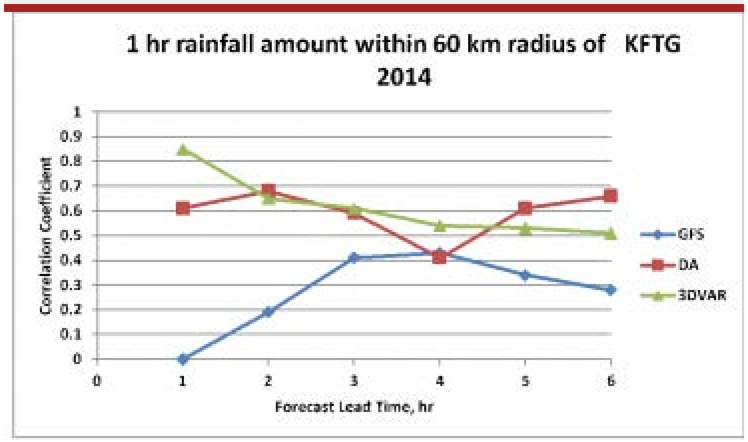

Figure 8. Comparison of the 3DVAR, 3DVAR_DA, and GFS models in 2014.

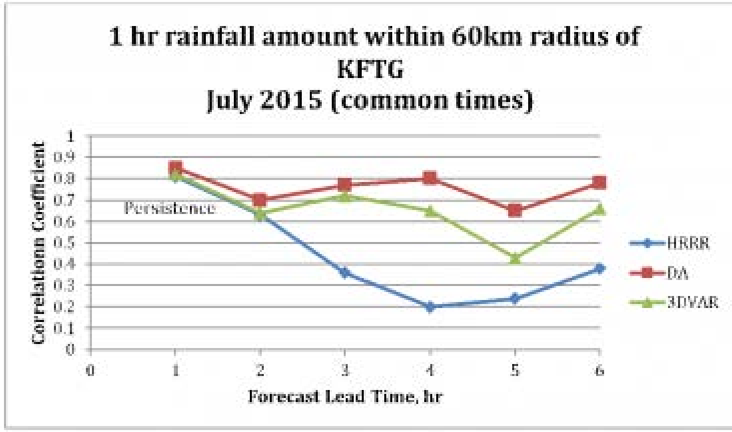

Figure 9 shows the performance of the models versus forecast lead time for each model. After a 2 hr lead time, the HRRR performance was significantly inferior to the 3DVAR methods.

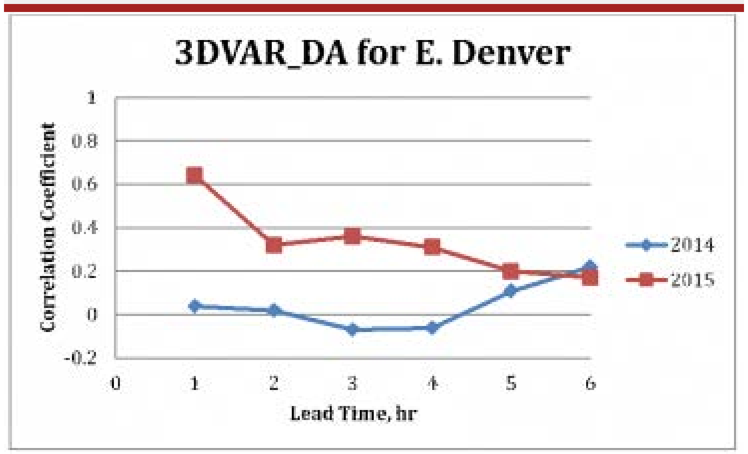

Figure 10. Correlation as a function of forecast lead time for 3DVAR_DA with rain gauge-measured rainfall for the average hourly

rainfall accumulation over Denver urban area. Performance for 2014 and 2015 are shown.

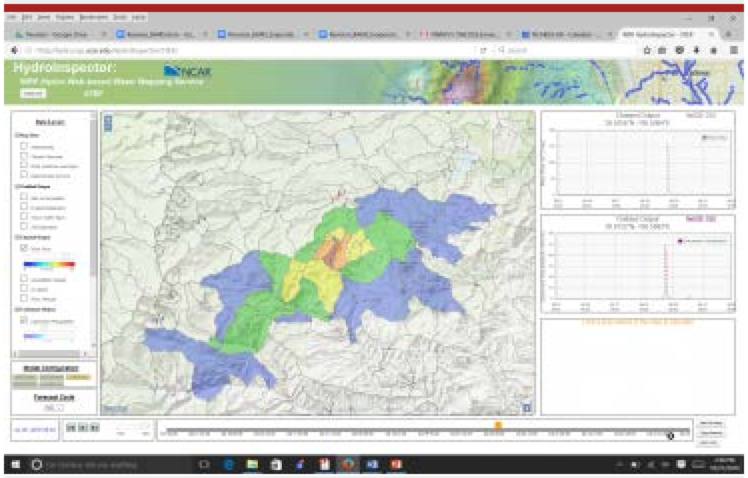

Figure 11. An example of outputs of heavy rainfall and streamflow forecast displays from the HydroInspector tool.

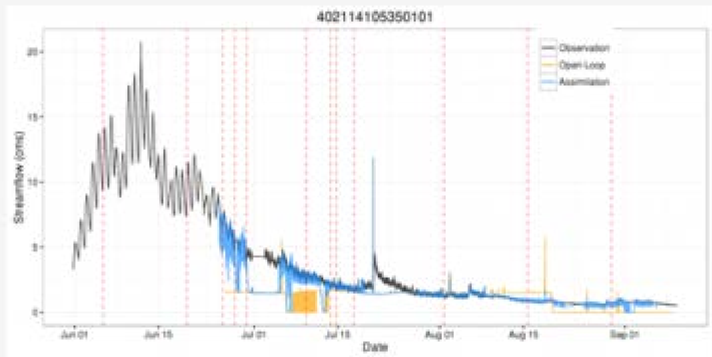

Figure 12. An example of entire summer streamflow analyses from observations (black), an open-loop (no data assimilation) version of the WRF-Hydro model (yellow) and the analyses from the assimilation system (blue)

2017 with system components upgraded based on research conducted during the winter/spring 2017. Other research plans for each of the STEP-Hydromet components are summarized below:

QPE

- No improvements are planned for the QPE component of the system.

QPN

- Detailed analyses will be conducted on the evolution of heavy rainfall and flash flood events from the 2016 demonstration. A climatology of heavy rainfall events along the Colorado Front Range during the past 8 years will be compiled.
- Analyses and evaluation of the performance of the Autonowcaster/Trident nowcasts with the new predictor field will be examined. 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.
- The effort on the development of the model-based nowcasting techniques will be continued using the VDRAS cloud model. A simplified scheme to linearly advect precipitation will be developed. The scheme will be compared with the full cloud model integration and extrapolation to assess its merit.

QPF

- New data assimilation capabilities that were developed in the past two years will be tested using selected 2016 cases. These new capabilities include the assimilation of “no rain” data from radar reflectivity, a large-scale analysis constraint to maintain the synoptic scale balance, and a divergence constraint.
- A research version with these new capabilities will be tested in real-time during the STEP Hydromet 2017.
- Develop an ensemble hybrid 3DVAR technique with the objective to improve the background error covariance of the model forecast.

WRF-Hydro

- Improve the process representation of flood inundation through improvements in the channel-land surface model coupling
- Conduct rigorous hydrologic model parameter calibration and regionalization over the STEP domain using the new National Water Model configuration of WRF-Hydro
- Expand domain eastward to capture more deep convection events
- Implement an upgraded streamflow data assimilation method which utilizes a time-filtered bias propagation that improves the blending between streamflow observations and the model simulated streamflow. Also, we will begin research on ENKF methods for join streamflow-land data assimilation
- Coordinate the potential generation of streamflow prediction ensembles with the rest of the STEP team.
- Modify HydroInspector web mapping service to:
  - Display retrospective model skill
  - Access and display real-time verification statistics
  - Display catchment averaged precipitation
  - Create time-lagged ensemble probabilities

Taken together, these goals are aimed at significantly improving streamflow and flood inundation prediction skill throughout the STEP domain. We will have a significantly stronger emphasis in 2017 on real-time model evaluation and diagnosis in order to better communicate combined precipitation and streamflow forecast skill.

2. IMPROVING WRF PHYSICS FOR IMPROVED PREDICTION OF HIGH IMPACT WEATHER

Impact of graupel parameterization on squall line simulation

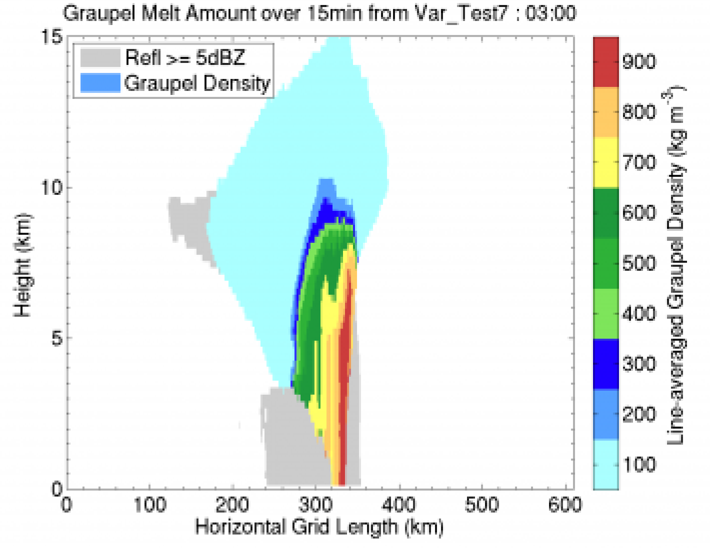

Figure 13. Line-averaged vertical cross section showing graupel density in the simulated idealized squall line at hour 3 in the simulation using the new variable graupel density parameterization.

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 by prescribed graupel density. In FY16, modifications were made to the Thompson microphysics code to allow for a variable graupel density to be diagnosed at every grid point and time step, rather than having the prescribed graupel density remain constant throughout the simulation domain and time period. The variable density scheme was also tested in the squall line simulation and results were presented at the ICCP conference in Manchester, England. The new scheme diagnosed high (hail-like) graupel density in the convective core and low graupel density in the areas farther from the core (Figure 13). This altered the distribution of graupel/hail in the storm and impacted the cold pool.

Evaluating performance of microphysical schemes

In order to evaluate impacts on storm structure, QPF, and, in particular, storm evolution, due to changes made to the Thompson microphysics scheme, an object-based evaluation tool that tracks storms with time is needed. The Method for Object-based Diagnostic Evaluation (MODE)-Time Domain (TD) is a tool developed at NCAR for such analysis, however there are several parameters that can be set in order to evaluate storms of a certain spatial scale and intensity. In FY16, various parameter settings for MODE-TD were explored by running the tool on a few test cases from the FY15 STEP-Hydromet summer demonstration to determine the optimal parameter settings and sensitivity of the results to the chosen settings. A key result of this study indicated that the tracking capabilities of the tool need improvement, but that bulk properties of the observed and modeled storms can be compared. This project mentored a SOARS student who participated in the analysis in the summer of 2016.

FY17 plans

- Complete the development of a prototype multi-moment graupel/hail hybrid category in the Thompson microphysics scheme to improve forecasted convective storm structure, evolution, and QPF.

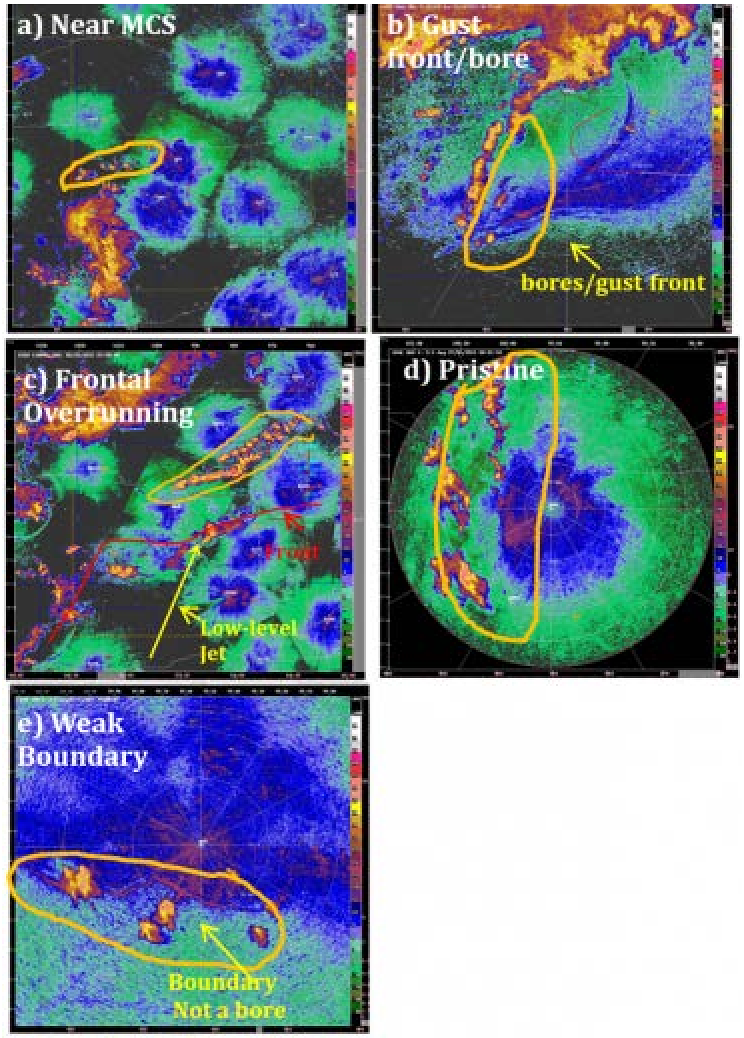

Figure 14. Radar reflectivity images showing different types of nocturnal convection initiation. The yellow outline indicates the storms associated with the indicated type of initiation.

Run MODE-TD on the FY16 STEP-Hydromet demonstration ensemble model microphysics members and compare results for the different microphysics schemes utilized. Use evaluation results to inform further microphysics parameterization improvements.

3. STUDY ON CONVECTIVE INITIATION WITH PECAN DATA

Preliminary analysis has been performed on all of the elevated convection initiation events (ECI) that occurred during the PECAN program. The different types of ECI are shown in Figure 14. Other datasets are being examined in addition to radar data, including GOES water vapor imagery, GOES Super Rapid Scan imagery collected during the first two weeks of the experiment, surface stations, 449 MHz profiler data, profiles obtained from mobile platforms, DIAL micro-pulse lidar, radar-derived Bragg-scattering profiles, and Wyoming King Air data.

A pristine ECI case on 4 July 2015 has been analyzed to understand the mechanisms leading up to the initiation of a hail-producing storm. After examination of all the above datasets, an elevated shear zone appears to be the only feature present that may have triggered this isolated, nocturnal storm in western Kansas. Another case of particular interest that is being analyzed is an ECI event that occurred on 25-26 June, arising from the isentropic lift of warm moist air by the Low Level Jet (LLJ) over a E-W stationary front in central Kansas. Two east-west bands of elevated convection formed simultaneously on the north (cooler) side of the front, as an MCS approached from the NW, as can be seen in Figure 15. Another unusual aspect of this case was the secondary and

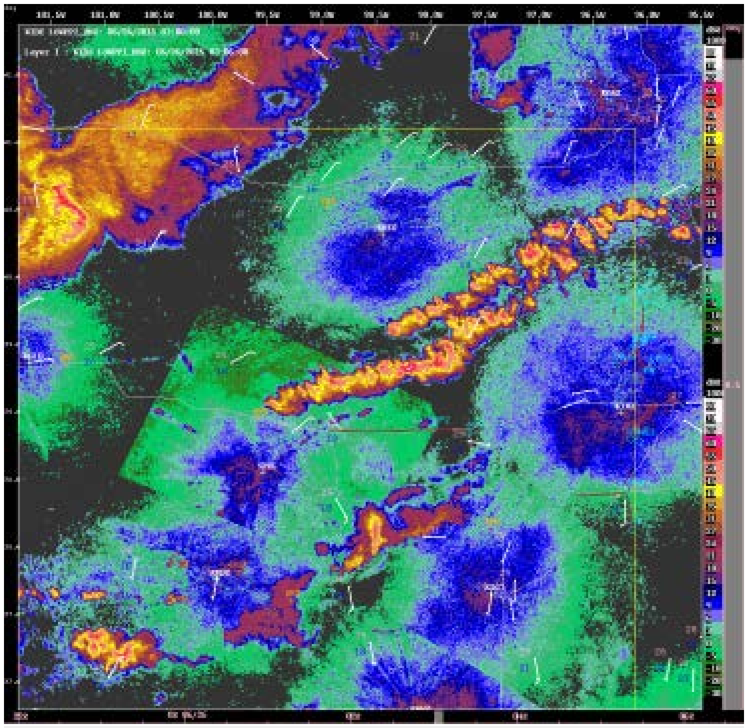

Figure 15. Elevated convection initiation on 26 June 2015 at 0306 UTC.

tertiary ECI that occurred in the same vicinity two more times during the evening. A model simulation is being run in conjunction with observational analyses to attempt to understand the initiation, structure and evolution of these storms.

FY2017 Plans

- Analyses of PECAN cases will continue in collaboration with scientists from EOL and MMM to understand the processes associated with nocturnal elevated convection initiation, and the predictability of these events.
- STEP scientists are contributing to a manuscript on PECAN ECI to be submitted to BAMS.
- Detailed analysis will be performed for a few selected cases using VDRAS to examine the dynamical mechanism of the elevated convection.

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COMPUTATIONAL HYDROLOGY

NEW SCIENCE TO SUPPORT FUTURE WATER RESOURCES PLANNING AND MANAGEMENT

Climate and hydrologic applications for water resources planning and management – such as climate impact assessments and streamflow forecasting – commonly neglect important sources of uncertainty, especially those associated with internal climate system variability, downscaling methods, and hydrologic modeling. Too often resources are limited and tools are unavailable to evaluate more than a single source of uncertainty (e.g., using multiple global climate models). As a result, evaluations of future risk may be over-confident.

Scientists and engineers in RAL's Hydrometeorological Applications Program are collaborating with the U.S. Army Corps of Engineers, the Bureau of Reclamation, and the University of Washington to build tools that will help to characterize uncertainties in climate impacts assessments at each step of the modeling chain. Through developing improved methods,

models, and datasets, this research improves the fundamental building blocks on which hydrometeorological analyses and applications depend. It also, importantly, provides useful tools and data resources for both researchers and practitioners to better reveal climate change risks and more effectively evaluate future change and adaptation options.

ACCOMPLISHMENTS

Models, methods, and datasets

The Computational Hydrology group has made multiple advances in developing models, methods, and datasets. These science advances collectively provide a strong foundation for understanding and adapting to future change, servicing multiple needs for multiple users. The key advances are as follows:

1. *Gridded meteorological ensemble tool (GMET)*: Generates high-quality, probabilistic gridded meteorological fields that can be used to quantify uncertainty of meteorological forcings useful for climate model evaluation, hydrologic model parameter estimation, and hydrologic data assimilation. The first application of GMET, an ensemble gridded dataset of precipitation and temperature for the period 1980-2012, was described by Newman et al. (2015) and is available at http://dx.doi.org/10.5065/D6TH8JR2. Subsequent applications of GMET focus on probabilistic evaluation of WRF model simulations (Prein et al., 2016; Liu et al., 2016).

More details on GMET are available at

https://ncar.github.io/hydrology/projects/meteorological_datasets

1. *Intermediate Complexity Atmospheric Research (ICAR) model*: a quasi-dynamical downscaling approach that uses simplified wind dynamics to perform high-resolution simulations 100 to 1000 times faster than a traditional atmospheric model and can therefore be used to better characterize uncertainty across climate models and in dynamical downscaling. Gutmann et al. (2016) describes the development of ICAR; the ICAR source code is available at https://github.com/NCAR/icar.

More details on ICAR are available at

https://ncar.github.io/hydrology/projects/intermediate-complexity_downscaling

1. *Ensemble Generalized Analog Regression Downscaling (En-GARD)*: a generalized ensemble downscaling utility that can apply most common downscaling methods, e.g. regression, analogs, and new hybrid analog-regression method. It is being used both for forecasting and climate downscaling applications. The development of En-GARD and assessment of forecasting and climate downscaling performance will be documented in a series of papers in the next year. Although it is still at an early stage, the En-GARD source code is available at https://github.com/NCAR/GARD.
2. *Structure for Unifying Multiple Modeling Alternatives (SUMMA) framework*: a new hydrologic modeling framework that provides multiple options to simulate all dominant biophysical and hydrologic processes from the treetops to the stream, and is particularly useful to characterize model and parameter uncertainty in hydrologic model simulations. Clark et al. (2015a; b; c) describes the development of SUMMA; the SUMMA source code is available at https://github.com/NCAR/summa. Some of the SUMMA concepts are used to unify land modeling activities across NCAR, using the ideas in Clark et al. (2015d) and Clark et al. (2016a).

More details on SUMMA are available at

https://www.ral.ucar.edu/projects/summa.

1. *Multi-scale Parameter Regionalization Flex (MPR-flex)*: a model-independent, flexible parameter estimation application that enables continental-domain application of multiple hydrologic models in a spatially consistent way. MPR-Flex is currently under development, and the first paper from this effort will be submitted in the near future (Mizukami et al., in prep).

More details on MPR-Flex are available at

https://ncar.github.io/hydrology/projects/parameter_estimation.

1. *mizuRoute*: a multi-method, continental-domain routing model that efficiently routes streamflow from any distributed hydrologic model through river networks, not just changes on a grid. It has been used to provides streamflow values at 54,000 river segments across the contiguous United States. Mizukami et al. (2016a) describes the development of mizuRoute; the mizuRoute source code is available at https://github.com/NCAR/mizuRoute.

More details on mizuRoute are available at

https://ncar.github.io/hydrology/projects/streamflow_routing.

1. *System for Hydromet Analysis Research and Prediction (SHARP)*: an integrative prediction framework that leverages the methodological advances outlined above to evaluate climate impacts and adaptation options, developed by using real-time demonstrations of streamflow predictions. This research is based on a comprehensive hydrologic predictability assessment, as described by Wood et al. (2016).

More details on SHARP are available at

https://ncar.github.io/hydrology/projects/streamflow_forecasting.

Applications of computational hydrology tools

To assess risks, it is essential to characterize and communicate the uncertainties in hydrologic projections, as illustrated in the figure below (from Clark et al. [2016b]). Each step in the climate impacts modeling chain (first column of the figure) has uncertainties. While several studies have sampled uncertainties by varying elements at each step (second column), they are typically limited by: (i) relying on small ensembles of models that are not independent, often relying on a single model for one or more stages in the modeling chain; (ii) not explicitly accounting for model errors when selecting models and interpreting their results; and/or (iii) presenting results in a way that gives the impression that the uncertainty is fully sampled, when it is not. However, large ensembles, while important in revealing uncertainties, can be computationally impractical in applications, and thus require the development of innovative methods to assess climate impacts.

A key application is to develop quantitative hydrologic storylines of climate change impacts, building on the work of Mizukami et al. (2016b). The work entails systematically characterizing uncertainties across the suite of models used for climate impact assessments; evaluating model fidelity, sensitivity and diversity; culling models to reduce these uncertainties; and distilling hydrologic projections into a discrete set of quantitative hydrologic “storylines” that represent key features from the full range of future scenarios (illustrated in figure and described in more detail in Clark et al [2016]).

These scientific advances provide opportunities to:

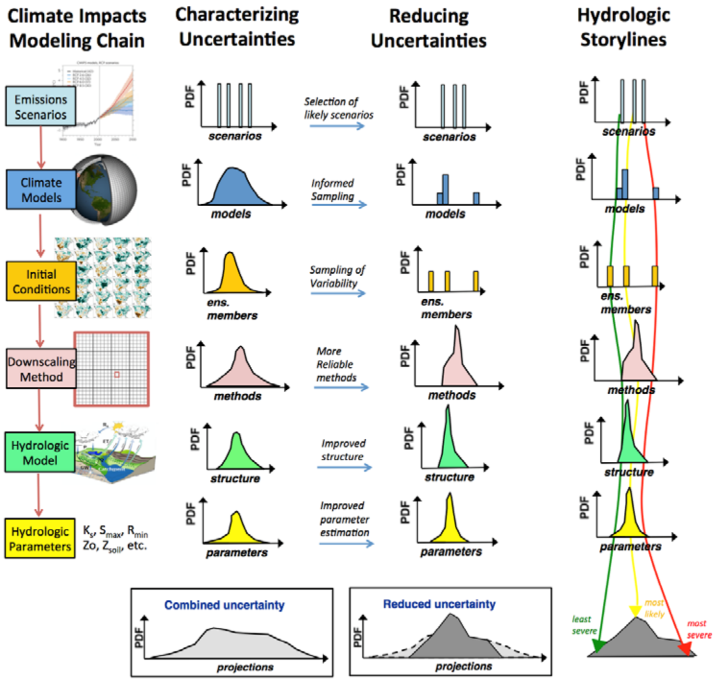
- Continue to refine model evaluation criteria and determine under which conditions models could be downweighted or excluded. Clustering will be used to maximize model diversity and reduce computational costs by identifying redundancies.
- Interact with the broader community to better define end-users needs and identify the specific decisions to be made in planning studies.
- Develop an approach to build quantitative hydrologic “storylines” (fourth column in figure). This will provide the applications community with a manageable subset of future hydrologic scenarios for climate impacts assessments that reveal underlying model uncertainties and are tailored to their planning studies.

We will pursue each of these opportunities in future work (next section).

Future plans

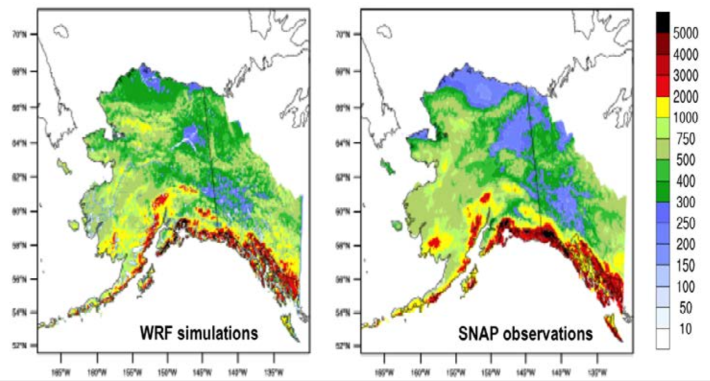
These scientific advances provide a new way to characterize climate impacts on water resources by:

- Moving to large ensembles: this effort, through the collection of tools outlined above, enhances the water resource research community’s ability to generate large ensembles that comprehensively characterize uncertainties and better reveal undiscovered risk.
- Generating hydrologic storylines: large ensembles, while important in revealing uncertainties, can be computationally impractical in applications. As such, there is work underway to distill future scenarios into a discrete set of quantitative hydrologic “storylines” that represent key, impact-focused, features from the full range of scenarios.
- Providing resources for the entire Nation: these tools provide consistent, continental-domain datasets and are currently being implemented in Alaska and Hawaii. Example WRF simulations over Alaska are provided in the figure below.



Schematic on approaches to explicitly characterize and reduce the myriad of uncertainties in evaluating hydrologic impacts of climate change, and develop quantitative storylines to support water resources planning. Figure from Clark et al. (2016b).

Issuing guidance for appropriate use: these tools and datasets are publically available and will be accompanied with documentation for how to use them to support adaptation planning and decision-making.



CAverage precipitation from September 2002 to August 2003 from the WRF model (WRF simulations) and gridded observations from the Scenarios Network for Alaska+Arctic Planning (SNAP observations).

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‹ Short-Term Explicit Prediction up Hydrometeorological Observations ›

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HYDROMETEOROLOGICAL OBSERVATIONS

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 FY2016 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.

HIGH ELEVATION MONITORING FOR SNOWPACK AND WATER SUPPLY PREDICTIONS

FY2016 Accomplishments

A network of snowpack, soil moisture, near surface meteorological and stream water level measurement stations was maintained in the Conejos River basin in southern Colorado (see Fig 1 below). White circles indicate location of NCAR measurement stations, blue squares are NRCS SNOTEL stations, green triangles are Colorado Division of Water Resources streamflow stations). These stations were deployed in 2014 as part of the inter-agency Rio-SNO-FLO project which is performing observational and modeling based research aimed at improving the characterization and prediction of snowpack and seasonal water supplies in the headwaters of the Upper Rio Grande. This work is being done in collaboration with the Conejos Water Conservancy District, the State of Colorado, the NOAA Severe Storms Laboratory and NASA's Jet Propulsion Laboratory. Research conducted during 2016 documented the performance of radar estimated vs. precipitation gauge measured snowfall, observed vs. modeled snowpack depth and near surface temperature, humidity and incoming solar radiation. These results are summarized in a report to the State of Colorado (Gochis et al., 2016; Karsten et al. 2016). The principal outcomes of this work were that research radars possessed significant skill in estimating mountain snowfall as validated by surface precipitation gauges in the southern Colorado region and that when used to drive a physics-based hydrologic model, resulting snowpack and streamflow simulations were significantly improved over simulations using background national analyses of precipitation. As a result, the State of Colorado is currently exploring financial alternatives to purchasing and deploying a gap-filling radar in the Upper Rio Grande basin.

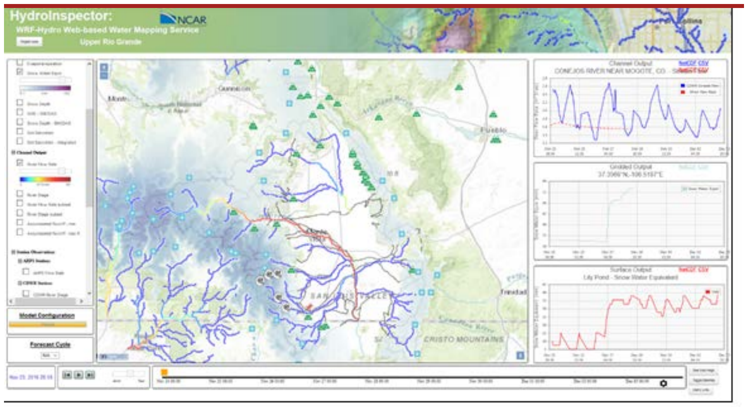

Figure 1: HydroInspector web mapping service display of observation stations (white circles) and observation and model time series (right hand side time series plots) from the Upper Rio Grande observation and modeling project.

Gochis, D.J, K. Howard, J. Busto, J. Deems, N. Coombs, L. Tang, I. Maycumber, K. Bormann, L. Karsten, A. Dugger, N. Langley, J. Mickey, T. Painter, M. Rchardson, and S.M. Skiles, 2016: Upper Rio Grande Basin Snowfall Measurement and Streamflow (RIO-SNO-FLOW) Forecasting Improvement Project. Project report submitted to the Colorado Water Conservation Board. Available online at: http://cwcb.state.co.us/public-information/publications/Pages/StudiesRep....

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Plans for FY2017

Based on the findings of the RIO-SNO-FLO project in the Upper Rio Grande basin NCAR will install 4 new SNOTEL-Lite stations in the Upper Taylor River basin in southern Colorado. (see Figure 2 near Crested Butte, Colorado; station locations are shown with yellow bubbles. Inset shows photo of the station hardware.) These stations are being built and installed in collaboration with the Upper Gunnison River Water Conservancy District (UGRWCD) and the Natural Resources Conservation Service (NRCS). Real-time measurements from these stations are being fed into the GOES satellite communication system and are being downloaded and integrated into the operational NRCS station data stream. NCAR will also prepare and display this information for the UGRWCD using the NCAR/RAL HydroInspector tool along with other model-based snowpack and streamflow prediction products.

Construct, install and operate 5 additional new SNOLITE stations in the headwaters of the Conejos River basin in Upper Rio Grande basin in southern Colorado. This work is being done in collaboration with the Conejos Water Conservancy District, the State of Colorado, the NOAA Severe Storms Laboratory and NASA's Jet Propulsion Laboratory. These stations will be used to validate model-estimated and remotely-sensed

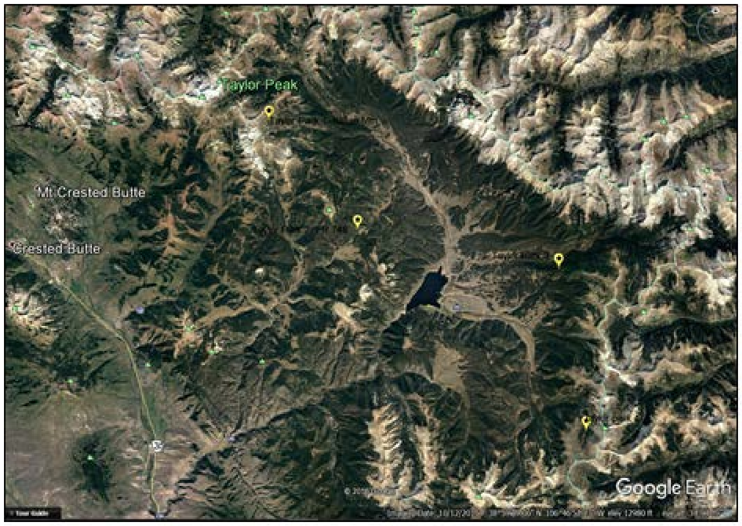

Figure 2: GoogleEarth map plot of the proposed installation sites (yellow balloons) of 4 new SNOTEL lite stations to be deployed in the Upper Taylor River Basin near Crested Butte, Colorado. Inset photo shows the system hardware.

observations of snowpack, soil moisture, precipitation and other near surface meteorological conditions. Once installed, these data will also be telemetered via GOES satellite back to NCAR for quality control, archival, analysis and model evaluation.

MEASUREMENTS AND MODELING OF LAND SURFACE HYDROLOGIC CONDITIONS IN THE NORTH AMERICAN MONSOON REGION

FY2016 Accomplishments

Over the past several years NCAR/RAL has collaborated with Arizona State University (ASU), the University of Sonora and other groups within Mexico to make observations of land surface hydrologic states and fluxes in the region of Northwest Mexico, within the climatic regime of the North American Monsoon region. NCAR is a partner to this project which is led by Prof. Enrique Vivoni of ASU and Prof. Enrique Yepez of U. of Sonora. Over the past year observational data collected from an intensively studied watershed in northern Sonora, the Rio San Miguel, was processed and used in the calibration and validation of the community WRF-Hydro model in the simulation of semi-arid hydrologic responses to monsoon rainfall and in its ability to represent observed land surface flux conditions.

The results of this joint observation-modeling analysis documented the role surface topography and dynamic vegetation phenology has in controlling the spatial and temporal distribution of soil moisture and surface energy fluxes across a steep mountain terrain gradient. The integrated network of rainfall, soil moisture/temperature, radiation and eddy covariance energy flux instrumentation developed under this project has provided some of the first available measurements of these important hydrometeorological variables in complex terrain within the North American Monsoon region. The results of this study have been summarized in Xiang et al., 2016a. A significant outcome of this work has been encapsulated in a follow-on model-based study using a fully-coupled implementation of the WRF/WRF-Hydro system in the simulation and analyses of land-atmosphere coupling behavior within complex terrain regions of the North American Monsoon. The findings from the fully coupled WRF/WRF-Hydro model experiments documented the differing ways vegetation structure and greenness and soil moisture impact land-atmosphere coupling pathways. While positive anomalies of both soil moisture and vegetation density can increase simulated precipitation, the boundary layer structure between soil moisture and vegetation structure anomalies is quite different suggesting there are different energetics that drive the precipitation response, namely, deeper, more vigorous convective circulations versus lower condensation levels. The results of this study are encapsulated in Xiang et al., 2016b.

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Plans for FY2017

This project is now complete, and no further observational plans exist at this time.

BIGHORN MOUNTAINS WINTERTIME CLOUD SEEDING FEASIBILITY STUDY

FY2016 Accomplishments

RAL participated in the deployment of a microwave radiometer and two high-resolution snow gauge sites in the northern region of the Big Horn Mountains in Wyoming for the winter of 2015–2016. These measurements were collected to monitor liquid water path and snowfall in the region. For additional details on this project please see the Winter Weather section of this report.

NSF SNOWIE RESEARCH PROGRAM AND FIELD CAMPAIGN

FY2016 Accomplishments

RAL deployed several instruments in Idaho for the upcoming SNOWIE field program (see Section on Winter Weather: Idaho Power Project). The instrumentation includes two high-resolution snow gauge sites, each with an ETI gauge, a Geonor gauge, and pair of Judd snow depth sensors were installed in the norther portion of the Payette River Basin, to augment snowfall measurements collected by Idaho Power during the SNOWIE campaign. In addition, four microwave radiometers were installed across the Payette Basin, along with a vertically-pointing Ka-Band radar at one radiometer site. Two additional sites with pairs of Judd snow depth sensors were also installed in the eastern, higher elevation portions of the Payette Basin. For additional details on this project please see the section on Winter Weather.

Plans for FY2017

Currently, the majority of the observational work associated with SNOWIE is planned to be completed during the winter of 2016-2017. Additional work in 2017 will focus on quality controlling and evaluating the SNOWIE observations and using them to evaluate and assimilate into hydrometeorological simulation and prediction models. Additional details on these plans can be found in the Winter Weather section of this report.

WMO-SPONSORED SOLID PRECIPITATION INTERCOMPARISON EXPERIMENT (SPICE)

Measurement of wintertime precipitation, both in solid and mixed precipitation phases, presents significant challenges to precipitation measurement instrumentation and can lead to large errors or uncertainties in precipitation estimates. Previously, the most recent comprehensive study, the “WMO Solid Precipitation Measurement Intercomparison” concluded in 1998 and focused on manual techniques of solid precipitation measurement. To address this need, the World Meteorological Organization (WMO) initiated the Solid Precipitation Intercomparison Experiment (SPICE) in 2012 and is currently in its final analysis phase. This experiment involved the participation of 15 snow measurement sites around the world. Each site was outfitted with a variety of automated snow measurement devices to test. The NCAR Marshall field site was one of the sites and included testing of over 50 automated instruments. NCAR RAL co-lead this effort with collaborators from around the world. This project is described in more detail in the Winter Weather section of this report.

MEASUREMENTS OF INTERCEPTED SNOW AND RAIN IN THE FOREST CANOPY

FY2016 Accomplishments

RAL has tested three methods of measuring snow and rain intercepted water content at Niwot Ridge, CO in 2016. The first method uses measurements of the tree stem compression to quantify changes in water stored in the canopy. This system was shown to be highly sensitive to freezing temperatures and a paper is in review documenting these measurements (Gutmann et al., 2016). The second system uses the same equipment measured at 10Hz, or accelerometers measured at

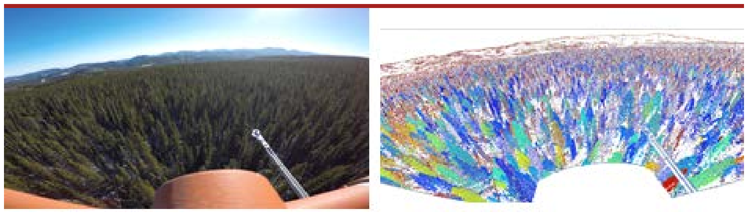

Figure 3: Still image from video captured from the top of the

10Hz, to quantify the magnitude and frequency of trees swaying in the wind. Initial analyses have shown these measurements have been shown to be less sensitive to freezing temperatures, and changes in the tree's intrinsic sway frequencies appear to be related to changes in water storage. The third system uses video cameras to measure tree sway frequencies. This system was just installed and tested this year. Initial results show that this system can measure the sway frequency of all trees that are well resolved in the video (figure).

Ameriflux tower at Niwot Ridge (left), and the sway frequency measured from video collected from this same vantage point (right)

Plans for 2017

The sway frequency measurements from both individual trees, and the video of the forest will be documented in a publication to be submitted in 2017. The sway magnitude data will also be investigated for their use in understanding momentum transfer from the atmosphere to the surface. Relevant measurements of wind speeds at multiple heights are available from the Ameriflux tower for comparison.

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NCAR UCAR Research Applications Laboratory

2016 Annual Report

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WINTER WEATHER

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 originally 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. Scientific results for work conducted in the Wind River and Salt River Ranges may be found in the 2015 Lab Annual Report.

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 Bighorn Range in north-central Wyoming. Key accomplishments in FY2016 for these Wyoming ranges, as well as plans for FY2017, are detailed below.

FY2016 Accomplishments

MEDICINE BOW/SIERRA MADRE FINAL DESIGN AND PERMITTING STUDY

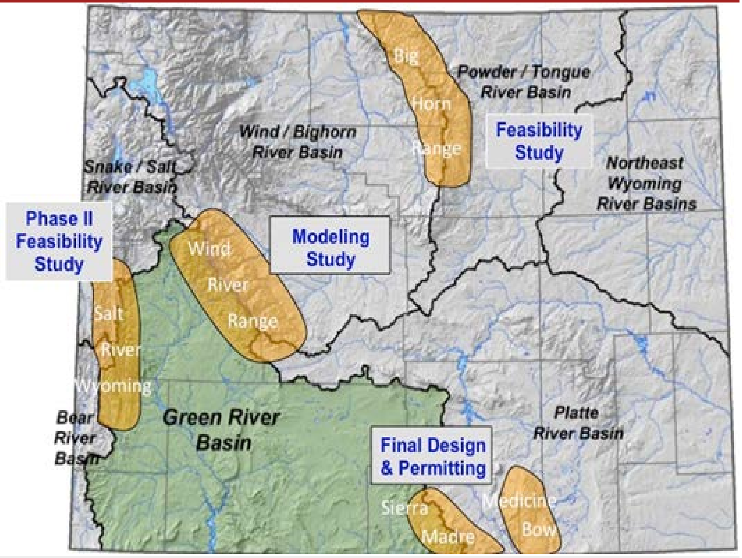

Figure 1. A map of Wyoming with coarse representation of topography and major river basins. Yellow areas denote the five mountain ranges under study related to winter orographic cloud seeding programs: Medicine Bow, Sierra Madre, Wind River, Salt River/Wyoming, and Bighorn Ranges.

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. RAL leads this program with collaboration from WMI and Heritage Environmental Consultants (HEC). This project began in June 2015 and highlights from the analyses conducted in FY16 are presented below. The results were submitted in a draft report to the WWDC in early FY17.

A climatological analysis indicated that the predominant wind regime is westerly and western regions of both mountain ranges were shown to have the most frequent occurrence of seedable conditions for both ground and airborne techniques. In order to test a wide variety of program design options based upon results of the climatological analysis, several groups of potential ground-based generator sites were established (see Figure 2).

Four cases were selected from the WWMPP Randomized Statistical Experiment (RSE) to represent a range of typical seeding conditions in the Sierra Madre and Medicine Bow region in order to investigate the potential designs of a ground-based seeding program using the NCAR cloud seeding model parameterization implemented in the Thompson microphysics scheme within the Weather Research and Forecasting (WRF) model. WRF simulations of these four cases showed that supercooled liquid water (SLW) was present in both ranges throughout the simulations in all cases, which was a prerequisite for precipitation enhancement via seeding. The WRF simulations of ground seeding showed that seeding depleted SLW in a shallow layer close to the terrain and increased precipitation over the mountain. The simulations also indicated that seeding simulated using all six of the Sierra Madre generator groups, including the two upwind groups (E–F), produced the greatest precipitation increases in *both* ranges for most of the cases

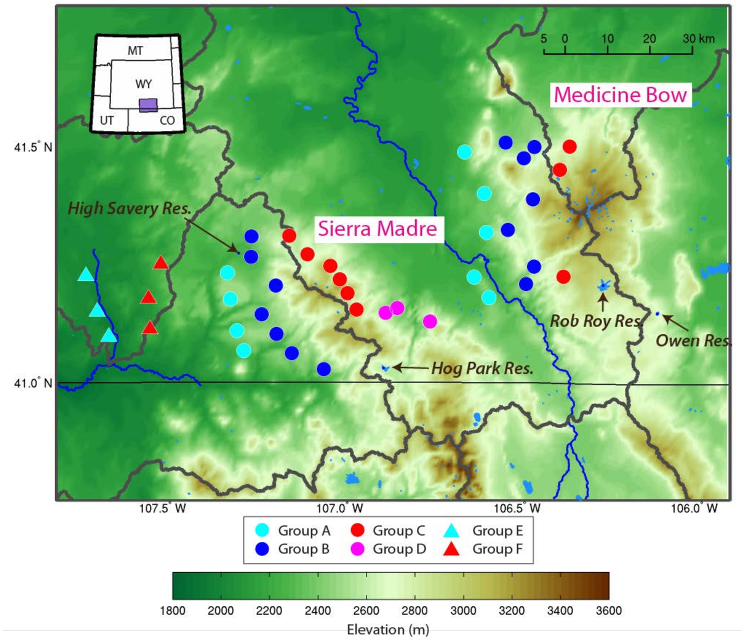

Figure 2. Topography map of the Medicine Bow and Sierra Madre Ranges (m) illustrating the locations of nine ground-based generator design groups.

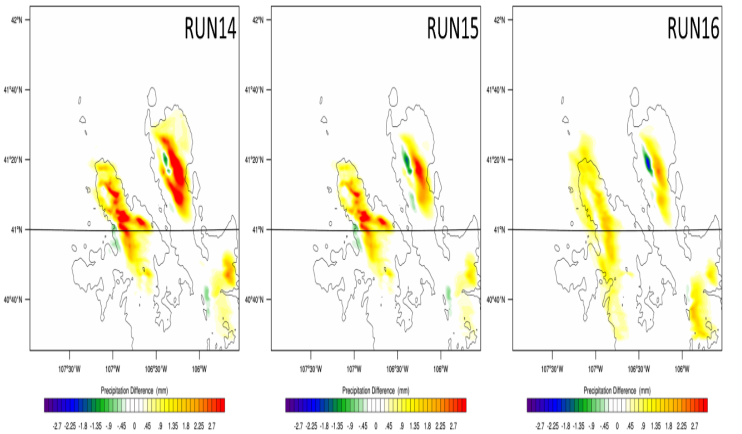

Figure 3. Change in precipitation (mm) due to simulated cloud seeding for model simulations using only Sierra Madre Groups A–F (RUN15) compared to two hours of simulated airborne seeding (RUN16) in the 13 January 2014 case.

tested. The airborne seeding test simulations showed that,airborne seeding for a period of about two hours was shown to produce nearly similar simulated seeding effects to that from ground seeding (compare RUN15 and RUN16 in Figure 3).

This project demonstrated a new method for estimating streamflow changes due to seeding impacts on precipitation using the WRF-Hydro hydrological model, coupled with results of cloud seeding simulations from the WWMPP. This WRF-Hydro simulation method directly ingested the timing, spatial distribution, and magnitude of the simulated seeding effect from cloud seeding simulations as forcing into WRF-Hydro over two water years from the WWMPP. These hydrological simulations indicated that the simulated cloud seeding yielded an additional 5,000–7,750 acre-feet of streamflow across the study region (see Figure 4). It should be noted, however, that at the present time this simulation represents only two years of simulated seeding cases from the WWMPP, which may not be representative of a longer-term average. Moreover, the seeding criteria in the WWMPP were fairly strict and RSE cases were limited to only 4 hours of seeding, so seeding impacts on streamflow from an operational program that has no time limit on seeding periods, for example, could be greater than these results imply. Similar methods should be used to evaluate such impacts on streamflow going forward.

A study to evaluate the cloud seeding model by simulating all 118 RSE cases from the WWMPP is underway. In FY16, the design of this study was developed and focuses on an ensemble modeling approach to better address uncertainties in the model. A set of 96 total simulations will be conducted for each RSE case: 24 serving as control simulations and 72 seeding simulations. The 72-member seeding ensemble will be used to address the seeding process uncertainties in the model. The members were designed to encompass uncertainties arising from the use of different initialization data sets, boundary layer schemes, cloud condensation nuclei and ice nuclei background levels, silver iodide (AgI)

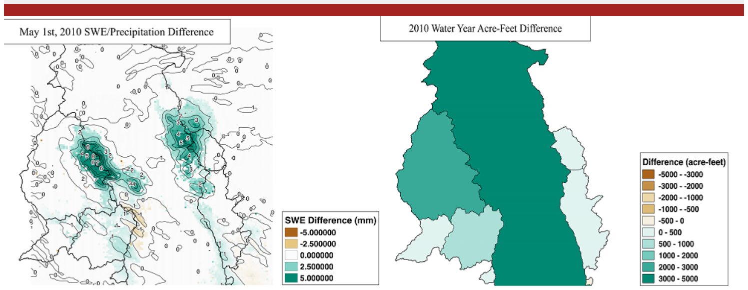

Figure 4. WRF-Hydro simulation results from water year 2010: difference between seeded and unseeded snow water equivalent

activation and removal functions, as well as spatial and temporal uncertainties of the simulated precipitation.

(SWE) for 1 May 2010 (colored), along with accumulated precipitation difference (mm; contour) on the left, and total accumulated streamflow differences (AF) for the 2010 water year from the non-seeded to seeded simulation by basin on the right. The basins shown in the right panel are outlined in thick black lines on the left for reference.

BIGHORN MOUNTAINS FEASIBILITY STUDY

The WWDC funded a feasibility study to assess the potential for cloud seeding in the Bighorn Mountains in north-central Wyoming. RAL leads this program with collaboration from WMI and HEC. This project began in June 2015 and highlights from a few tasks completed in FY16 are provided below. A draft report summarizing the results of this study was submitted to the WWDC in August 2016.

A climatological study of the project area was conducted to determine the characteristics of wintertime precipitation in the Bighorn Mountains and estimate how frequently environmental conditions would be amenable to seeding. The climatology analysis indicated that the typical wind regimes in the Bighorns are westerly to northwesterly, with few easterly (upslope) events on the eastern slopes. A spatial mapping analysis revealed that liquid water content (LWC) most frequently develops on the western and northeastern slopes of the mountains with the most frequent seeding opportunities on the western slopes. A microwave radiometer and high-resolution snow gauges were deployed to the northern end of the Bighorns during the winter of 2015–2016 in order to collect measurements of liquid water path and snowfall, to aid in this investigation.

Based only on temperature and LWC criteria, ground seeding had equal or more frequent opportunities than airborne seeding during the November–April wintertime period. When considering additional criteria required for ground-based seeding (wind direction and stability for transporting ground-released AgI into the targeted clouds), ground-seeding opportunities dropped to nearly zero in the eastern and southern regions, and were substantially reduced in the western region. In fact, airborne seeding potential in the western region is greater than ground seeding potential in the western region, especially when considering the additional criteria necessary to implement ground-based seeding (Figure 5).

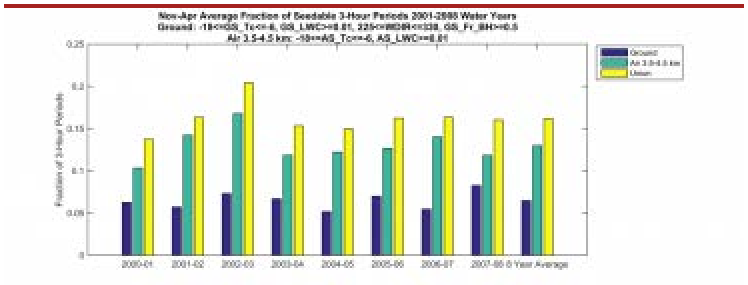

Figure 5. Ground (0–1 km AGL; blue) versus airborne (3.5–4.5 km MSL; green) seeding opportunities by November–April season in the western region (fraction of hours in the season that meet the designated criteria, listed atop the figure), and the 8-year average. The frequency of occurrence of cases from the union of both ground and airborne seeding potential is shown in the yellow bar for each time period.

Three test cases were simulated with the NCAR cloud seeding model to evaluate the impact of six groups of proposed ground generators and several potential aircraft tracks (Figure 6). The test cases were selected to represent various meteorological scenarios encountered in the Bighorn Mountains, but not every scenario may have been represented by this limited sample.

Based upon the model simulations of the three test cases, in general, ground seeding had very limited spatial impact on the region, and Groups A and B rarely impacted the target area. Group C had positive simulated seeding effects in some meteorological conditions, especially when the winds had a north-northeasterly component. Groups D and F yielded the best results for ground-based seeding, yet the impact area was still rather small and confined to very narrow plumes (Figure 7). In the cases tested, Group E had quite minimal overall simulated impacts (Figure 7).

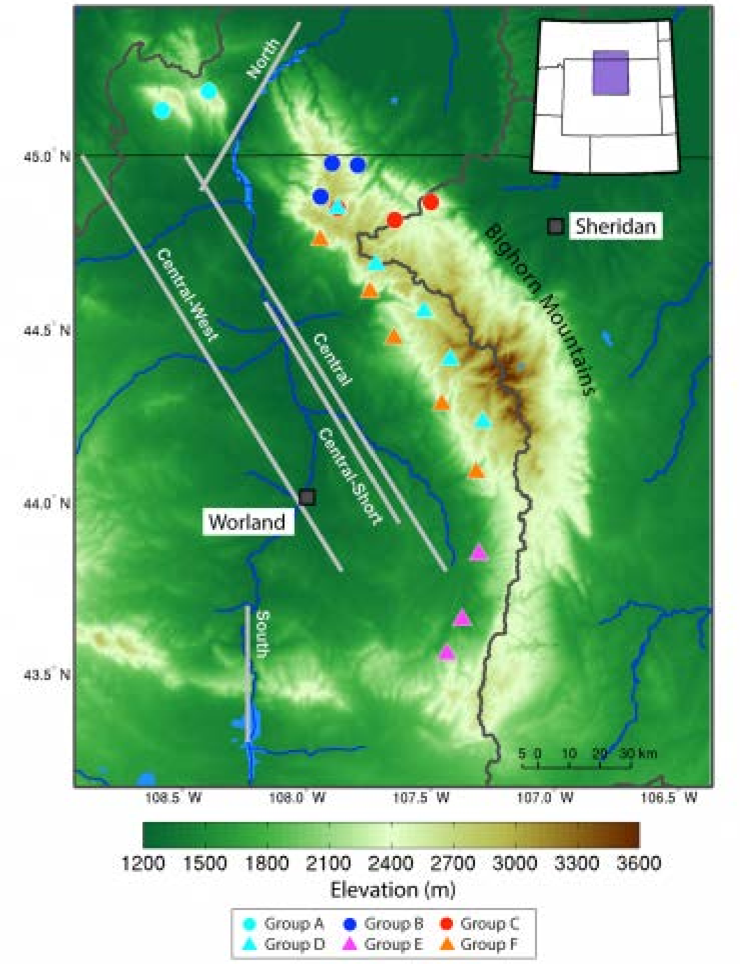

Figure 6. Map of the proposed ground generator groups and potential airborne seeding flight tracks tested with the model.

Airborne seeding tended to yield the most widespread and biggest simulated seeding effects in these cases (Figure 7). The benefit of airborne seeding is that it can be performed wherever the most SLW is present. This can include situations where elevated SLW extends quite far upwind (to the west) of the mountains, as occurred in some of these cases. In fact, airborne seeding is the only way to impact elevated SLW layers over the Bighorn River Basin because the air is too stable in this valley to use ground generators to reach those higher altitudes. Yet, it should be noted that not all of the simulated seeding effects from seeding further upwind impact the higher elevations of the Bighorn Mountains; rather they broadly impact the Bighorn Basin in general. Based on the modeled climatology, easterly upslope events include SLW, but occur infrequently. Therefore, due to the lower frequency of occurrence, siting ground generators on the eastern slope of the Bighorns is not advised, but it should be noted that airborne seeding is versatile enough that it can also be used to target easterly upslope events.

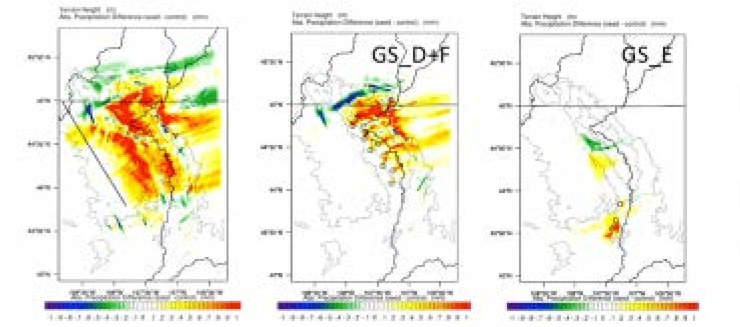

Figure 7. Simulated seeding effects (changes in precipitation, mm) for the 20 November 2007 case from simulated airborne seeding along the Central-West track (left), ground-based seeding with Groups D+F (middle), and ground-based seeding using Group E (right).

FY2017 Plans

- Complete the model evaluation of the WWMPP RSE for the Medicine Bow/Sierra Madre Final Design and Permitting study, and submit a final report on the findings
- Submit revised, final report on the Bighorn Mountains Feasibility Study

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 hydroelectric generation. The program has been focused in the Payette River basin in western Idaho and the upper Snake River system in eastern Idaho (Figure 8), and has recently expanded into the Boise and Wood basins in western Idaho.

In FY16, RAL completed a numerical modeling “Phase Five” 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 Five was to complete the development of a real-time cloud seeding forecast

guidance system using the WRF model developed in Phases Three–Four, including a real-time web-based display to provide IPC forecasters with graphical output from the real-time forecast system. Since the completion of Phase Five, a Phase Six study was begun with goals to continue research and improvements to the cloud-seeding module utilized in Phases One–Five. Planning for an upcoming field project, SNOWIE, funded by the National Science Foundation (NSF) in partnership with IPC is also underway.

FY2016 Accomplishments

In 2016, 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 2015-2016 winter season;
- completing a prototype web-based display system to incorporate the IPC observational data in near real time and the display of model validation data alongside available observations, and then running it during the 2015-2016 season;
- simulating cloud-seeding effects for selected cases that were seeded by Idaho Power during the winter season (hereafter, the retrospective cases);
- improving the dispersion and physical removal processes of AgI in the model;
- comparing model simulation results with observations when available, such as measurements of silver in the snow; and,
- preparing for an upcoming NSF field project called Seeded and Natural Orographic Wintertime clouds: the Idaho Experiment (SNOWIE)

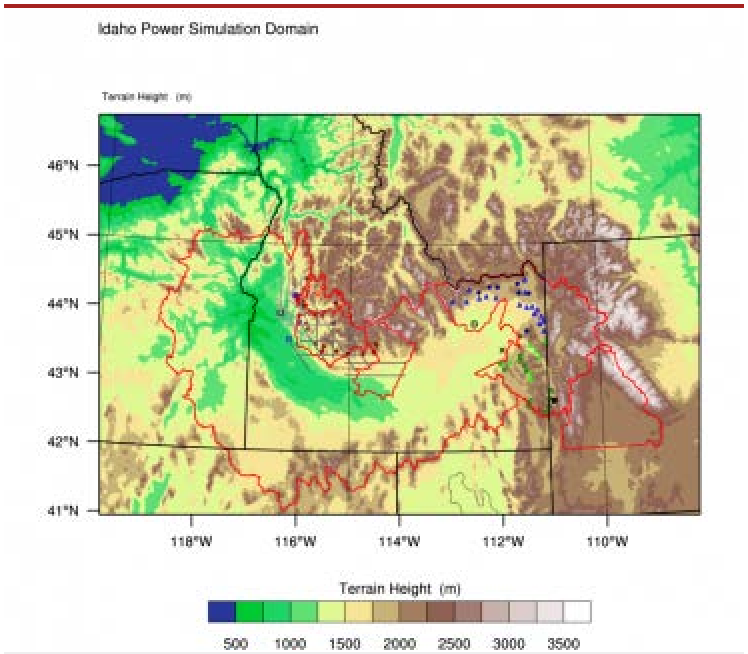

Figure 8. Map of the Snake Watershed in Idaho (large red outline) and existing ground generator and observational facility sites on a map of terrain height (m; color shading). The Payette River Basin, Boise Basin, and Woods Basin target areas are located (north to southeast) in the western Snake watershed, 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).

Given that the dispersion of AgI is a key process that determines the targeting efficiency and ultimately the seeding effect on the ground, improving how the model simulates this process is of paramount importance for the model to realistically simulate cloud seeding impacts. Therefore, simulations were performed to understand the behavior of AgI dispersion using different Planetary Boundary Layer (PBL) and Land Surface Model (LSM) schemes, as well as testing the new inline dispersion model (i.e. HYSPLIT) feature in the WRF model. The results of these tests were then utilized to simulate three cases from the 2015–2016 winter season in which trace chemistry (i.e. silver) measurements in the snow had been collected for comparison with the model simulations. The trace chemistry sampling experiment to measure silver in the snow was carried out by Boise State University. The measurements were collected in target and downwind areas to serve as validation data for the AgI dispersion simulated by the model. However, the original cloud seeding module (Wintertime AgI Seeding Parameterization, or WASP) did not consider some physical processes related to AgI removal that can impact the simulated silver deposition

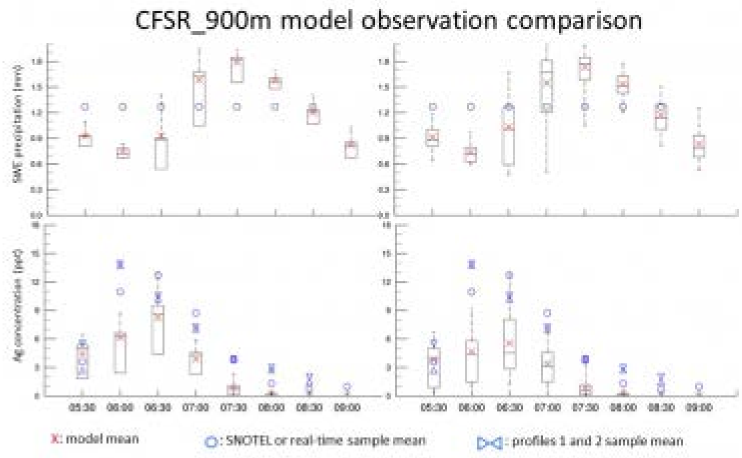

Figure 9. Box and whisker plots of model-simulated SWE (top) and Ag concentration (bottom) for every 30 minutes from 0530 to 0900 UTC (black boxes, red ‘x’ for mean). The distributions for the boxes and whiskers (dashed lines) were based upon the 9 data points surrounding the sampling site (left column) and 25 data points (right column). Overlaid on each panel are observations from the SNOTEL (blue open circles; top row) and BSU lab Ag in snow measurements (blue open circles for measurement mean and blue triangles to show the profile sample means; bottom row) from the 0200-0530 UTC period. (The model simulation of precipitation showed a 3.5-hour time offset in when the simulated storm began producing precipitation, thus the time offset analyzed above).

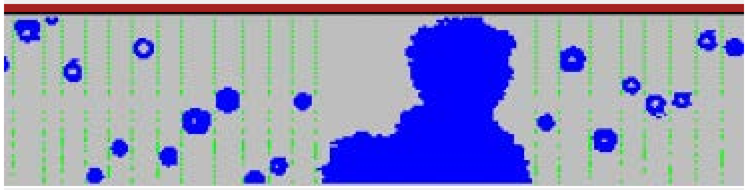

Figure 10. Images from the Cloud Imaging Probe on the Univ. Wyoming King Air on 12 February 2014 at 4300 m MSL altitude (–10°C) indicating supercooled drizzle-sized drops and occasional dendritic ice crystals. The vertical axis corresponds to 1600 µm.

and downwind seeding effect. To address these issues, the WASP was modified to include the missing physics: AgI self-coagulation, AgI scavenging by precipitating particles, and AgI dry deposition due to surface roughness and turbulence. At the same time, the WASP was implemented into the new Thompson-Eidhammer microphysics scheme in WRF v3.7.1 to take advantage of prognostic aerosol effects on clouds and precipitation. An example analysis comparing the silver in snow measurements with the model simulations is presented in Figure 9.

Five cases from 2015–2016 were selected for further study with retrospective case simulations. These cases were chosen to evaluate the potential seeding effects for cases seeded by IPC in a manner not specifically called by the real-time model. Additional simulations for each case were also run to test the sensitivity of the results to initialization time, whether the new scavenging processes added to the cloud seeding parameterization were turned on or not, and to seeding rate or ground or airborne seeding method. Several model simulations were also conducted in order to optimize the program design of the IPC cloud seeding program, including testing the impacts of doubling the number of ground-based generators versus doubling the seeding rates of existing generators, using aircraft instead of or in addition to ground generators, and investigating using bin microphysics schemes in a real three-dimensional simulation to see if a more sophisticated microphysics scheme improved simulation results. The latter bin microphysics test simulations were performed on a case that occurred when “pre-SNOWIE” research aircraft measurements were being made in February 2014. This case consisted of stable orographic wintertime clouds with freezing drizzle observed near Boise, Idaho during an atmospheric river event during which the University of Wyoming King Air collected in situ microphysical measurements as well as cloud radar measurements. Analysis of the observations (Figure 10) and measurements collected in this case and model simulations of this case were presented at the American Geophysical Union (AGU) fall meeting in December 2015 and at the International Conference on Clouds and Precipitation (ICCP) in July 2016.

A new program, Seeded and Natural Orographic Wintertime clouds—the Idaho Experiment (SNOWIE), was funded by NSF in the spring of 2016. The project is led by Dr. Jeff French (Univ. Wyoming), with involvement from Dr. Bart Geerts (Univ. Wyoming), Bob Rauber (Univ. Illinois), and Katja Friedrich (Univ. Colorado), as well as Roy Rasmussen, Sarah

Tesendorf and Lulin Xue of RAL.   With funding support from IPC, RAL has also been heavily involved in the planning of this field project, from the proposal writing to planning for the operations and deploying instruments (i.e., high-resolution snow gauges, radiometers, snow depth sensors) to the field (Fig 11 below).The project will take place in January–March 2017 and aims to evaluate ground and airborne cloud seeding using physical and numerical modeling approaches, as well as to validate the cloud seeding module. RAL will participate in the SNOWIE field project and continue making improvements to the cloud seeding forecast guidance system. As part of the Phase Six effort, RAL has developed a new case-calling algorithm that will be tested in parallel with the real-time modeling system during the 2016–2017 winter season. New features will also be added to the web-based display.

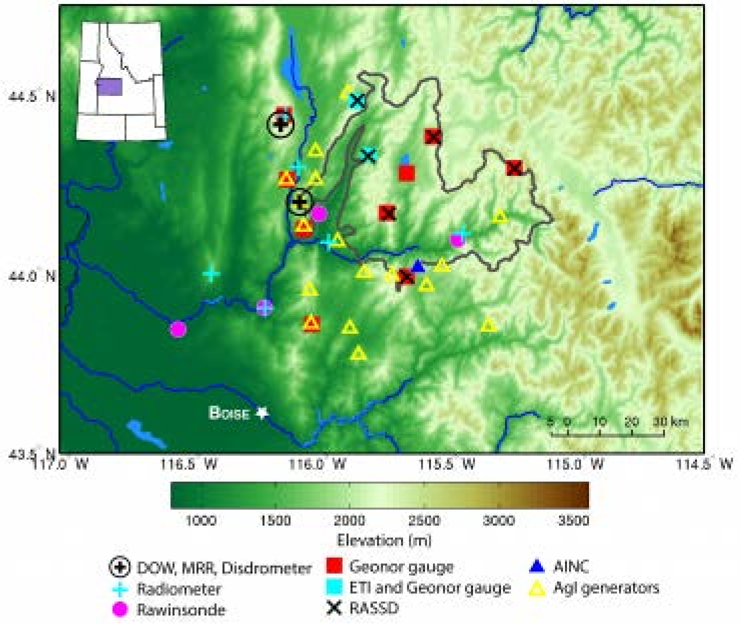

Figure 11: Map of ground-based instruments deployed for SNOWIE

FY2017 Plans

- Run the newly created seeding case-calling algorithm in parallel with the real-time model for the 2016-2017 season;
- Run updated display system with new features for 2016–2017 winter season;
- Conduct the SNOWIE field project and collaborate with SNOWIE university PIs to perform preliminary analysis on high priority cases;
- Run simulations of cases with silver in snow samples and collaborate with Boise State University to compare model results with measurements;
- Perform detailed case study simulations and analyses to improve the cloud seeding module, using cases from SNOWIE and pre-SNOWIE;
- Publish journal papers on the major findings from these studies.

‹ Hydrometeorological Observations   up   WMO Solid Precipitation Inter-comparison Experiment (SPICE) ›

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WMO SOLID PRECIPITATION INTER-COMPARISON EXPERIMENT (SPICE)

EVALUATION OF SOLID PRECIPITATION GAUGES AT THE MARSHALL FIELD SITE AND NUMERICAL MODELING AS PART OF THE WMO SOLID PRECIPITATION INTER-COMPARISON EXPERIMENT (SPICE)

Background

Precipitation is one of the most important atmospheric variables for irrigation, water resources, 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. To address the need for an assessment of automatic precipitation measurements currently in use, the World Meteorological Organization (WMO) initiated the Solid Precipitation Intercomparison Experiment (SPICE) in 2012. This experiment involved the participation of 15 snow measurement sites around the world, each of which was outfitted with a variety of automated snow measurement devices to test. The NCAR Marshall field site was one of the sites selected and ultimately hosted more than 50 automated instruments. NCAR was also the official data archive site for the experiment. The experiment concluded its three-year data collection period on April 30th, 2016.

FY2016 Accomplishments

Data from the SPICE field sites are being analyzed by scientists from NCAR and NOAA. The data are being compared to reference measurements made by a Double Fence Intercomparison Reference gauge (DFIR) at each primary site. A fundamental result is that the collection efficiency of snowgauges for snow depends the type of shielding used, a finding which is in agreement with previous studies. The equation correcting a gauge for undercatch is termed a transfer function. One of the key accomplishments was the determination that a universal transfer function could be used for a given shield configuration independent of the location of the gauge. These results have been written up in various publications and also in a final report. The final report is undergoing internal review and should be available in early 2017.

FY2017 Plans

Finalize the SPICE final report and associated publications. Continue operating the Marshall Field site as funding allows. Start planning for a potential future study that examines the cause of for the undercatch of snowgauge/shield pairs using a combined modeling/observational approach.

‹ Winter Weather up Land Atmosphere Interactions ›

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LAND ATMOSPHERE INTERACTIONS

BACKGROUND

The main objectives of the land-atmosphere interaction group are to understand, through theoretical and observational studies, the complex interactions (including biophysical, hydrological, and biogeochemical) between the land-surface and the atmosphere cross a wide range of temporal and spatial scales. The ultimate goal is to improve the community Noah and Noah-MP land-surface models and to integrate such knowledge into numerical mesoscale weather prediction and regional climate models in order to improve prediction of the impacts of land-surface processes on regional weather, climate, and water system. In 2016 efforts were focused in the following areas:

1. Understanding and mitigating uncertainties in the community Noah-MP land model simulations over the complex terrain Tibet region

Despite the widespread use of the new community Noah with multiparameterization (Noah-MP) land-surface model (LSM), it has not been rigorously evaluated over the complex Tibetan Plateau (TP). A new study in 2016 assessed uncertainties in Noah-MP simulations of a cropland site using observations from the 2008 Joint International Cooperation program (JICA) field campaign. This assessment was conducted in the context of performing a total number of 4,608 Noah-MP physics ensemble simulations using two analysis methods—the natural selection approach and Tukey's test—in which the impacts of uncertainties in atmospheric forcing conditions, vegetation parameters, and sub-processes on model simulations were identified. The control ensemble simulation (Ens 1 in Fig. 1) significantly underestimated (overestimated) latent (sensible) heat fluxes. Uncertainty in precipitation data (Ens 2) exerts greater influence on the general behavior of Noah-MP ensemble simulations than that in the leaf area index (LAI) (Ens 3). However, using a more realistic seasonal LAI improves the seasonal variations of surface heat fluxes. Combining a better precipitation forcing dataset and MODIS monthly LAI (Ens 4) significantly reduces the uncertainty range of the ensemble mean of surface heat fluxes (Fig. 1). The uncertainty analysis results using the natural selection method are largely similar to that from Tukey’s test, but show some subtle differences. Both methods reveal greater uncertainties in the following sub-process schemes: canopy resistance, soil moisture threshold for evaporation, runoff and groundwater, and surface-layer parameterization for this cropland site (Zhang et al. 2016). The uncertainty analysis identifies the parameterization schemes that demonstrably degrade model performance. The uncertainties in ensemble simulations were significantly reduced when those schemes were excluded, and it was possible to configure an optimal combination of parameterization schemes to obtain similar performance to the ensemble mean of the “best” ensemble experiment.

A similar study was conducted for the sparsely vegetated Amdo site located in the Central TP, using the Noah-MP ensemble simulations LSM to assess the relative importance of parameterizing vertical soil heterogeneity, organic matter, and soil rhizosphere, and their impacts on seasonal evolution of soil temperature, soil moisture, and surface energy and water budgets. Representing layered soil texture and organic matter does not improve low biases in topsoil moisture. Reducing the saturated conductivity from the mucilage in the rhizosphere produces better results. Surface sensible and latent heat fluxes are better simulated in the monsoon season as well. Adding layered soil texture and organic matter in Noah-MP retard the thawing in deep soil layers, and the rhizosphere effect delays thawing even more in the transient season. Uncertainties in soil initialization significantly affect deep-soil temperature and moisture, but uncertainties in atmospheric forcing conditions mainly affect topsoil variables and consequently the surface-energy fluxes. Differing land-surface physics cause 36% uncertainty in the accumulated evapotranspiration and subsurface runoff (Gao et al. 2015).

Reference:

Gao, Y., K. Li, F. Chen, Y. Jiang, and C. Lu, 2015: Assessing and improving Noah-MP land model simulations for the central Tibetan Plateau. *J. Geophys. Res., DOI: 10.1002/2015jd023404.*

Zhang, G., F. Chen, and Y. Gan, 2016: Assessing uncertainties in the Noah-MP ensemble simulations of a cropland site during the Tibet Joint

International Cooperation program (JICA) field campaign. *J. Geophys. Res., 121, doi:10.1002/2016JD024928.*

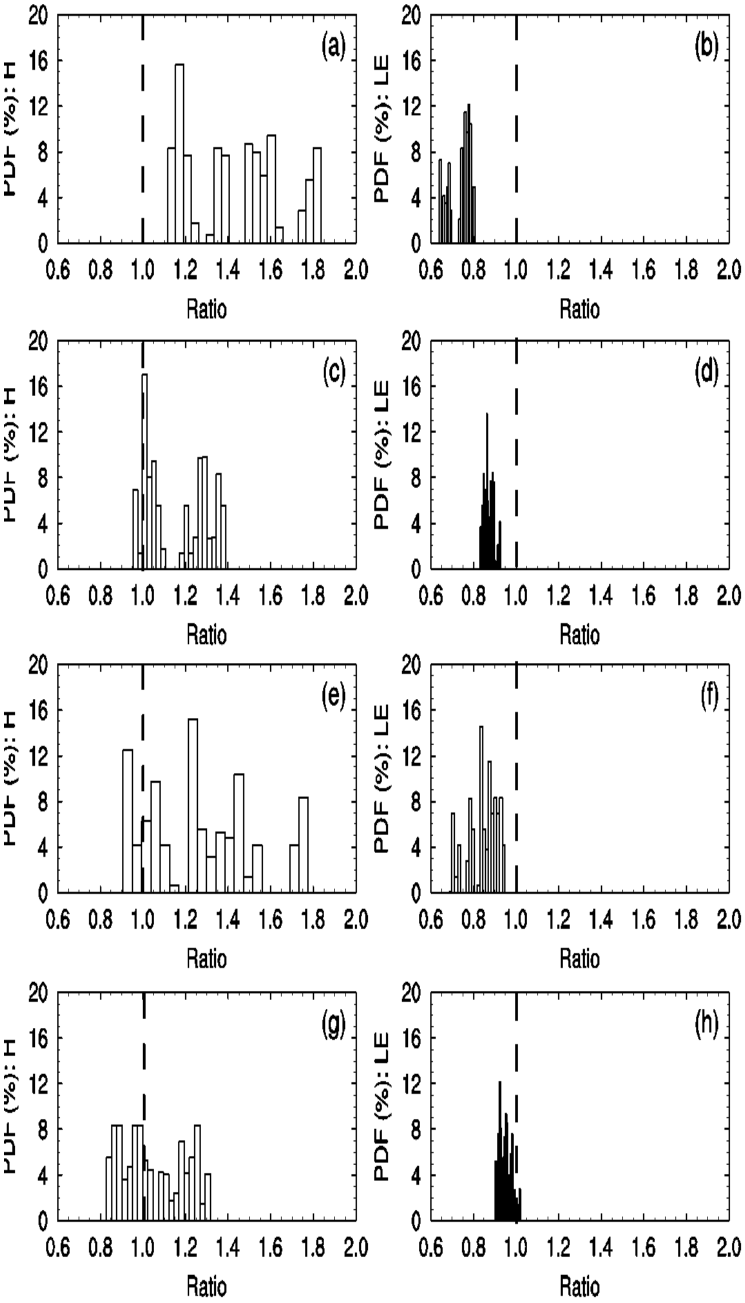

Fig. 1. The probability density distribution of flux simulations in ensemble experiment Ens1 (top panel), Ens2 (second panel), Ens3 (third panel) and Ens4 (bottom panel) in 2008. The x-axis: the ratio of simulated daytime accumulated sensible heat fluxes (H) to observed values (left panel) and the ratio of simulated accumulated latent heat fluxes (LE) to observed values(right panel) (daytime: 10am-15pm); The y-axis: probability distribution of these ratios; Ratio < 1: accumulated flux is underestimated; Ratio >1: accumulated flux is overestimated; Vertical dash line: ratio = 1, i.e., observed and simulated accumulated flux are equal.

2. Developing the WRF-Crop modeling capability

This project aims to improve the representation of cropland-atmosphere interactions in the community Noah-MP LSM with the ultimate goal to integrate it in a coupled model to improve seasonal weather forecasts and regional climate simulations for the NCAR Water System Program. 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.

We have introduced dynamic corn (Zea mays) and soybean (Glycine max) growth simulations and field management (e.g.,

planting date) into Noah-MP and evaluated the enhanced model (Noah-MP-Crop) at field scales using crop biomass datasets, surface heat fluxes, and soil moisture observations. 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 (Fig. 2). This model is able to capture the seasonal and annual variability of LAI, and to differentiate corn and soybean in peak values of LAI as well as the length of growing seasons. Improved simulations of crop phenology in Noah-MP-Crop led to better surface heat flux simulations, especially in the early period of growing season where current Noah-MP significantly overestimated LAI. The addition of crop yields as model outputs expand 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. The capability introduced in Noah-MP allows further crop related studies and development.This new Noah-MP-Crop modeling capability was released in the WRF version 3.7 in 2016. Further test and evaluation are undertaken in the context of coupled WRF regional climate simulations.

References:

Liu, X., F. Chen, M. Barlage, G. Zhou, D. Niyogi, 2016: Noah-MP-Crop: Introducing Dynamic Crop Growth in the Noah-MP Land-Surface Model. *J. Geophys. Res., DOI: 10.1002/2016JD025597*

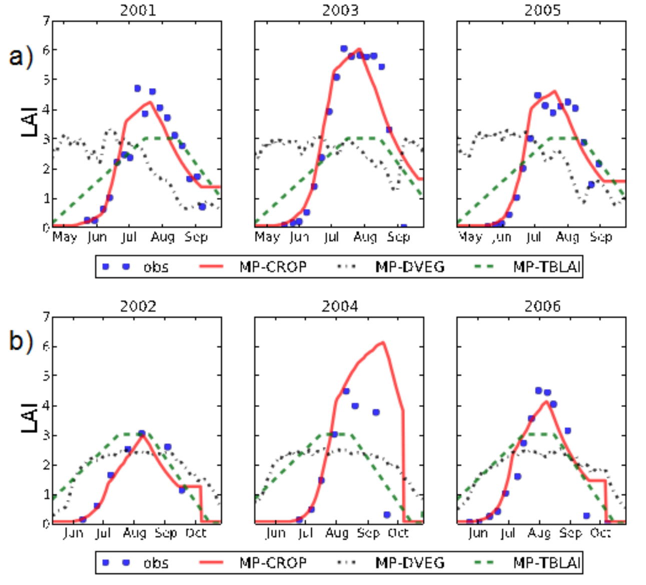

Figure 2. a): Comparisons of simulated LAI for corn at the Bondville (Illinois) site; b): Comparisons of simulated LAI for soybean at the Mead (Nebraska) site. MP-Crop: simulation with Noah-MP-Crop model; MP-DVEG: simulation with default Noah-MP dynamic vegetation model; NP-TBLAI: simulation using the Noah-MP look-up table LAI.

4. Enhancing the WRF-urban modeling system and its applications to real-time weather forecasts for mega cities

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 (UCM) have been developed and implemented into the WRF model to capture urban land-surface processes, but those UCMs were coupled to the simple Noah LSM. We recently couple the more advanced Noah-MP LSM to WRF-Urban as well as to the urbanized high-resolution land data assimilation system (u-HRLDAS). This new modeling capability was tested over Phoenix and Beijing metro areas and will be released in WRF in 2017.

We also applied WRF-Urban to assess the degree to which a detailed urban modeling approach can improve real-time weather prediction for cities (Barlage et al. 2016). The 1 km Institute of Urban Meteorology (IUM) operational model has a high-temperature bias, especially at night, and a high wind speed bias in urbanized areas, limiting the ability of IUM to provide accurate, high-resolution prediction of thermal stress and air quality for the densely populated Beijing-Tianjin metro region. WRF-Urban hindcast results showed that non-turbulent kinetic energy (TKE) planetary boundary layers (PBL) schemes perform better than their counterpart TKE-based schemes at night, reducing the warm bias by about 1°C in nonurban areas. However, the best performing urban PBL scheme still produced ~2°C warm bias. Considering aerosol effects in the solar radiation scheme improves downward solar radiation and surface energy budgets but has negligible effect on the simulated temperature. UCMs and the specification of various urban model parameters have comparable or even more significant contributions to forecast biases in temperature and wind speed than PBL schemes. The predicted PBL height using an optimized urban parameter table is lower by about 100–200 m, which is about 50–100% of the interurban scheme effect on the PBL height. Overall, the Building Effect Parameterization urban

scheme with the default parameter table, or a parameter table with less urban heat storage, is recommended for the best results in urban areas and shows that most of the urban areas of Beijing and Tianjin have a greater than 4°C improvement in absolute temperature bias and more than 1 m s−1 improvement in absolute wind speed bias (Fig. 3).

References:

Barlage, M., S. Miao, and F. Chen, 2016: Impact of physics parameterizations on high-resolution weather prediction over complex urban areas. *J. Geophys. Res.,* 121, 4487–4498, doi:10.1002/2015JD024450.

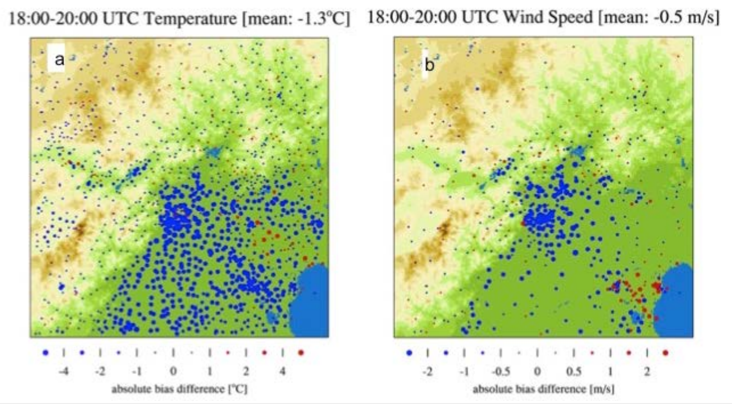

Fig. 3. 18 – 20Z absolute bias difference in two-meter temperature (a) and ten-meter wind speed (b) between a simulation using BEP with reduced parameter table and the operational 1 km IUM setup. Blue (negative) indicates AWS sites where bias improved; red (positive) where bias degrades.

5. Understanding effects of fire-induced surface changes on the diurnal temperature changes over the Hayman Fire scar

Results from the 2010 BEACHON experiment showed that nighttime temperatures over the 2002 Hayman fire scar (the Hayman, CO site) were significantly warmer than over a site outside the fire scar (the Manitou, CO site). Temperature differences reached up to 7 K at the surface, and extended to an average of 500 m AGL. Afternoon temperatures through the planetary boundary layer (PBL) were similar at the two locations. PBL growth during the day was more rapid at Manitou until 1300 local time, after which the two daytime PBLs had similar temperatures and depths. Observations were taken in fair weather, with weak winds. Simulations results, using WRF coupled to Noah-MP suggest that the fire-induced loss of surface and soil organic matter accounted for the 3-4-K warming at Hayman relative to its pre-fire state, more than compensating for the cooling due to the fire-induced change in vegetation from forest to grassland. Modeled surface fluxes and soil temperature and moisture changes were consistent with observational studies comparing several-year-old fire scars to adjacent unaffected forests.

The remaining difference between the two sites is likely from cold-air pooling at Manitou. However, it was necessary to increase vertical resolution and replace terrain-following diffusion with horizontal diffusion in ARW-WRF to better capture nighttime near-surface temperature and winds. Daytime PBL growth and afternoon temperature profiles were reasonably reproduced by the basic run with post-fire conditions. However, winds above the surface were only fairly represented, and refinements made to capture cold pooling degraded daytime temperature profiles slightly.

References:

LeMone, M. A., B. Wan, M. Barlage, and F. Chen, 2017: The influence of fire-induce surface changes on the diurnal temperature change over the Hayman fire scar. doi: 10.1175/JAMC-D-16-0132.1

6. Water System: Improve the community Noah-MP LSM to enhance 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 the operational National Water Model (NWM) and RAL/HAP WRF convection-permitting climate modeling efforts. To enhance its global applicability, the Noah-MP model was evaluated using snow and surface-heat-flux observations obtained from the Colorado Headwaters, 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 parameterizations have been improved such as canopy snow interception and sublimation for forested regions. New parameterizations of organic soil (Chen et al. 2016), sparse vegetation rhizosphere

(Gao et al. 2015), simple nitrogen dynamics (Cai et al. 2016), and a dynamic crop-growth model (Liu et al. 2016) have been introduced to Noah-MP and evaluated against field observations.

Dynamical Downscaling Modeling (DDM) is important to understanding regional climate change and developing local mitigation strategies. The accuracy of DDM depends on the physical processes involved in the regional climate model as well as the forcing datasets derived from global models. We investigated the relative role of LSM and forcing datasets in the DDM over the Tibet Plateau (TP), a region complex in topography and vulnerable to climate change. Three WRF dynamical downscaling simulations configured with two land surface schemes (Noah versus Noah-MP) and two forcing datasets (CCSM vs ERA-Interim) were performed for the 1980 to 2005 period. The downscaled temperature and precipitation were evaluated with observations and inter-compared regarding temporal trends, spatial distributions, and climatology. Results show that the temporal trends of the temperature and precipitation are determined by the forcing datasets, and the forcing dataset with the smallest trend bias performs the best. Relative to the forcing datasets, land surface processes play a more critical role in the DDM over the TP due to the strong heating effects on the atmospheric circulation from a vast area at exceptionally high elevations (Fig. 4). By changing the vertical profiles of temperature in the atmosphere and the horizontal patterns of moisture advection during the monsoon seasons, the land surface schemes significantly regulate the downscaled temperature and precipitation in terms of climatology and spatial patterns (Gao et al. 2016). This study emphasizes that the selection of land surface schemes is of crucial importance in the successful DDM over the TP.

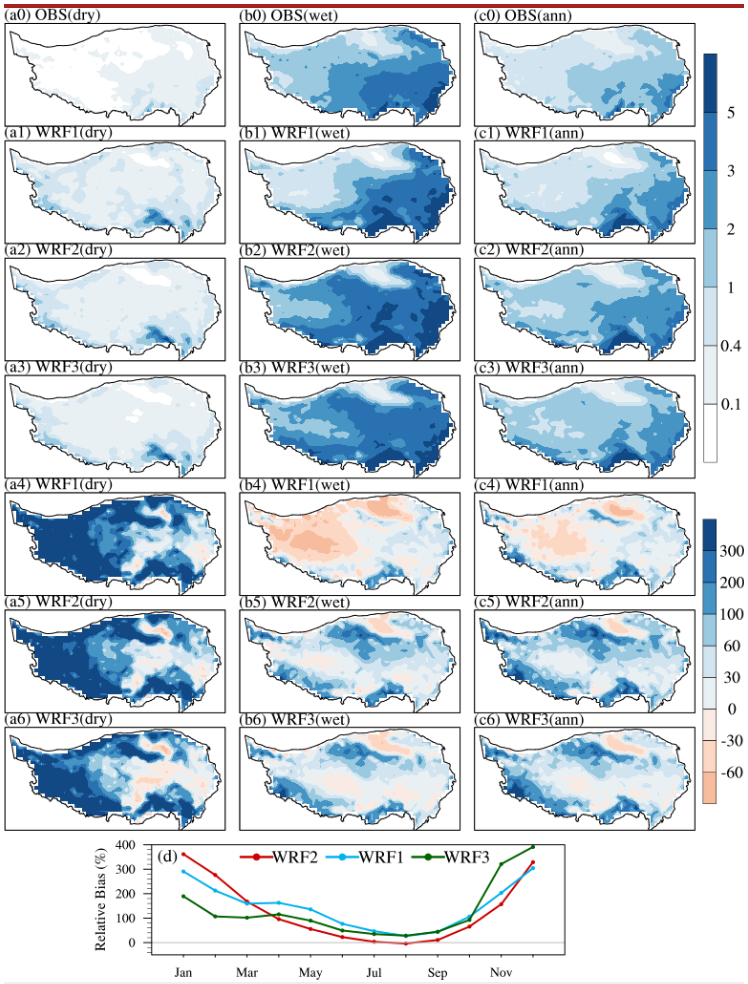

Fig. 4. Seasonally (dry and wet) and annualy (ann) averaged observed precipitation (OBS, a0-c0, unit: mm d-1), three simulations (a1-c3), relative biases of simulations (a4-c6, unit: %), and the annual cycle of the monthly precipitation relative bias of the three simulations (d, unit: %) compared to OBS. WRF1: ERA-I with Noah; WRF2: ERA-I with Noah-MP; and WRF3: CCSM with Noah-MP.

References:

Chen, L., Y. Li, F. Chen, A. Barr, M. Barlage, and B. Wan, 2016: The incorporation of an organic soil layer in the Noah-MP Land Surface Model and its evaluation over a Boreal Aspen Forest. *Atmospheric Chemistry and Physics, 16, 8375-8387, doi:10.5194/acp-16-8375-2016.*

Cai, X., Z.-L. Yang, J. B. Fisher, X. Zhang, M. Barlage, and F. Chen, 2016: Integration of nitrogen dynamics into the Noah-MP land surface model for climate and environmental predictions. *Geoscientific Model Development,* 9, 1–15, doi:10.5194/gmd-9-1-2016.

Gao, Y., X. Xiao, D. Chen, F. Chen, J. Xu, and Y. Xu, 2016: Quantification of the relative role of land surface processes and large scale forcing in dynamic downscaling over the Tibetan Plateau. *Climate Dynamic, doi:10.1007/s00382-016-3168-6*.

Liu, X., F. Chen, M. Barlage, G. Zhou, D. Niyogi, 2016: Noah-MP-Crop: Introducing Dynamic Crop Growth in the Noah-MP Land-Surface Model. *J. Geophys. Res., DOI: 10.1002/2016JD025597*

‹ WMO Solid Precipitation Inter-comparison Experiment (SPICE) up Streamflow Prediction ›

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STREAMFLOW PREDICTION

Traditional operational hydrologic forecasting relies on legacy conceptual watershed models coupled with expert forecaster judgment – a medley of scripted processes and manual adjustments to data, analyses, and products made by trained hydrologists. While this approach benefits from the rich experience of hydrologists, the manual effort and ad hoc workflows limit the capacity to test the potential of new scientific approaches. Because the current practice is not reproducible, it cannot quantify forecast uncertainties, which decision makers increasingly require to balance risks and opportunities during challenging hydrometeorological events. Due to the reliance on hydrologists to adjust models in real-time, this practice is also unable to scale up to meet growing user needs by generating predictions at higher resolutions (i.e., at more locations), higher frequency and for more variables (e.g., showing inundated areas, snowfall or soil moisture).

Recent decades have seen numerous scientific and technological advances to meet these needs. These are now beginning

to filter into operational streamflow forecast practice in centers around the world. Technology advances related to computing, data storage, and connectivity provide a foundation for transforming the computational side of streamflow prediction, while high-potential research can be found in the areas of remote sensing, physical, distributed earth system modeling, parameter estimation, data assimilation, verification, statistical post-processing, weather and climate prediction, and uncertainty estimation through the use of ensembles.

Scientists and engineers in RAL's Hydrometeorological Applications Program at the National Center for Atmospheric Research are undertaking research in new directions to facilitate the transition of these advances into operational streamflow forecasting practice in the US. These project areas are described below.

ASSESSING THE VIABILITY OF OVER-THE-LOOP STREAMFLOW FORECASTING TO SUPPORT RISK-BASED WATER, ENERGY, AND HAZARD MANAGEMENT

The U.S. Army Corps of Engineers and Bureau of Reclamation have jointly sponsored a multi-year project to evaluate and provide a real-time demonstration of the viability of new science-based techniques and strategies for real-time hydrologic flood and drought forecasting in support of real-time water decisions. NCAR has collaborated with both agencies and the University of Washington to develop and run a fully automated streamflow forecast system called SHARP (System for Hydromet Analysis, Research, and Prediction). The system produces real-time ensemble streamflow predictions for lead times of days to seasons, using state-of-the-science weather and climate forecast datasets, hydrologic models, statistical methods and other tools. Overall, the approach enhances the physical realism of real-time watershed monitoring and prediction, while maintaining the computational agility needed to depict uncertainties (e.g., using ensemble techniques). The research will help us understand the tradeoffs of making components of our nation's hydrologic monitoring and prediction workflows more automated and objective, opening the door to advances such as more complex watershed models and uncertainty-aware products. The overarching goal is to strengthen our nation's scientific foundation for operational hydrologic prediction to better manage resources and risk in the face of changing weather and climate extremes.

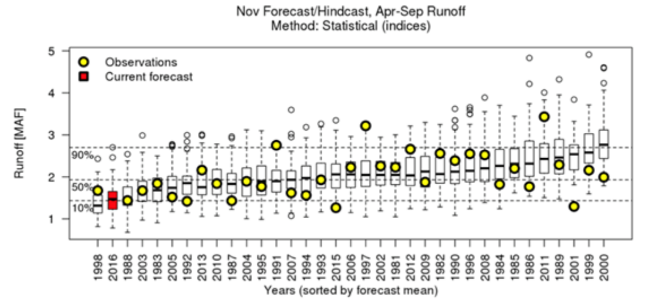
FY2016 Accomplishments

- Assembling the building blocks for monitoring and prediction within an experimental real-time operational platform serving a selection of watersheds across the United States. Elements include higher complexity hydrologic modeling, statistical post-processing, hydrologic data assimilation, and ensemble techniques for hydrometeorological monitoring, weather and climate downscaling, and verification.
- Facilitating a systematic intercomparison of monitoring and prediction techniques, enabling a structured way to assess whether a new technique improves watershed analyses and increases predictability relative to current approaches. For example, seasonal reservoir inflow predictions can be generated using a range of techniques (statistical, dynamical, and hybrid methods) that leverage predictability from both the land surface and climate, or by using simple versus complex hydrological models.
- Evaluating the practicality of new science through interaction with reservoir managers to foster two-way learning that helps both researchers and streamflow prediction and water management communities identify opportunities to integrate advanced methods into prediction services and increase water management flexibility in the future.
- Enabling a real-world assessment of the suitability of more modern, complex watershed models for water management applications. This work is providing an analytical test bed comprising hundreds of calibrated watershed models across the United States for understanding hydrometeorological trends and variability.

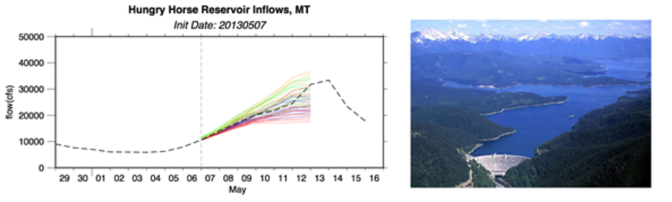
FY2017 Plans

- Expand SHARP implementation to contrast the forecast performance of a broader variety of watershed models in a real-time context.
- Demonstrate and evaluate the medium-range to seasonal ensemble prediction approaches across the entire western US.
- Raise awareness and promote discussion about alternative modeling and streamflow forecasting approaches within the research, operational and management communities.

SUPPORTING THE NOAA NATIONAL WATER MODEL THROUGH HIGH-PERFORMANCE, PHYSICS-BASED MODELING AND DATA ASSIMILATION



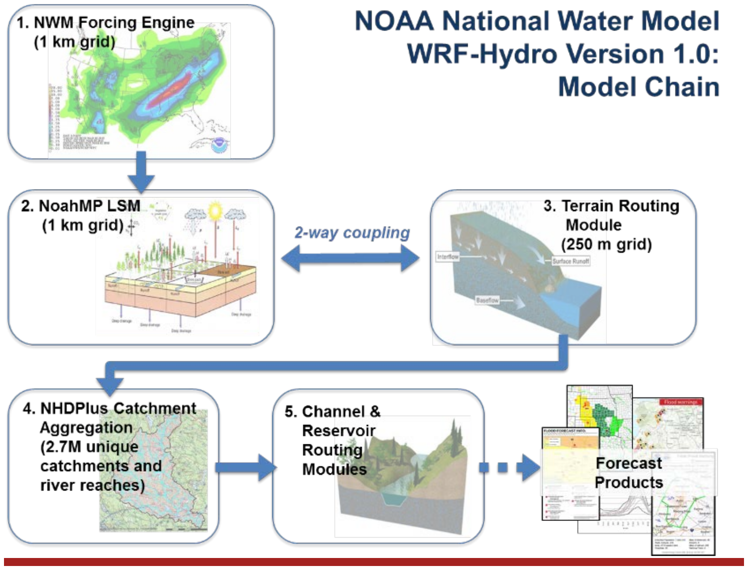
Water Supply Forecast/Hindcasts for Hungry Horse Reservoir, MT.



Short-range reservoir inflow ensemble forecasting (left) for Hungry Horse Reservoir, MT (right).

Impacts-based forecasting of hazardous weather and water events requires 1) accurate and timely situational awareness, 2) reliable and consistent forecast products, 3) a comprehensive geospatial intelligence framework to geo-locate risks and hazards, and 4) an effective communications framework to support the deliverable of actionable information to the public and decision makers. To enable these capabilities, NOAA has undertaken a major effort to improve its forecast services through the development of a new National Water Model (National Water Model: http://water.noaa.gov/about/nwm) which runs on NOAA's centralized Weather and Climate Operational Supercomputing System (WCOSS). Version 1 of the NOAA National Water Model utilizes the community WRF-Hydro modeling system (https://www.ral.ucar.edu/projects/wrf_hydro) and was co-developed for operational implementation by the NOAA Office of Water Prediction, the NOAA National Water Center, NCAR/RAL, the USGS, CUAHSI and other members of the academic community.

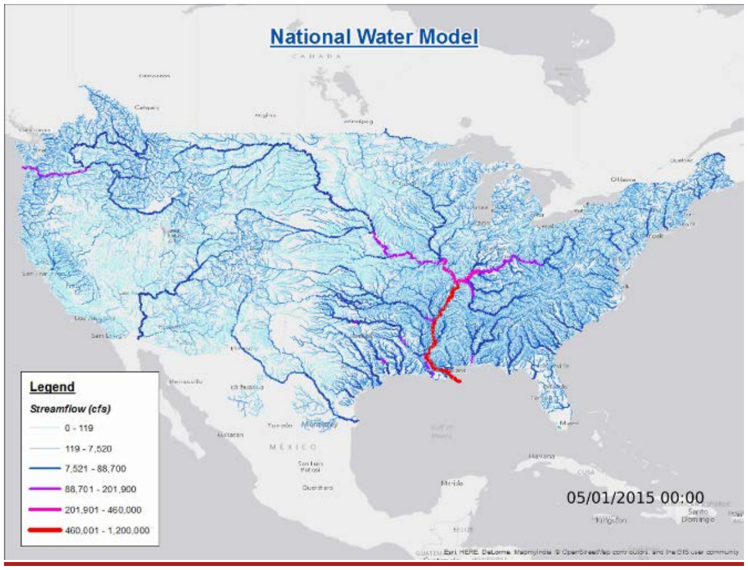
FY2016 Accomplishments



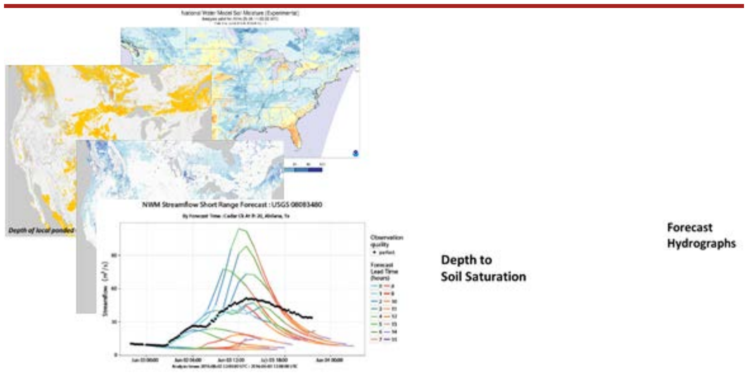
The new National Water Model utilizing WRF-Hydro became operational on the NOAA WCOSS supercomputer on Aug. 16, 2016, delivering streamflow forecasts on the 2.7 million river reaches of the USGS NHDPlusv2 hydrography dataset as well as gridded analyses of a host of other hydrologic variables across the Nation. National Water Model version 1.0 operational goals were to:

- Provide consistent, operational forecast streamflow guidance for currently underserved locations
- Generate, regularly cycling, spatially continuous estimates of hydrologic states for the nation (snowpack, soil moisture, channel flow, major reservoir inflows, flood inundation)
- Seamlessly interface real-time hydrologic products into and advanced geospatial intelligence framework
- Implement an Earth system modeling architecture that permits rapid model evolution of new data, science and technology

These goals were accomplished through the rapid development and implementation of the WRF-Hydro modeling framework onto operational NOAA supercomputers. The NWM runs in four configurations: 1) Analysis and assimilation mode, 2) Hourly short-range 15 hour deterministic forecasts, 3) Daily medium-range, ten day deterministic forecasts, 4) 16x daily, long-range 30-day ensemble forecasts. Forecast products from the National Water Model are now being served through a host of official NWS forecast outlets including the National Water Center, River Forecast Centers, Weather Forecast Offices and the National



Centers for Environmental Computing. In addition to national streamflow maps and animations, experimental visualization products include:



A comprehensive, open source model evaluation system, called 'Rwrfhydro' (https://github.com/mccreigh/rwrfhydro), was developed to support a wide range of model verification and evaluation activities. As the NWM development effort has proceeded and expanded, the Rwrfhydro toolkit has grown to enable a large variety of analyses of different hydrologic variables. Together these analyses are beginning to provide a more holistic evaluation of the full modeling system. Since operational testing began in the late spring of 2016, real-time verification statistics have been tracked and are now being used as a baseline for future model upgrade and development efforts.

FY2017 Plans

Based on initial verification results from the operational NWM and ongoing research within RAL and its collaborators in the academic and agency communities, a number of model upgrades and improvements are being worked on which will be incorporated in future NWM versions. These research and development activities include:

- Improvements to the land surface physics controlling terrestrial hydrologic behavior
- Enhanced parameter estimation, multi-variate calibration and parameter regionalization
- Improvements in channel hydraulics and in inundation representation
- Development of regional, hyper-resolution nests of the NWM for detailed, extreme event forecasting
- Enhancements to the baseline streamflow data assimilation system

These and other improvements to the NWM will be transitioned into operations through two upgrades of the model on the NOAA supercomputer during FY2017.

IMPROVING SEASONAL WATER SUPPLY PREDICTIONS THROUGH IMPROVED OBSERVATIONS AND HIGH RESOLUTION, PHYSICS-BASED MODELING

FY2016 Accomplishments

Development of accurate seasonal water supply forecasts presents one of the most significant challenges in managing tightly administered waters of the Upper Rio Grande River basin. An additional challenge is presented by the lack of high spatial and temporal resolution of

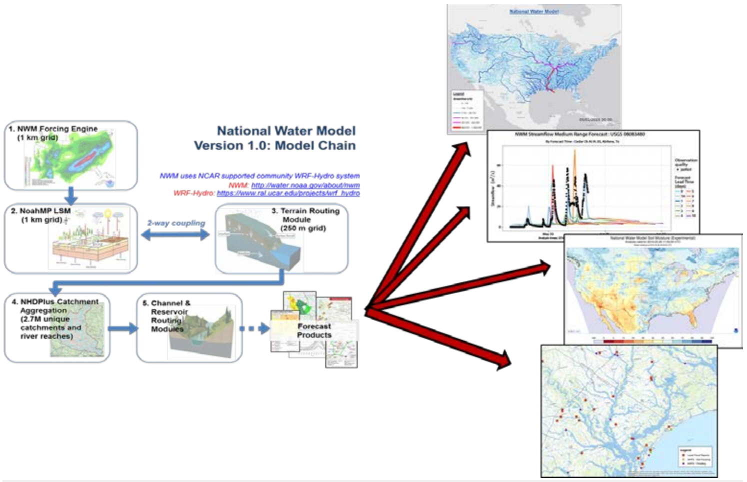


Figure 1: HydroInspector web mapping service display of NCAR observation stations (white circles), State of Colorado observation stations (green triangles), NRCS SNOTEL sites (blue squares) and observation and model time series (right hand side time series plots) from the Upper Rio Grande observation and modeling project.

precipitation and snowpack in this relatively remote, high elevation watershed. To address this issue RAL has partnered with the Conejos Water Conservancy District, the State of Colorado, the NOAA Severe Storms Laboratory and NASA's Jet Propulsion Laboratory to coordinate a comprehensive observational and modeling study, called RIO-SNO-FLO, to explore opportunities for improving seasonal water supply forecasts. A research radar, an airborne lidar and multispectral imager and multiple in situ surface measurement stations were deployed to provide new observations of precipitation, snowpack, soil moisture, streamflow and other meteorological conditions (See Figure 1). A more detailed description of these observations is provided in the Hydrometeorological Observations section of this report. Research conducted during 2016 documented the performance of radar estimated vs. precipitation gauge measured snowfall, and observed vs. modeled snowpack depth and near surface temperature, humidity and incoming solar radiation. These results are summarized in a report to the State of Colorado (Gochis et al., 2016) and a manuscript now in preparation (Karsten et al. 2016). The principal outcomes of this work are that research radars possess significant skill in estimating mountain snowfall as validated by surface precipitation gauges in the southern Colorado region and that when used to drive a physics-based hydrologic model, resulting snowpack and streamflow simulations were significantly improved over simulations using background national analyses of precipitation. As a result, the State of Colorado is currently considering the purchase and deployment of a gap-filling radar in the Upper Rio Grande basin.

During FY2016, improvements in the implementation of WRF-Hydro and in the specification of meteorological forcings gained during the first year of the RIO-SNO-FLO research program were incorporated into a new experimental seasonal water supply prediction system. This capability used an ensemble research version of the WRF-Hydro/National Water Model described above. During the 2016 Water Year, NCAR/RAL produced monthly, seasonal water supply forecasts and compared those real-time forecasts with other operational water supply forecasts from the Natural Resources Conservation Service (NRCS) and the NOAA/West Gulf River Forecast Center. The performance of those forecasts shown in the figure below, highlight that the real-time experimental WRF-Hydro ensemble total seasonal streamflow volume forecasts (blue triangles) compared favorably against the other two operational forecasts as compared with the observe runoff volume (blue line). This system is now being upgraded and expanded for Water Year 2017.

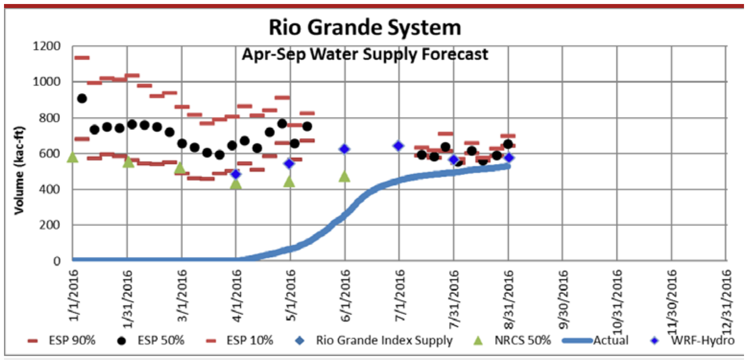


Figure 2: Experimental real-time WRF-Hydro (blue diamonds) and operational (NOAA/WGRFC-black circles, NRCS-green triangles) seasonal water supply forecasts. Figure provided by James Heath of the Col. Div. of Water Resources.

Gochis, D.J, K. Howard, J. Busto, J. Deems, N. Coombs, L. Tang, I. Maycumber, K. Bormann, L. Karsten, A. Dugger, N. Langley, J. Mickey, T. Painter, M. Rchardson, and S.M. Skiles, 2016: Upper Rio Grande Basin Snowfall Measurement and Streamflow (RIO-SNO-FLOW) Forecasting

Improvement Project. Project report submitted to the Colorado Water Conservation Board. Available online at: http://cwcb.state.co.us/public-information/publications/Pages/StudiesRep....

Karsten, L., D.J. Gochis, A. Dugger, K. Howard, L. Tang, J. Deems, T. Painter, G. Fall, C. Olheiser, 2016: Assessing the impact of operational meteorological forcings and experimental radar snowfall estimates on simulated snowpack conditions in the headwaters of the Upper Rio Grande River basin, In preparation.

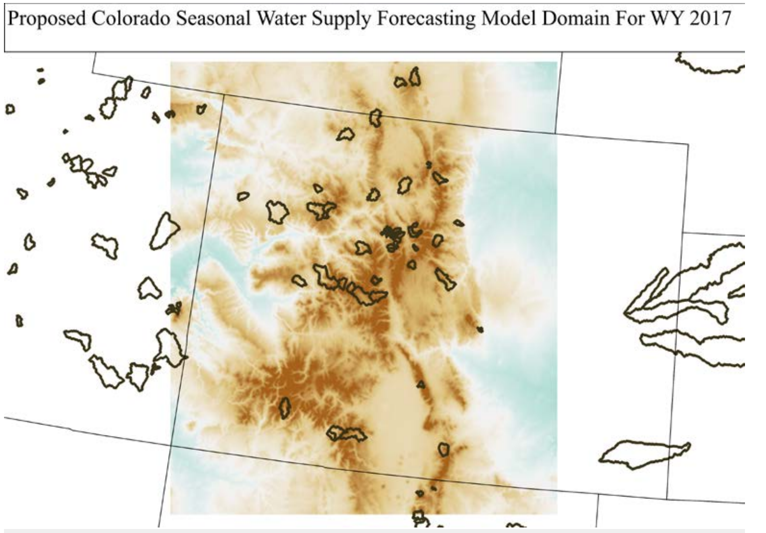


Figure 3: Map of expanded central Rocky Mountain seasonal water supply forecasting domain to be used beginning in Water Year 2017. Inset watersheds indicate headwater catchments used in model calibration.

Plans for FY2017

For 2017, RAL is expanding the ensemble seasonal water supply forecasting domain to encompass all of the central Rocky Mountain headwater basins emanating from Colorado. (See Figure 3).

The streamflow prediction development activities associated with this effort include:

- Expansion of the modeling domain to provide a more robust assessment of the ensemble water supply prediction system in regions other than the Rio Grande headwaters.
- Improved WRF-Hydro calibration methods, similar to those being developed for the NWM effort described above.
- Development of new, enhanced forcing and streamflow forecast bias-correction techniques.
- Enhanced evaluation of model forcings and model snowpack with additional observational instrumentation being deployed by project collaborators.
- Deployment of four additional in situ surface observations in the Upper Taylor River basin near Crested Butte, Colorado for enhanced snowpack monitoring and model evaluation. (See the Hydrometeorological Observations section of this report for more details on this activity.)
- Display of model analyses and forecasts on the HydroInspector web mapping service

IMPROVING OPERATIONAL FLOOD FORECASTS IN THE US NORTHERN PLAINS REGION THROUGH ASSIMILATION OF PONDED WATER RETRIEVALS

A better accounting for ponding within the land surface water balance can improve predictability for runoff and streamflow, with consequent benefits for society through improved river forecasting and decision-making in water management and emergency response to flooding events. There are currently no quantitive estimates of the volume of water detained on the landcape during such ponding events, and we lack a sufficiently comprehensive understanding of the phenomenon for practical enhancement of operational forecasting. The upper midwestern US terrain and land use characteristics provide an ideal setting to demonstrate and achieve practical application of NASA remote sensing in the operational flood forecasting context.

NCAR has teamed up with scientists from Purdue and NASA, as well as forecasters from the NWRFC, to use satellite data primarily from the MODIS sensors (see below right) and LandSat to derive estimates of surface ponded water volume and extent, and use them to update real-time streamflow forecasting models. It has upgraded the NASA Land Information System (LIS) -based VIC hydrology model to include surface ponding schemes, and is beginning to evaluate strategies for improving hydrologic simulation and prediction through data assimilation of the ponded water datasets. A website describing project objectives, information and datasets can be found at: http://www.ral.ucar.edu/staff/wood/nasa_thp/.

IMPROVING SUB-SEASONAL TO SEASONAL STREAMFLOW PREDICTIONS IN THE LOWER COLORADO AND RIO GRANDE RIVER BASINS

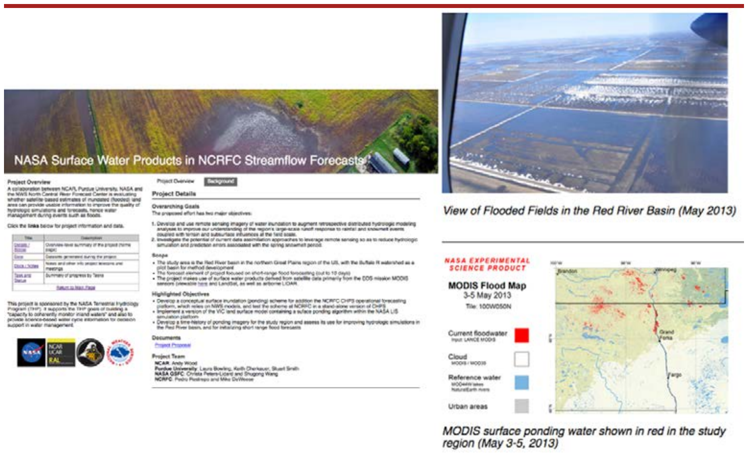


Figure 4: Schematic of the components of SHARP, a research system now running in real-time at NCAR to produce daily-updating ensemble flood forecasts (7 day lead times) and bi-weekly seasonal streamflow predictions for a small number of pilot basins in the Western US.

Operational streamflow forecasts at daily to seasonal lead times are critical to Reclamation’s management of reservoirs in the Colorado River basin that store and allocate water to serve water needs worth billions of dollars annually in seven south-western states. These forecasts sometime fail to predict the real-time conditions that are later observed by Reclamation operators, which can lead to sub-optimal outcomes for decisions in water operations, especially during extreme events such as droughts or floods. Recent studies show that changes in climatic conditions have resulted in changes to temperature and precipitation patterns throughout the West. Anecdotal evidence suggests that differences between streamflow forecasts versus observation is increasing, perhaps due to the fact that existing forecast methodologies must incorporate increasing variability and uncertainty, and extreme weather events. In addition, some current forecast methods (such as regression-based forecasting) are to some extent dependent on the assumption that climate and weather patterns are stationary over multi-decadal periods, but this is traditional concept has been all but abandoned in the hydrometeorological sciences in recent years.

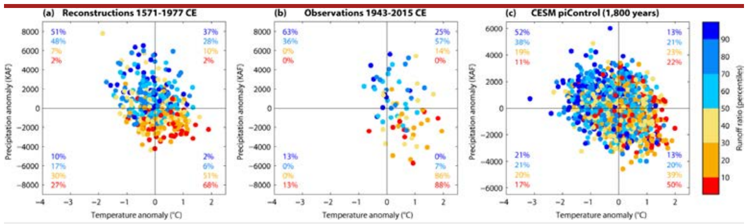


Figure 5: Runoff ratio at Otowi Bridge (colors) as a function of water year precipitation and annual mean temperature from (a) reconstructions, (b) observations, and (c) CESM control simulation (1,800 years total). All time series are relative to their median; in the case of observations, relative to the median of the reconstructions. The colored numbers give the percentage of very low (< 10th percentile), low (< 30th), high (> 70th), and very high (> 90th) runoff ratio years that fall within a given quadrant of precipitation and temperature anomalies.

NCAR has undertaken a project that is co-funded by Reclamation and NOAA through the ‘Postdocs Applying Climate Expertise’ (PACE) program, to understand the implications of potential climate change in the US Southwest for subseasonal-to-seasonal (S2S) lead forecasts, and to apply this understanding to improve operation long-lead water supply predictions. NCAR is collaborating closely with Reclamation water managers in the Lower Colorado and Rio Grande River basins, include site visits and a recent jointly submitted journal paper (Lehner et al, 2016).

To date, the project has found that recent spring runoff declines in the Rio Grande Basin are highly unusual (through a paleo analysis), and that warming temperature trends are contributing to this decline in efficiencies. Additional findings included that:

The decreasing runoff efficiency trend from 1986-2015 in the Upper Rio Grande River basin is unprecedented in the last 440 years

Very low runoff ratios are 2.5 to 3 times more likely when temperatures are above- normal than when they are below-normal

The trend arises primarily from natural variability but runoff sensitivity to temperature implies further declines should warming continue

Publications

Lehner, F, E. Wahl, AW Wood, and DB Blatchford, 2016, Assessing recent declines Southwestern US runoff efficiency from a paleological perspective, Geophys. Res. Lett. (submitted)

‹ Land Atmosphere Interactions up Climate and Managed Water Systems ›

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CLIMATE AND MANAGED WATER SYSTEMS

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 water resource management effort.

Climate Informed Decision Support for Denver Water

There is a growing recognition that planning for adaptation to climate change must proceed despite the limited predictability of hydro-climatic changes on temporal and spatial scales relevant for water resource planning (Yates and Miller 2011; Deser et al. 2012a,b). However, conventional "top down" adaptation approaches are poorly suited to the task. This approach involves downscaling future climate scenarios, generating input data for impact models, evaluating the consequences relative to present climate, and finally considering adaptation responses. Typically, large uncertainties attached to climate model scenarios accrue into even larger uncertainties in downscaled regional climate change scenarios and impacts. An alternative is to turn the traditional top-down framework upside down, placing greater emphasis on identifying and appraising adaptation choices from the outset (Wilby and Dessai 2010). In this configuration, the scenario is used later in the process to evaluate the performance or "stress test" adaptation decisions. For work with Denver Water we have adopted this so-called 'bottom-up' approach, where the collaborative decision support process comprises four key elements (Figure 1-1): i) identifying management strategies or adaptation option(s) to be evaluated; ii) modelling the water supply through physical representation of the hydrologic cycle; iii) modelling the water collection and distribution systems in the context of the hydrologic cycle and the legal water rights; and iv) stress-testing the system using scenarios of future climate and non-climatic conditions to explore the performance of the adaptation option(s) in supporting overall water management objectives.

RAL scientists, working under funding from NCAR's Assessment Program, have developed the WEAP-*Denver Water (WEAP-DW)* model to simulate the current water management system under plausible scenarios of variable climate and associated changes in watershed conditions (including dust-on-snow; land use/land cover changes, etc.) both with and without specific drought mitigation policies in place. With this capability, the WEAP-*DW* model has also been configured as a seasonal forecasting tool that is able to generate seasonal streamflow forecasts as inputs into the West Slope water supply decision framework and Denver Water's systems on the East side of the continental divide, including of the major water diversions from Dillion Reservoir through the Roberts Tunnel and diversions from the Fraser River.

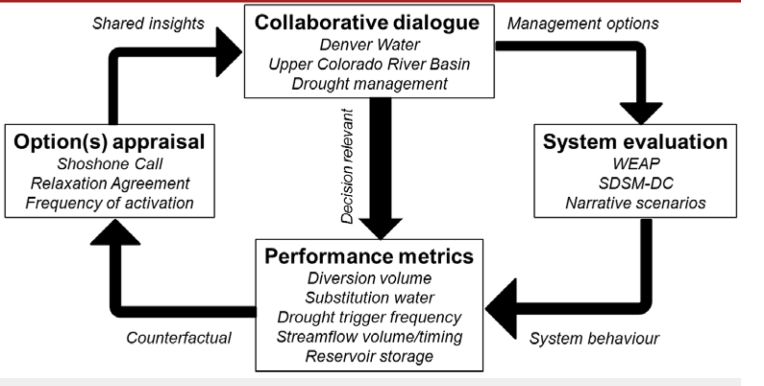

Figure 1. The adaptation option appraisal process.

FY2016 Accomplishments include:

- Advancing the WEAP-DW model through the development of custom seasonal forecasts for Denver Water, with a hindcast analysis and a demonstration forecast for the 2016 water year, with inflow estimates to Cheesman Reservoir and other points of interest.
- Using this new capability, we explored the skill of these forecasts and evaluated whether they can offer early insights into anomalous years with a sufficient degree of skill.
- We explored how a seasonal climate forecast might be used to weight the years of the ESP, to provide a likelihood and a Like-Year outcome.
- If early insights can be realized, we asked how management might use these forecasts to make management decisions or adaptations.
- Training of Denver Water staff on the use and application of the WEAP-dW model. Training will continue in 2017.

Plans for FY2017:

- Continued training session for Denver Water staff in the use of WEAP-DW
- Provide a final report on the seasonal forecasting project and a final evaluation of the 2016 Water Year forecasts.
- Develop a peer review paper with Denver Water on this forecasting work.

Work with Denver Water to further advance the WEAP-DW model to include additional watershed of the South Platte Basin extending to the Colorado-Nebraska border; The new basins will include, among others, Clear Creek, Boulder Creek, the St. Vrain, the Big Thompson, the Poudre River, and other tributaries of the South Platte River. Improvements will include:

1. An updated climate forcing dataset for the new catchments to be added to the model that extend through 2016.
2. Addition of the water infrastructure of the new elements of the South Platte Basin, such as local reservoirs and diversions.
3. An initial calibration of the model, for the new tributaries and the South Platte mainstem, with calibration of some of the tributary flows and South Platte flows at Kersey and Julesburg. We will submit a report documenting the additions to the model by 31 July, 2016.

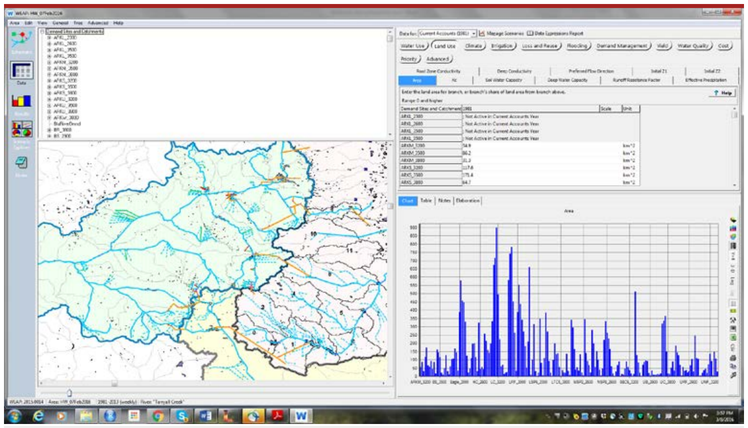

Figure 2. Example of the WEAP-DW domain.

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Yates D., Miller K. (2011) Climate Change in Water Utility Planning: Decision Analytic Approaches. The Water Research Foundation, Denver, 80pp.

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 project began in the fall of 2014 and is expected to run through the spring of 2017. Accomplishments to date include: The project has conducted several training activities on tropical cyclone forecasting, on the general use of NCAR's Weather Research Forecast (WRF) model for both weather and regional climate applications; the management and operation of high performance Linux computer clusters; and the

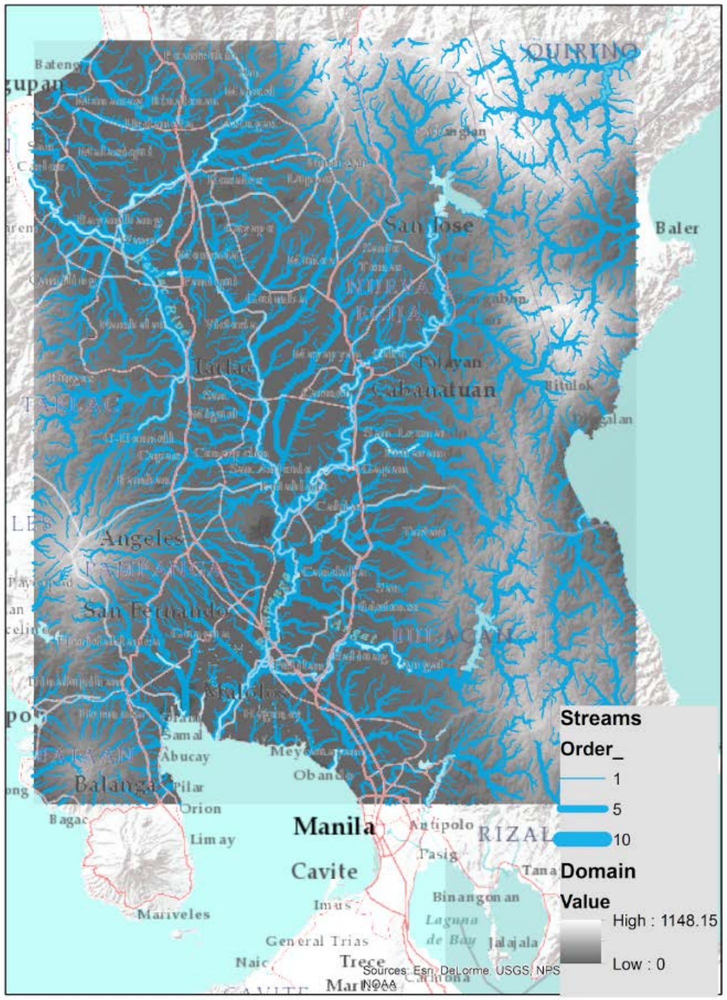

Figure 3. The WRF-Hydro domain over the PamPanga River Basin.

development and application of flood forecasting capabilities using NCAR’s WRF-Hydro system. In the spring of 2017, we will conduct a final regional climate modeling workshop and continue on the development of a flood forecasting system for the Pampanga Basin in the Philippines using WRF-Hydro.

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 are yielding 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. RAL staff conduct training workshops each year in Colombia for in-country scientific staff.

A draft publication has been developed, with an expectation of submission in the spring of 2017.

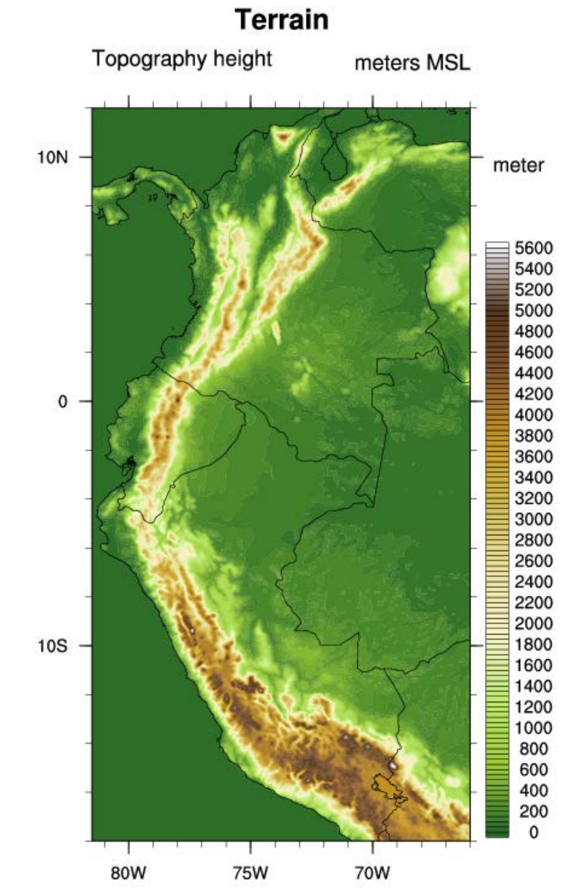

Figure 4. The high resolution WRF domain over the Northwestern Andean Region.

Public Health Benefits of Green House Gas Mitigation: Abu Dhabi

RAL continues to work with the Climate Change Research Group in support of the Environmental Agency of Abu Dhabi's efforts to develop a research program to assess climate change 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. The major accomplishment has been the development of a report with the EAD and the CCRG group on the potential public health co-benefits of reducing local sources of greenhouse gases. This report was finalized in fall of 2015 and published by the EAD in the spring of 2016.

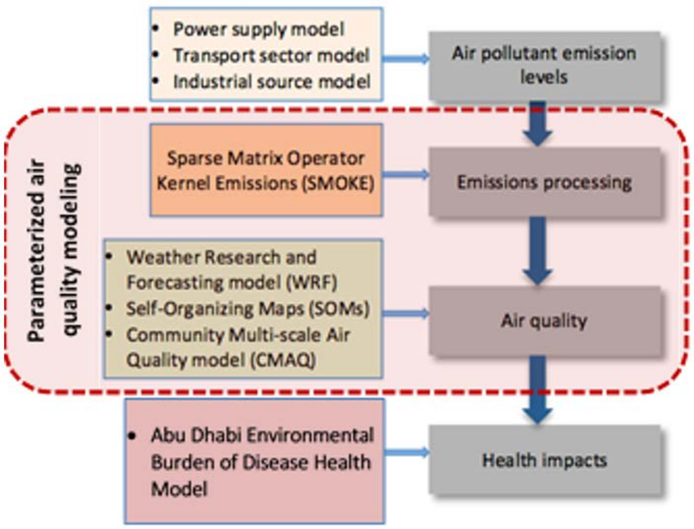

Figure 5. The analytical framework developed for the public health co-benefits project. NCAR's role was the air quality modeling

Regional Atmospheric Modeling under Climate Change for the Arabian Gulf: Al Ain

This project, conducted with the Climate Change Research Group, is examining the impacts of climate change on water resources in Al Ain, the second largest city of Abu Dhabi Emirate in the United Arab Emirates. Using the Water Evaluation and Planning (WEAP) modeling system, an analytical framework was developed to examine the interactions between water supply and demand and agricultural production in the context of climate change, population growth/socioeconomic development, and various agricultural water development strategies.

Using historical data from 2005-2015, the model was configured, calibrated and validated and then used to look ahead into the 21st century to explore different assumptions regarding resource use and

climate change. A policy scenario intended to promote the resilience of the water system in the Al Ain region in the face of climate change was investigated. Results were reported with regard to water consumption in various sectors, groundwater levels, and impacts on agricultural production. While the integrated water-agriculture models and policy analysis methods demonstrated in this project are powerful tools for quantifying the interactions of the water supply and demand in the Al Ain region, the ability to explore the full range of options within the context of this initial study is limited. It would be very useful to continue to develop these capabilities with a broad array of stakeholders, where the tools could be used to explore more targeted questions and regional differences. It will also be important in devising relevant policy scenarios to address the issue of renewable groundwater supply. The region's brackish and fresh groundwater systems are quite independent and a strategy for addressing them in the face of climate change should be found.

component depicted in the light red bounding box.

A draft publication on the regional climate modeling work is planned for submission by February 2017.

Regional Water-Energy Nexus and Climate Change in the Arabian Peninsula

The Water-Energy Nexus (W-E Nexus) constitutes the interconnectivity of water-energy systems, such as energy needed for the desalination, treatment, and transport of water and waste water, and water needed for energy extraction and production. By its nature, the W-E Nexus constitutes a set of interactions, tradeoffs, and system balances among its component pieces, which makes its analysis challenging and not necessarily straightforward. To examine the regional W-E Nexus in the Arabian Peninsula, the project constructed and linked water and energy models (WEAP and LEAP, respectively) in the Arabian Gulf region-specifically Kuwait, Bahrain, Qatar, UAE, Eastern Saudi Arabia and Northern Oman. The coupled water-energy models required detailed data, which were obtained through literature reviews and repeated consultations with key stakeholders in the region. As part of this process the outputs of both models were validated for historic periods using existing data to ensure that the models could adequately represent the systems under investigation.

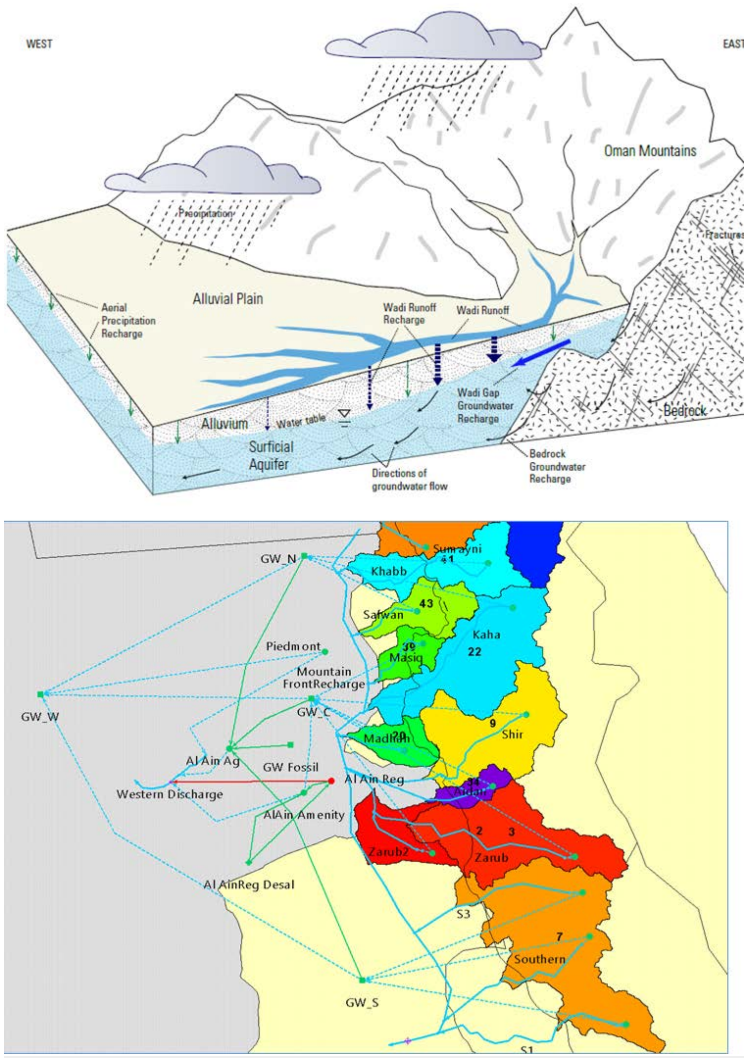

Figure 6. Schematic of the hydrologic mechanisms that contribute to renewable groundwater in the Al Ain Region (top); and the WEAP implementation of those processes (bottom).

With the validation verified and the data entry complete, the project deployed the models in simulating future conditions to the year 2060 for five different scenarios. Since the future is uncertain, the models examined two baseline and three policy scenarios of different resource management futures. The baseline scenarios include an investigation of future conditions if current water and energy management practices are kept in place. These are the *Business-as-Usual* scenarios and include one where the historic climate repeats itself (the *BAU* scenario) and a second with future climate change conditions based on the United Nation Framework Convention on Climate Change (UNFCC) Representative Concentration Pathway (RCP) 8.5 trajectory adopted by the IPCC for its fifth Assessment Report (AR5) in 2014.

The analysis shows that water needs for the Gulf countries can mostly be met in any scenario through combinations of

groundwater, desalination and wastewater reuse, with some regional fossil groundwater basins drawn potentially to extinction by 2060 under the most intensive resource-use scenarios. The scenarios produce different water use for the countries, for example the *Integrated Policy* Scenario embeds the implementation of all policies and measures that would reduce water demand in the region, resulting in diminishing indoor water use starting in 2020. Since water provision impacts energy demand (requiring pumping, desalination, and transport), any decreases in water demand will exert similar effects on the energy sector supporting water provision. As groundwater resources are depleted, desalination becomes the main water resource in the region, followed by treated wastewater, which will be limited to amenity and agricultural sectors.

While the analysis includes both a demand oriented scenario (*High Efficiency*) and a supply oriented scenario (*Natural Resource Protection*), the results of the analysis strongly suggest that the region will need to simultaneously pursue demand and supply side policies to achieve more sustainable uses of water and energy over the next half century (the *Integrated Policy* scenario).

We are developing manuscripts for this regional water energy nexus work to be submitted to the peer review.

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CSAP DIRECTOR INITIATIVES

BACKGROUND

The Climate Science and Applications Program promotes societal resilience to environmental variability and change by integrating social and earth system sciences. Each of the six programs, (Natural Resource Governance, Urban Futures, Weather Climate and Health, GIS Program, Regional Climate for Adaptation, Behaviors, Decisions and Risk) have active research efforts in their respective areas. The CSAP directorate carries a number of research, assessment, and organizational efforts designed to increase effectiveness of the program within the institution and national and international efforts

FY 2016 ACCOMPLISHMENTS

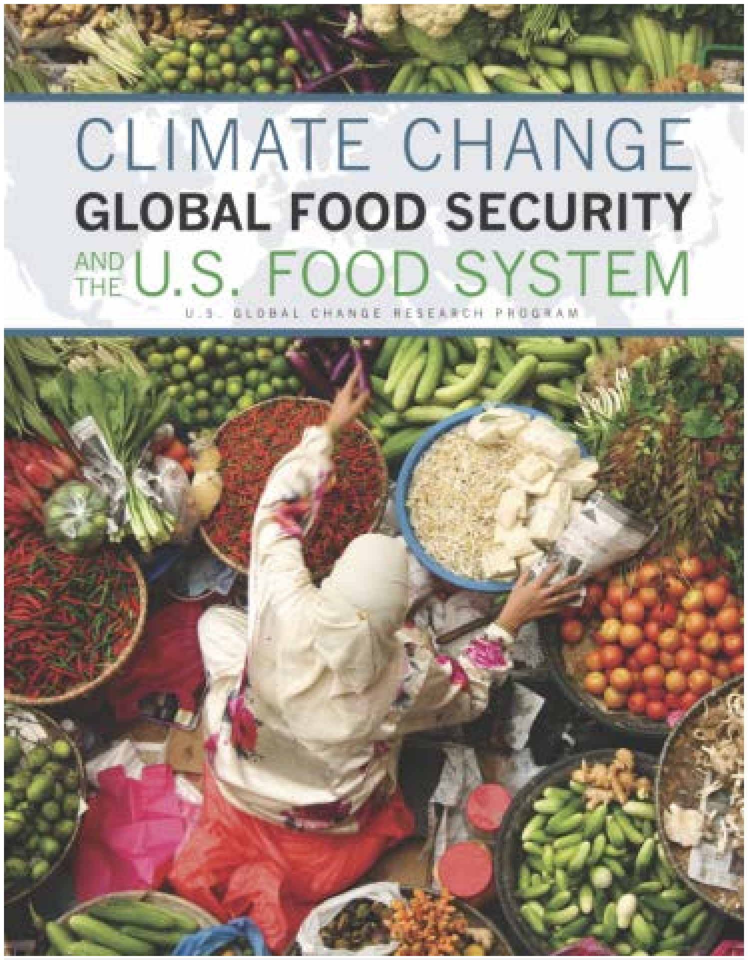

Figure 1 Cover of the Climate Change, Global Food Security and the U.S. Food System report

CSAP contributed scientific and administrative support for the USDA Climate Change Program Office report "Climate Change, Global Food Security and the US Food System" which was USDA's contribution to the US National Climate Assessment. Formally released at the Paris COP climate negotiations by Secretary of Agriculture Tom Bill Vilsack, this report has received a very positive reception within USDA. Other elements include producing a high quality video summary of the report, organizing a AGU double session and Town Hall on the report, and organizing a workshop on the topic at NCAR July 12-15 2016. The workshop focused on addressing complex and challenging climate change and global food security problems through integrated, interdisciplinary research as well as broad participation of researchers and decision-makers, especially from traditionally underrepresented populations and communities. According to the USDA program manager, this has been the most-read scientific report the Department of Agriculture has ever produced and is being incorporated into the USDA's longer-term strategic plans and interdepartmental activities.

As a group, CSAP defined a common research protocol RISE (Research on Interactions between Society and the Environment) that defines the group's joint coproduction approach to their interdisciplinary social/environmental research. Sustainable and resilient responses to environmental variability and change must draw upon an integrated, science-based understanding of the complex interactions between social and environmental systems. That understanding must be incorporated into iterative planning processes. In this approach, CSAP scientists work closely with stakeholders and collaborators to develop knowledge and solutions to complex socio-environmental problems. Together we identify the scales that are relevant for decision-making and propose sound solutions informed by interdisciplinary scientific research. Our process follows a three-phase co-design, co-production and co-implementation research framework. Co-located social and earth system science expertise allows CSAP scientists to iteratively and transparently address every step of the research process, from problem definition to (scalable) solutions in order to address longstanding and emerging challenges at

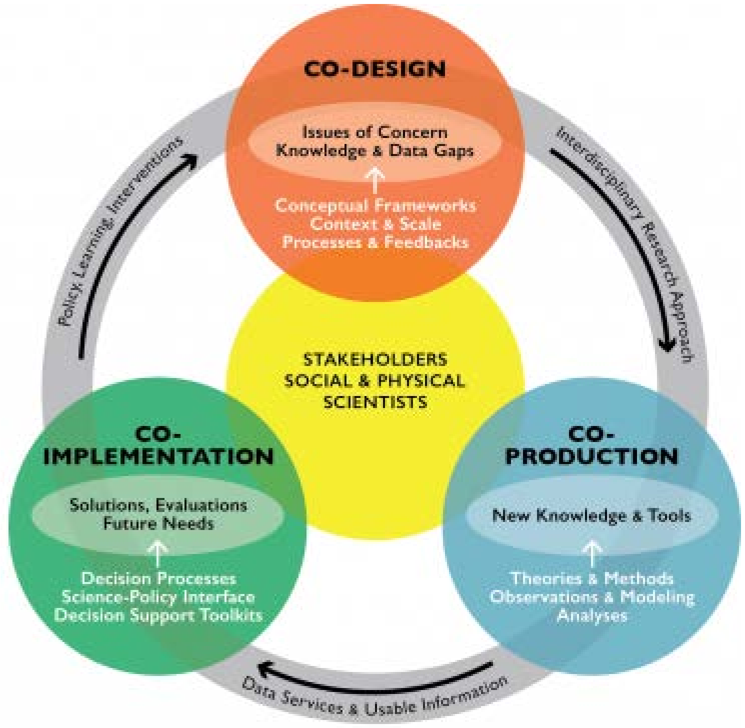

Figure 2 RISE co-production framework

the intersection of society and the environment.

CSAP was the NCAR host of the workshop “Co-Producing Actionable Science for Water Utilities: Case Studies and Next Steps” with the Water Utility Climate Alliance, May 2-3, 2016. This invitation–only meeting brought decision-makers, scientists, and federal program managers together to review a number of recent collaborative projects between water managers and their science partners. These project reports were used as a starting point for designing future of water utility focused decision support efforts. The plenary and breakout sessions focused on identifying activities might be pursued to develop advanced national climate services for water utilities to create a robust, functional, and accessible science/decision making environment in which to make water climate adaptation investments. Follow-on activities include a subgroup to work with NOAA to develop the concepts from this workshop into a national climate service for water decision-making.

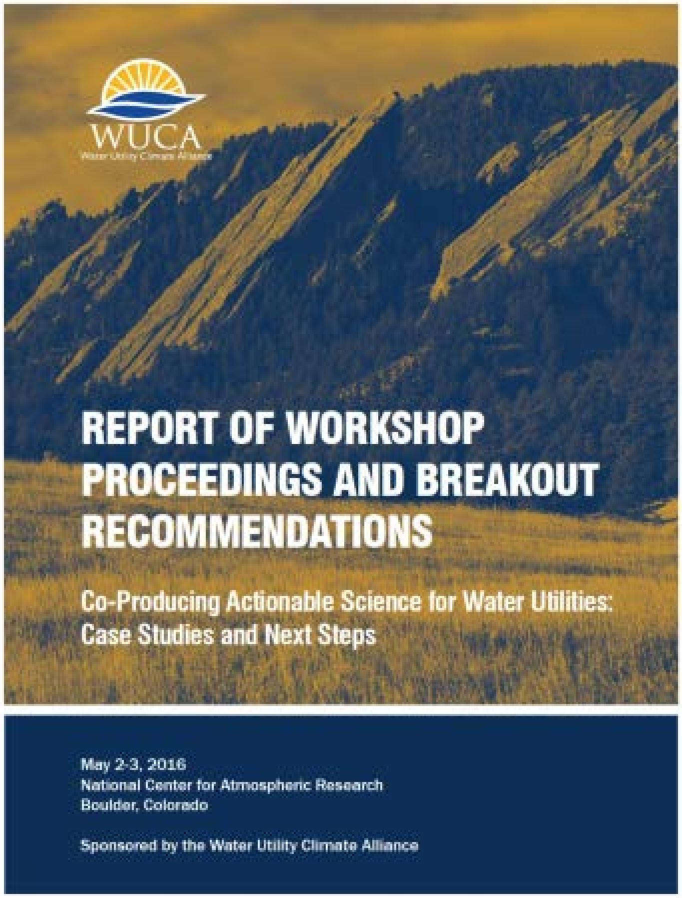

Figure 3 Workshop Proceedings

CSAP co-organized the “International Water and Climate Forum” with the Association of Metropolitan Water Agencies, Dec 7-9 2015. This was attended by several CSAP members and featured a side meeting connecting water system decision makers with scientists on CSAP’s EaSM project. This Forum brought together scientists and water utility decision-makers who are early adapters of climate adaptation and mitigation to advance the understanding of current best practices and lessons learned in implementing actionable climate information.

CSAP has been one of the leads developing a concept for a “US National Center for Advanced Social informatics and Analytics” with Michael Barton (ASU) and Lillian Alyssa (University of Idaho). After an initial

meeting in 2014, the team coordinated the writing of a white paper proposing a National Center for Human Systems Science (NCHSS) designed to bring modeling of the dynamics of human systems and coupled human-natural systems to the level of the physical process models. This concept was prepared based on a request from the Assistant director of the NSF Social. Behavioral, and Economic Sciences Directorate, but is envisioned this to be broader than NSF alone, which will require significant dialog and input from other federal and local agencies, and potentially private sector organizations too. On March 23, 2016, the team met with senior program managers from USDA and DOE to get their advice on how to involve more federal agencies in this process so that mission-critical needs for useful and reliable social/behavior science can best be met. The initiative was briefed to representatives of multiple federal agencies through the coordinating US Global Change Research Program in late summer and a follow-on meeting was held at the Institute for Social Research at the University of Michigan in Fall 2016 to present this concept to an expanded group of social/behavioral scientists focusing on how to better integrate social/behavioral science with biophysical science.

The CSAP Director, Lawrence Buja, participated in the “Linking Earth System Dynamics and Social System Modeling” workshop to develop a three year NSF research plan and timetable to identify the most tractable components for modeling the coupled Human-Earth system that can be scaled up from the local to the global. The goal of the workshop was to develop a strong research plan and timetable for the integration of human systems models with Earth system models and begin the process of developing a joint modeling effort that represents the effects of human activities on environmental change in better ways than is done currently. Follow-on activities include a white paper on summarizing the results of the first meeting and proposing community meetings to insert this CHESS (Coupled Human-Environmental System Science) initiative into the 2018-19 NSF planning process and an AGU session on “Advances in Integration of Earth System Dynamics and Social System Models (Global Environmental Change Session 12792).”

FY17 PLANNED ACTIVITIES

- Assist USDA with its 2017-2022 Strategic Plan for Climate Change Science. Conduct research on the social science aspects of agriculture decision making to better understand behaviors and decisions in the face of weather and climate risk.
- Co-organize the fifth International Conference on Climate Services (ICCS5) to be held in Cape Town, South Africa in Feb 2017. The theme of ICCS5 is “Innovation and Capacity Building.”
- Publish a paper “Identifying research priorities to advance climate services” in the journal *Climate Services* with lead author Catherine Vaughan from IRI. This paper is based on the results of community surveys and the “Research needs for Climate Services” sessions co-chaired by CSAP at the Fourth International Conference on Climate Services.
- Work with the University and NCAR Co-Chairs of the CESM Societal Dimensions Working Group to organize a new initiative leveraging the large number of CESM Large, Medium, and Perturbed physics ensembles to quantify climate impacts at the present day to thirty-year decision time-scales.

‹ Climate, Weather and Society up Socioecological Systems in a Changing Climate: Governance and Adaptation ›

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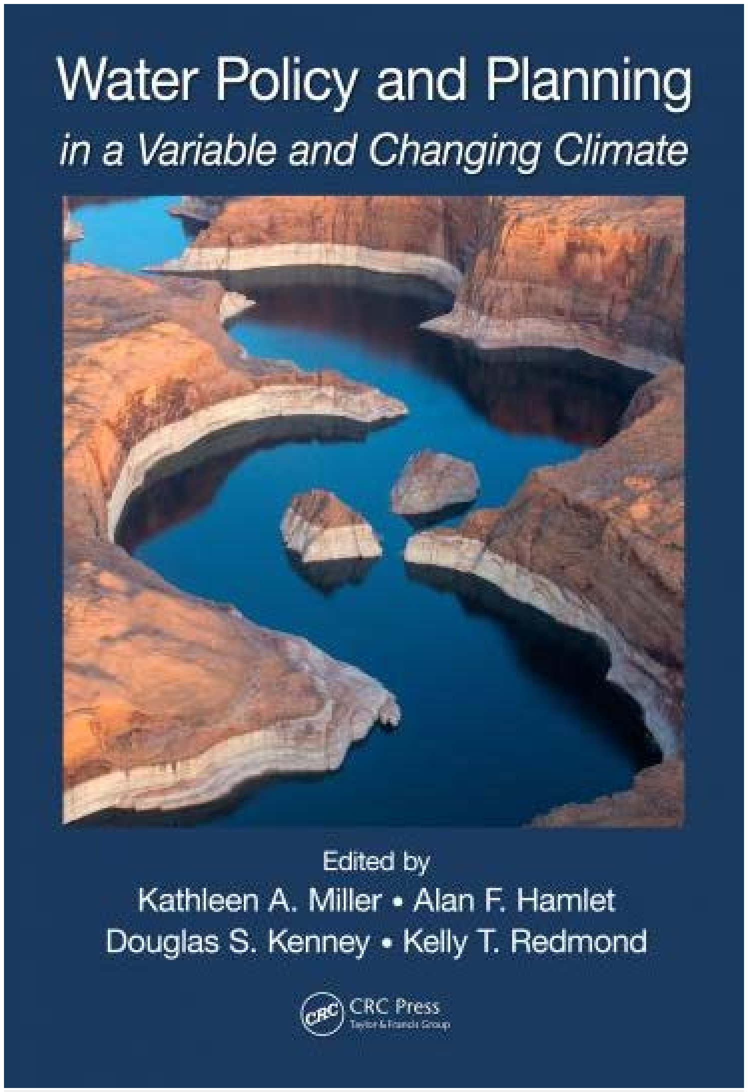
2016 ACCOMPLISHMENTS

In her capacity as lead editor, Kathleen Miller completed final editorial tasks for the book, *Water Policy and Planning in a Variable and Changing Climate*, published by CRC Press - Taylor and Francis Group in June 2016 This volume is designed to serve as an educational resource for both the natural science and water policy communities. The book’s 21 chapters focus on the relevance of climate variability and change for addressing the major ongoing water policy challenges confronting water planners and policy makers in the western United States. Case studies provide insights into emerging water management challenges, creative approaches to planning for managing climate-related risks, and the role



Water Policy and Planning in a Variable and Changing Climate

that the science community can play in contributing to collaborative problem-solving.

Dr. Miller also completed work on a chapter entitled "Extreme drought and California's water economy: Challenges and opportunities for building resilience." This will be included in a book edited by K.N. Ninan (Centre for Economics, Environment and Society, Bangalore, India) and M. Inoue (University of Tokyo, Japan). The book is currently in press and is scheduled for publication by Edward Elgar Press in early 2017. This chapter describes the factors that have caused different groups of water users to face very different vulnerabilities to the ongoing multi-year extreme drought in 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 new legislation and 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.

Other work focused on developing a methodology for assessing the agricultural economic impacts of alternative policies for meeting Georgia's interstate streamflow obligations to Florida in the Apalachicola-Chattahoochee-Flint (ACF) River Basin. The nature of Georgia's obligations are currently undergoing review pursuant to a complaint filed by the state of Florida in the U.S. Supreme Court. Work in FY16 was hampered by the fact that the Court case severely limited the ability of her collaborator, Dr. Masters (Albany State University), to participate in the research. The litigation also has resulted in data inaccessibility and restrictions on the release of information related to the project. Despite those difficulties, the research team identified a set of experimental-farm data that could be used to estimate the yield-impacts of various levels of supplemental irrigation applications across different water-year types. Under the joint supervision of Drs. Miller and Masters, a graduate student performed a preliminary analysis of that data which suggests a tendency for the marginal product of irrigation water to diminish as irrigation applications are increased. A more rigorous analysis of that data set is planned for FY17. This project is primarily supported by the NOAA-SARP program, with NSF co-sponsorship of part of Dr. Miller's time.

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NCAR OpenSky link: http://n2t.net/ark:/85065/d7fq9z63

Miller, Kathleen A., *In Press.* "Extreme Drought and California's Water Economy: Challenges and Opportunities for Building Resilience," K.N. Ninan and M. Inoue (Eds.), *Building a Climate Resilient Economy and Society – Challenges and Opportunities.* Edward Elgar.

FY17 PLANS

Work will continue on the Georgia water policy and drought risk management project until Dr. Miller's planned retirement in March 2017. Her current work includes tracking the progress of the Supreme Court litigation by reviewing publicly available reports of the Special Master's investigation.

Research will continue to focus on the design of incentive systems for drought year water withdrawal reductions. The analysis will focus especially on measures that are spatially-differentiated to best protect streamflows in the Flint River Basin while minimizing economic disruption. Planned work includes exploring the experimental farm data in greater detail to inform our assessment of policy options. Analysis of the total yield impacts of different levels of restrictions on irrigation applications will be used to evaluate the impacts of specific irrigation pumpage reductions on farm-level profits and related economic activity. Combining these results with the project's already completed spatially-explicit estimates of the impact of groundwater extraction on surface water flows will provide insights on the cost-effectiveness of alternative strategies for meeting desired flow targets.

‹ CSAP Director Initiatives up Urban Futures ›

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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.

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.

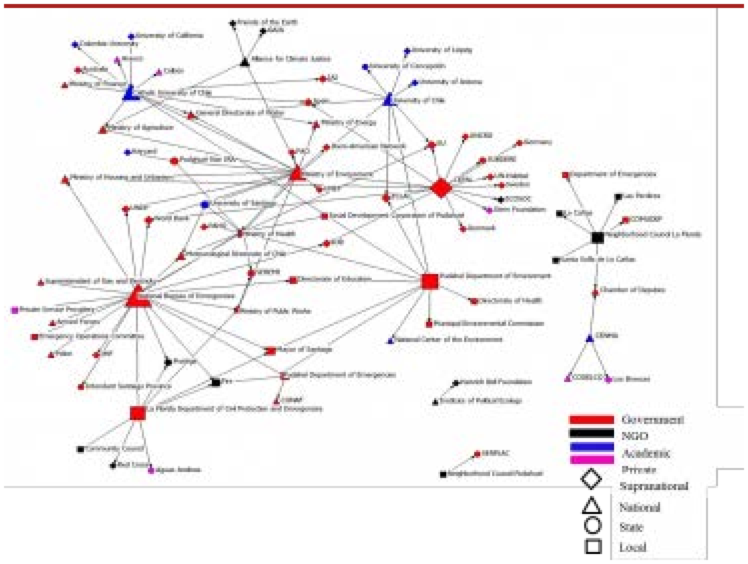

Figure 1: Santiago Chile actor network. Size of nodes is proportional to the number of ties. Note the peripheral not connected to the main network

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.

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

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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
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.

"Happiness cannot be traveled to, owned, earned, worn or consumed. Happiness is the spiritual experience of living every minute with love, grace, and gratitude."

I cannot own, earn nor wear the bliss of Thanksgiving. I only can appreciate the opportunity it offers to hear interesting and funny anecdotes, and an ambience of love and sharing.

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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, other laboratories in NCAR, university partners, federal agencies, and state and local agencies 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 2016 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 2016. 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. Two manuscripts addressing various aspects of the SIMMER project were submitted or published in peer-reviewed journals in FY16. 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 explored 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 is supporting a new investigation of the combined role of heat and indoor air pollution in increasing vulnerability among the elderly in Houston. Two postdoctoral researchers hired in FY16 are working on the project.

Toward Malaria reduction

Dr. Mary Hayden of RAL 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. During FY16 focus group discussions, key informant interviews and household surveys were conducted to better understand ways to include more women in vector-control at household, regional and national scales.

Human–Environmental Interaction and Risk for *Aedes*-transmitted arboviruses

Aedes (Ae.) aegypti transmits the viruses that cause Zika, dengue, chikungunya and yellow fever. An ongoing Zika pandemic in Latin America and the Caribbean has been linked to birth defects in newborns and neurological disorders in adults, initiating a massive public health response and garnering extensive media coverage. The other three viruses are important threats as well: dengue viruses infect about 400 million people each year, chikungunya has been linked to chronic health problems such as arthritis and a new yellow fever outbreak in Angola has stoked fears of imminent vaccine shortages.

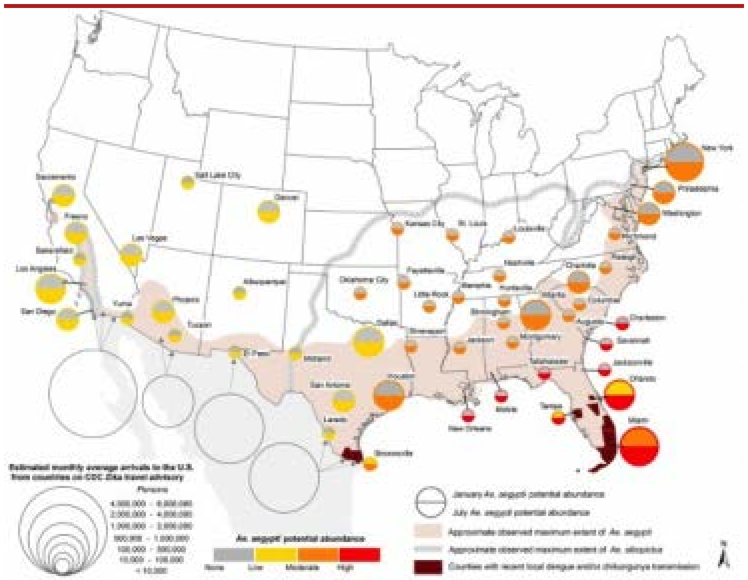

Fig. 1. U.S. map showing 1) Ae. aegypti potential abundance for Jan/July (colored circles), 2) approximate maximum known range of Ae. aegypti (shaded regions) and Ae. albopictus (gray dashed lines), and 3) monthly average number arrivals to the U.S. by air and land

RAL scientists have been involved in a number of projects investigating *Ae. aegypti* and the viruses it transmits. In FY16 they concluded a four-year NIH-funded project led by the University of Arizona. Efforts in that project focused on collecting immature and adult *Ae. Aegypti*, as well as data on climate, socioeconomic conditions, and human behavior in cities in the Sonoran desert extending from Tucson, AZ to Hermosillo, Sonora, Mexico, in order to better understand virus ecology. Under new funding from NASA, model simulations of Ae. Aegypti and the viruses it

from countries on the CDC Zika travel advisory.

transmits will be conducted along the transect to answer key questions about the role of climate in virus transmission. Two key papers on *Ae. aegypti* were published in FY16. One examined the future range of *Ae. Aegypti* under climate change and human population change scenarios. The other explored Zika risk in the United States by examining the seasonal cycle of Ae. aegypti as well as other socioeconomic, travel and virus history factors that influence transmission (Fig. 1). The press release for the paper received the most media news clips of any NCAR news clip in the past 5 years.

Lyme Disease in the United States

NCAR is working with CDC to better understand the meteorological drivers of Lyme disease ecology. Hayden and Monaghan participated in the U.S. Global Change Research Program report on Climate Change and Human Health in the United States, which focused on Lyme disease and West Nile virus; the report was published in FY16. Monaghan also participated in two papers led by CDC mapping locations of *Ixodes* tick vectors of Lyme disease in the United States.

CDC-NCAR Postdoctoral Fellowship

Two new CDC-NCAR Postdoctoral Fellows were hired in FY16 and began their two-year tenures in September 2016. 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. Ryan Michael is working on extreme heat, air quality and human health issues with NCAR and CDC's National Center for Environmental Health. Ubydul Haque is working on climate and vector-borne disease issues with CDC's Division of Vector-Borne Diseases. They are being mentored by Hayden and Monaghan.

Community Outreach

- Hayden hosted a session on Women in Vector Control at the Annual Meeting of the American Society of Tropical Medicine and Hygiene that was attended by approximately 100 people.
- Monaghan lectured on Zika and mosquitoes to a group of US grade-school students from Latin America as part of the FIRST (For Inspiration and Recognition of Science and Techology) program.
- Monaghan mentored and served on the thesis committee of Kelly Neely, an MS student at Texas Tech University. He traveled to Lubbock to attend the thesis and give a pair of lectures on *Ae. aegypti* and the viruses it transmits.
- Hayden and Monaghan lectured to students in the Public Health Program at U. Colorado Denver.
- Hayden mentored a Ugandan MS degree-seeking student on her thesis work.

FY 2017 PLANS

Work will continue on the NASA-funded *Ae. aegypti* mapping project, on CDC research efforts focused on Lyme disease, and on an EPA-funded project investigating heat, air quality and health outcomes. Monaghan also anticipates working with CDC on projects aimed at better understanding Zika virus ecology through mathematical modeling. A major focus in FY 2017 will be to continue writing proposals to secure additional grants for further climate and health research.

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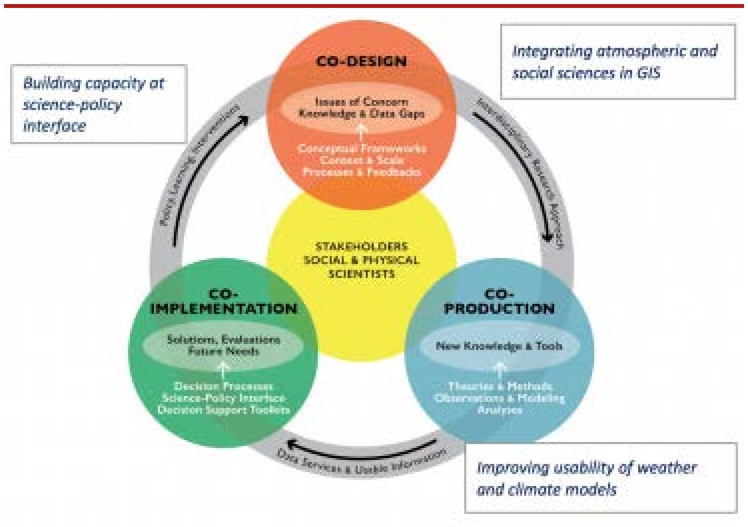
GEOGRAPHIC INFORMATION SYSTEMS (GIS) PROGRAM



The Geographic Information Systems (GIS) program 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. Current research activities in the GIS program

occur in three thematic areas:

- Integrating atmospheric and social sciences with GIS;
- Improving usability of weather and climate models;
- Conducting GIS-focused educational activities and building capacity at the science-society interface.

These three areas directly map to the Research on Interactions between Society and the Environment (RISE) framework (Figure 1).

Figure 1. GIS program’s focus areas mapped onto the RISE framework.

INTEGRATING ATMOSPHERIC AND SOCIAL SCIENCES WITH GIS

Climate and society are coevolving in a manner that may place vulnerable populations at greater risk to weather and climate stresses. Understanding societal risks and vulnerabilities to weather hazards and climate change requires integration of georeferenced information from physical and social sciences, including weather and climate data, information about natural and built environments, demographic characteristics, as well as social and behavioral processes. NCAR’s GIS program is working towards 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*. Current projects in this area of research are focused on extreme heat, air pollution and human health, drought risk analysis, and hurricane risk communication for preparedness and response.

Urban heat and air pollution risks

Building on the successful completion of a NASA-funded project, System for Integrated Modeling of Metropolitan heat Risk (SIMMER), in 2016, we continued to address interdisciplinary questions about current and future urban vulnerability to extreme heat and its interaction with air pollution. Several manuscripts addressing various aspects of the SIMMER project were submitted or published in peer-reviewed journals and in an edited book in FY16. 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 explored 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. A book chapter discussed co-design, co-production and co-implementation process of the SIMMER project, thus providing a research example of stakeholder engagement in an interdisciplinary study.

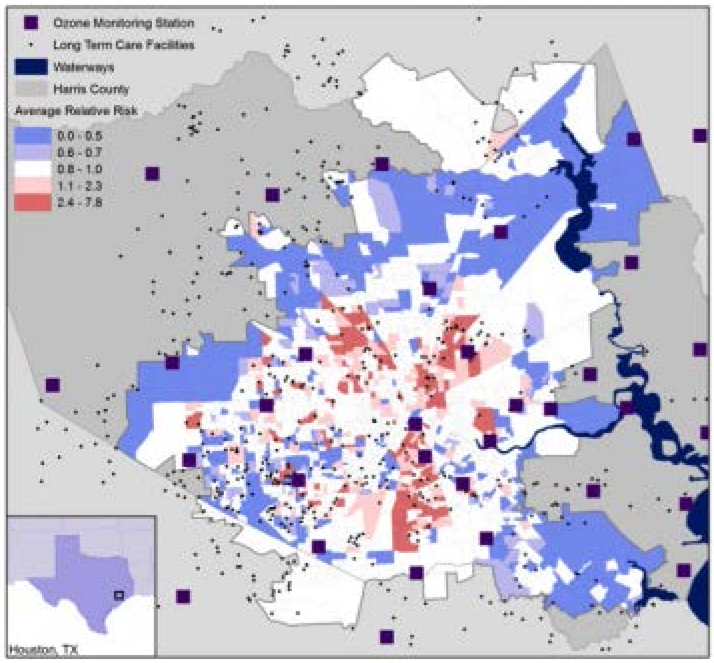


Figure 2. Relative risk of heat-related mortality in Houston (from Heaton et al. 2014) and locations of ozone monitoring stations and long-term care facilities.

Recent funding from EPA is supporting a new project, “Heat and Ozone in Metropolitan Environments: Assessing Indoor Risks” (HOME AIR), that focuses on the linkages between outdoor and indoor air quality and thermal comfort, with the goal of improving conditions and lowering pollutant exposure for at-risk populations. The scientific goals of the HOME AIR project include 1) quantifying current and future health risks of an older population to urban air pollution and extreme heat, indoors and outdoors; 2) improving understanding of how emerging trends in building design and management practices affect indoor air quality; and 3) building local capacity in reducing negative health outcomes during episodes of poor air quality and extreme heat. The first HOME AIR stakeholder workshop, “Extreme Heat and Ozone: Assessing Health Risks of Older Houstonians,” conducted in

2016, brought together researchers and practitioners to outline project goals and develop collaborative networks in Houston. Two postdoctoral researchers hired in FY16 are working on the project.

Publications:

Wilhelmi, O. and M. Hayden, 2016. Reducing Vulnerability to Extreme Heat through Interdisciplinary Research and Stakeholder Engagement. In*: Extreme Weather, Health, and Communities. Interdisciplinary Engagement Strategies* (S. Steinberg and W. Sprigg, Eds.): 165-186. Springer Press.

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Marsha, A., Sain, S., Heaton, M., Monaghan, A., Wilhelmi, O. 2016 Influences of climatic and population changes on heat-related mortality in Houston, Texas, USA. *Climatic Change*. DOI: 10.1007/s10584-016-1775-1

IMPROVING USABILITY OF WEATHER AND CLIMATE MODELS

As a national center, NCAR aims to provide atmospheric data and models outputs to the broader community. The GIS program develops methods and tools that facilitate the use of NCAR models in GIS. We work with industry and international standards organizations to improve interoperability of common atmospheric data formats, as well as develop tools and applications to increase usability of models.

Climate change web-based GIS applications

Since 2005, the NCAR GIS program has served a large international community of GIS users interested in examining the facets of global climate change. The GIS Climate Change Scenarios portal was the first internet gateway in which users were able to access global climate model data in GIS formats. This data portal provides access to global and downscaled datasets of climate change scenarios generated for the IPCC by the Community Earth System Model (CESM). Users can access global 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's Climate Inspector application allows for the visualization of climate change in space and time. This interactive web application displays anomaly temperature and precipitation values from the IPCC AR5 runs of the NCAR CCSM4 model. The user interacts with the data by clicking and moving a pin on the map to change location, using a time slider to change time period, and altering the emission trajectory. This interface provides a rich environment from which users can assess what future changes in climate may occur as well as some of the model uncertainty associated with those changes.

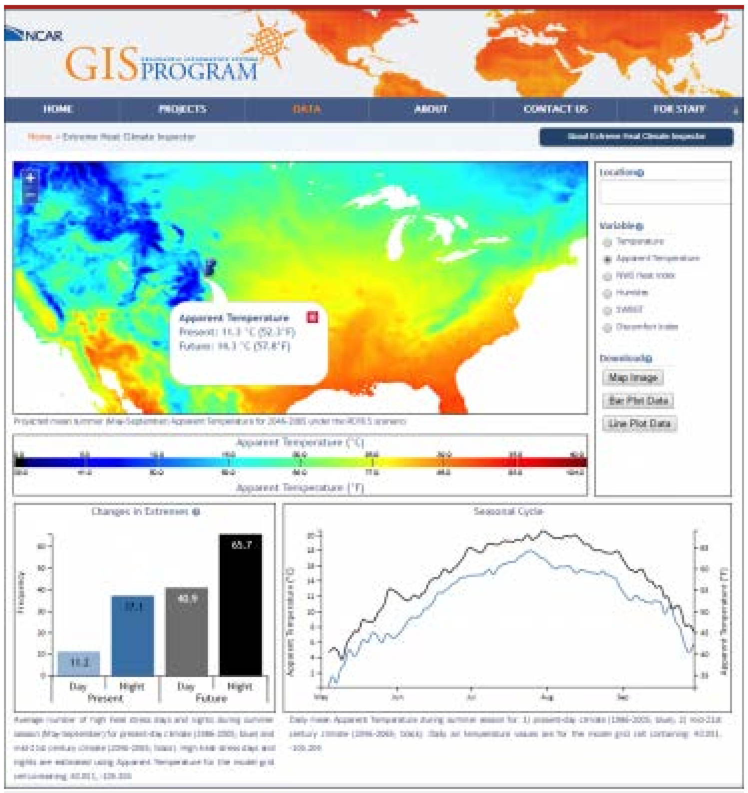

Figure 3. The Extreme Heat Climate Inspector is an interactive web

application which expands GIS mapping and graphing capabilities to visualize projected extreme heat. The data displayed in this app were produced at NCAR for the NASA-funded study, "System for Integrated Modeling of Metropolitan Extreme heat Risk" (SIMMER).
https://gis.ucar.edu/heatinspector

In 2016, the Climate Inspector platform has been extended to several "inspector-style" applications across RAL's programs (e.g., Hydro Inspector, Extreme Heat Climate Inspector, UAE Climate Inspector). For example, the Extreme Heat Climate Inspector provides outputs from a NASA-funded project on current and future extreme heat vulnerability. The project quantified the importance of explicitly characterizing urban properties to improve urban meteorological simulations, and the role of climate change in the future heat stress across the United States and southern Canada. Climate model simulations from SIMMER suggest high heat stress days and nights in cities across the U.S. Extreme Heat Climate Inspector allows users to explore projected changes in temperature as well as the five commonly used heat stress indices: National Weather Service Heat Index, Apparent Temperature, Simplified Wet Bulb Globe Temperature, Humidex, and Discomfort Index. Through this interactive application, users can see the variations in high heat stress days and nights in cities and rural areas across the United States, and can explore spatial patterns and seasonality of extreme heat across the United States, southern Canada, and northern Mexico.

Publications:

Wilhelmi, O., J. Boehnert, and K. Sampson, 2016. Visualizing the climate's future, *Eos, 97,* doi:10.1029/2016EO042207.

CONDUCTING GIS-FOCUSED EDUCATIONAL ACTIVITIES AND BUILDING CAPACITY AT THE SCIENCE-SOCIETY INTERFACE

GIS education at the science-society interface focuses on integrating climate science and data with traditional GIS data, and performing spatial analysis to facilitate interdisciplinary research to build capacity for decision-making. We offer workshops, colloquia, and training programs which include:

Concepts of physical and social sciences of risk and vulnerability to weather hazards and climate change; Integration of scientific data and knowledge for risk assessment, mapping, and decision making; and strategies and tools for practical communication of scientific data to non-scientific audiences and decision makers. Our trainings apply a suite of different GIS applications and tools, from Esri software to open source tools such as Quantum GIS, GRASS GIS, and MultiSpec. Several training modules are available on our website.

GIS Tutorial for Atmospheric Sciences

Geographic information systems (GIS) and other geospatial technologies have become increasingly valuable to the atmospheric sciences for weather, climate, hydrometeorology, and societal impact studies. As use and application of GIS continues to expand in the atmospheric sciences sector, the need to introduce GIS to atmospheric science degree-seeking students has become increasingly important. Additionally, meteorologists, climatologists, and other atmospheric science professionals are seeking more access to and training in these spatial technologies. A new course, *GIS Tutorial for Atmospheric Sciences,* has been developed for weather and climate students and practitioners as a way to meet this need. This course was developed as a joint partnership between the National Environmental Modeling and Analysis Center at the University of North Carolina at Asheville and the GIS Program at the National Center for Atmospheric Research (NCAR). This course is intended to teach basic and intermediate Geographic Information Systems (GIS) concepts, methods, and terminology using weather and climate case studies.

Publications:

Boehnert, J., J. G. Dobson, and O. Wilhelmi, 2016. Teaching the integration of geography and atmospheric sciences, Eos, 97, doi:10.1029/2016EO046011.

Dobson, J.G. and J. Boehnert, 2016. GIS Tutorial for Atmospheric Sciences. Available online: https://gis.ucar.edu/projects/course-introduction-gis

BRoadening Participation in the Interdisciplinary Geosciences: Hands-on Training and Education (BRIGHTE)

GIS education at the science-society interface is an important component of the GIS program. Our society is facing many challenges related to weather, climate and climate change. Extreme weather events, such as droughts, floods, hurricanes, and extreme heat events affect communities across the world. Addressing these complex and challenging problems requires an integrated, interdisciplinary research as well as broad participation of researchers, educators and decision-makers, especially from traditionally underrepresented populations and communities.

BRIGHTE workshop series provide an opportunity for participants to embrace an interdisciplinary approach to these scientific and societal challenges. Workshop training materials typically focus on integration of atmospheric science and data with traditional GIS data and spatial analysis to facilitate interdisciplinary research and decision making. Workshop themes range from human health and weather disasters to food security and climate adaptation.

Figure 4. 2016 BRIGHTE workshop participants: "Integrating Weather and Climate into GIS Curriculum

In 2016, we conducted two workshops. Workshop on "Integrating Weather and Climate into GIS Curriculum" was funded by NCAR Directorate Diversity Fund. This workshop aimed to enhance geospatial education by integrating major issues of environmental change into the GIS curricula. This 3-day workshop introduced GIS faculty and instructors from U.S. universities and colleges to fundamental concepts of atmospheric and related sciences. Participants learned about state-of-the-art research in weather, climate, and societal applications. The workshop included lectures, small group discussions, and hands-on GIS exercises.

A second workshop, "Climate change, food security and the U.S. food systems" was funded by the USDA. The workshop participants leaned about climate change, food security, and food systems in the context of the recent USDA Climate Change and Global Food Security report for the U.S. National Climate Assessment. The workshop featured lectures from domain experts, hands-on GIS exercises, a poster session, and a field trip. Participants gained knowledge of a broader framework for interdisciplinary science, research tools, and data sources that they can incorporate into specific projects at their home institutions as well as in their communities. The GIS training focused on integrating spatial information about climate change, agriculture, and food security in a meaningful and innovative way.

Figure 5. 2016 BRIGHTE workshop participants: "Climate change, food security and the U.S. food systems.

FY2017 Plans

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 tourism, and hurricanes and social vulnerability.

Our web-based applications will be extended to develop public health-relevant web-based tools and web services.

Domain-specific GIS modules that have been created for the workshops will be made available to the broader community of researchers, educators and practitioners. ArcGIS-based training materials will be adapted for open source QGIS.

‹ Weather, Climate and Health up Regional Climate Science ›

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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 through synthesis and translation, (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.

FY2016 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 5.2 was released in August 2016. 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 expansion is particularly useful since climate simulations cannot reproduce individual 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 (2D + time) perspective facilitating a more intuitive and quantitative yet engaging 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

Building on the toolset developed under the National Climate Predictions and Projections (NCPP) platform funded through the NOAA Climate Program Office, RC4A with Jonathan Vigh have drastically expanded the processing and analysis capabilities and developed the Climate Risk Management engine (CRMe).

CRMe offers efficient ways to convert basic climate variables into a rich set of indicators that represent climate and weather characteristics that are important to different sectors and applications. Particularly of interest are analyses of hazards and their projected changes. At the heart of CRMe is the ability to perform comparisons with observational records to assess fidelity in the model data and to facilitate the study of processes and potential impacts of changes.

Streamlined access, calculations, evaluation, analysis, interpretation and translation: these are the key objectives for CRMe and its support of the study or regional climate changes and their potential impacts. This work was done in close collaboration with public and private partners at the regional, national, and international levels to determine how well climate products can reproduce observations and thus how well-suited these commonly used products are for application and decision-making. CRMe strives to ingest evaluation as a critical step into the data dissemination process through enriching raw climate data with diagnostics and extensive, standardized metadata.

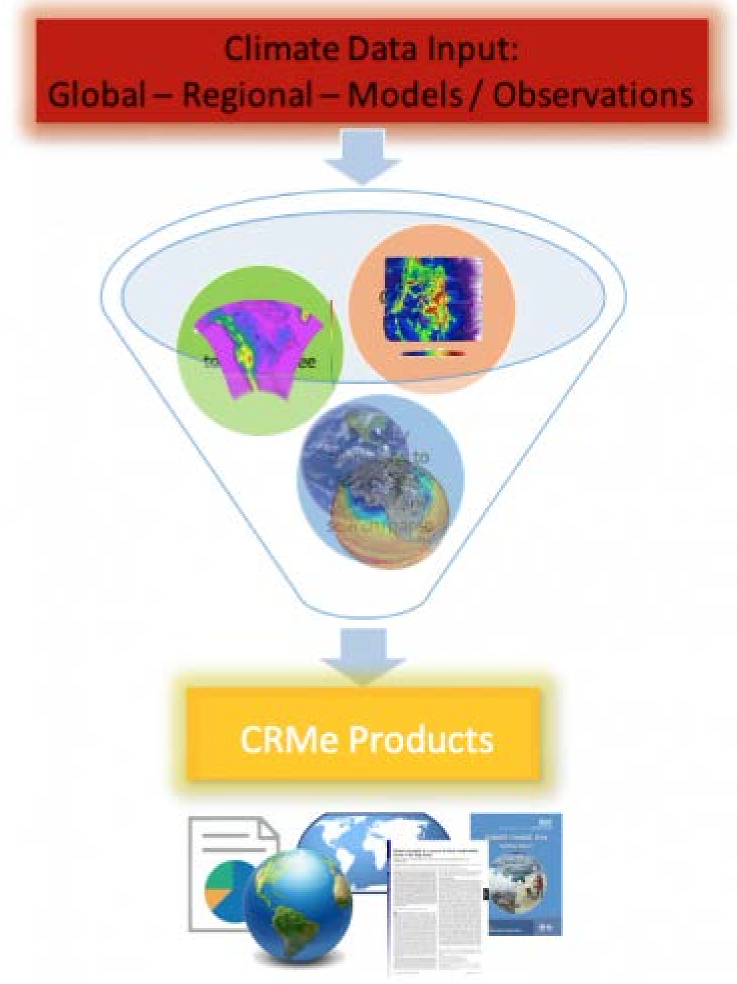


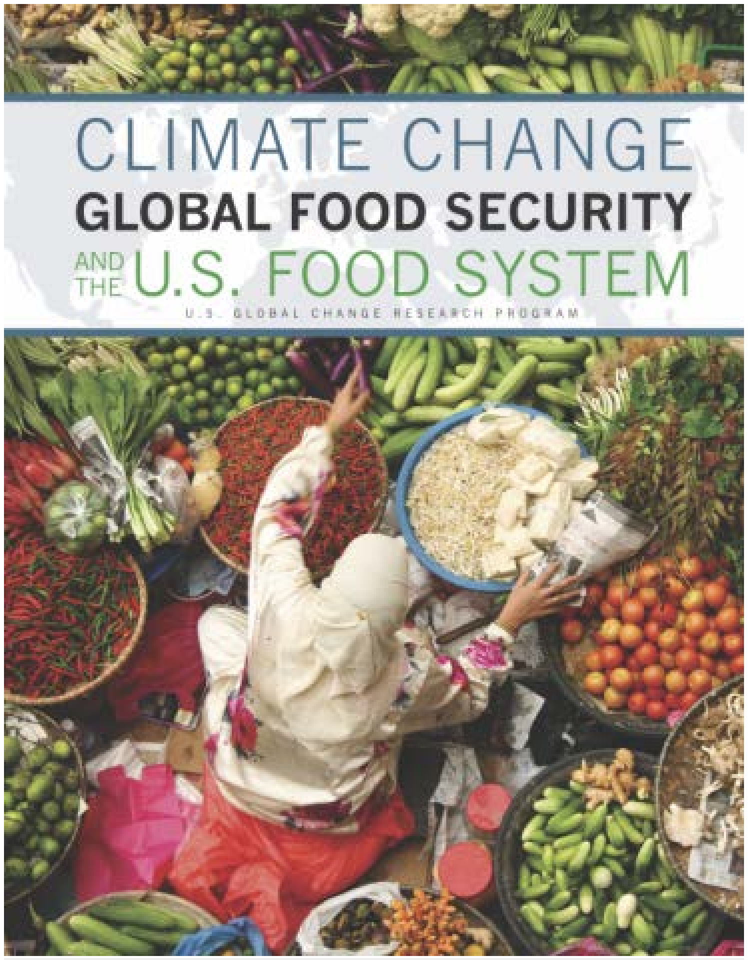
Figure 1: The Climate Risk Management engine (CRMe) can process any spatial data that is available in standard format. Products are indicators, climatologies, advanced statistics and comparisons. A suite of observational datasets is available as reference.

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 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. This report was recognized by the U.S. Department of Agriculture (USDA) with the Abraham Lincoln Honor Award in the category of Increasing Global Food Security Outreach.

FY 2017 PLANS

In 2017 the RC4A effort will further develop the tools necessary for an integrated climate risk management capability. This will entail the treatment and analysis of time series to better represent scenarios of possible weather sequences with big impacts on society. Further, the use of dashboards will be expanded to more effectively condense and summarize the relevant climate change information for different sectors and diverse audiences. These dashboards will serve as templates for work with the World Bank and the InterAmerican Development Bank to



"Climate Change, Global Food Security, and the U.S. Food System"

assist in climate change risk screening. 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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