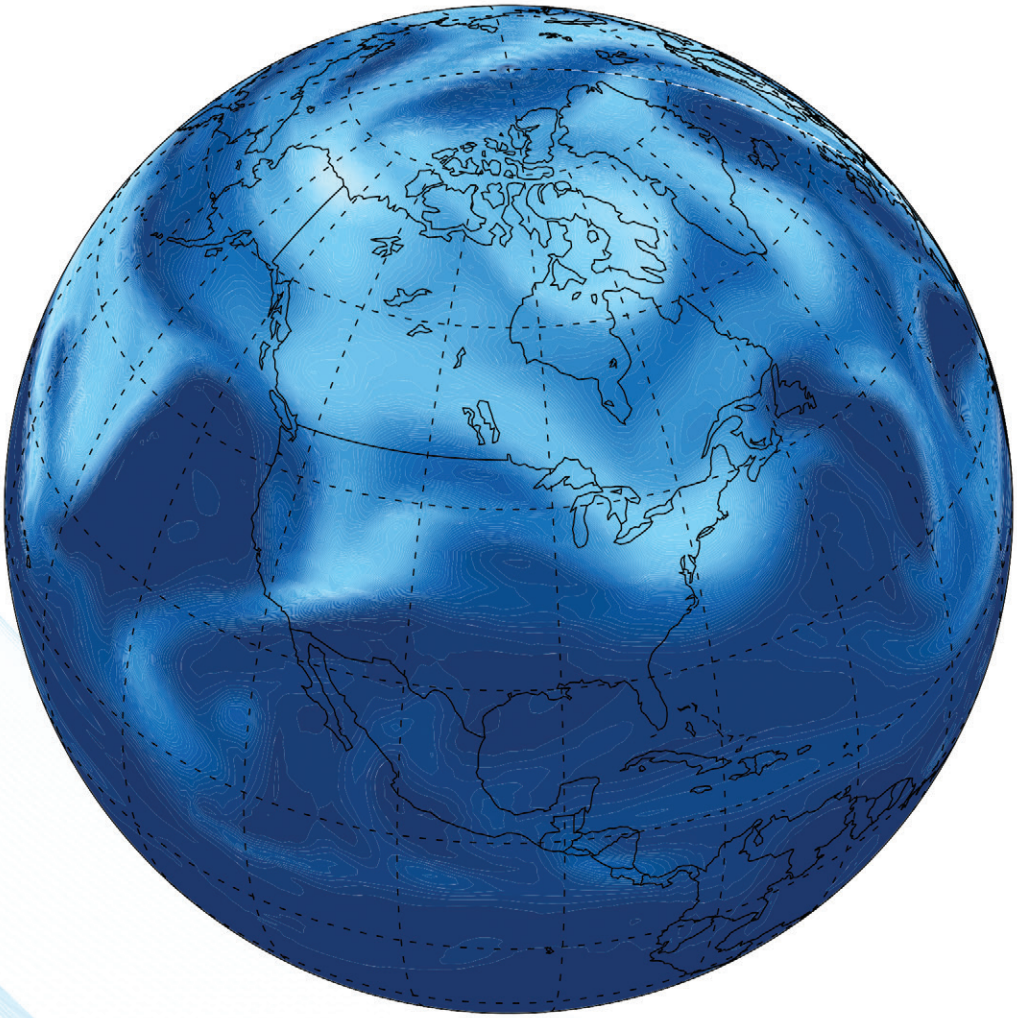
Climate Change Science Institute

FY 2015 Annual Report



Climate Change Science Institute
Oak Ridge National Laboratory

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MISSION STATEMENT

Advancing knowledge of the Earth system, describing the consequences of climate change, and evaluating and informing policy responses to climate change.

For more information, please go to http://climatechangescience.ornl.gov.

Oak Ridge National Laboratory (ORNL) is the largest US Department of Energy (DOE) science and energy laboratory, conducting basic and applied research to deliver transformative solutions to compelling problems in energy and security. ORNL supports DOE's national missions of scientific discovery, clean energy, and security.

ORNL is managed by UT-Battelle for DOE.

Major funders of Climate Change Science Institute (CCSI) research projects include the DOE Office of Science Biological and Environmental Research and Advanced Scientific Computing Research Programs, the US Geological Survey (USGS), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the US Environmental Protection Agency (EPA).

ON THE COVERS

Front: *Contours of "potential vorticity" within a recent prerelease ACME simulation covering the present day. Potential vorticity measures the fine scale dynamical behavior of the large-scale extra-tropical atmosphere and can be used to track the connection between large scale flow anomalies and surface temperature extremes.* ***Back:*** *The Grand Coulee Dam on the Columbia River. The dam provides electricity generation as well as irrigation water.*

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Jack D. Fellows, director, Climate Change Science Institute at Oak Ridge National Laboratory.

Letter from the Director

2015 was a historic year for the world. It was the hottest year on record, and a landmark international climate agreement to limit global warming was adopted. President Obama called this agreement a "turning point for the world," reflecting that climate change is finally being taken seriously among world leaders. There are issues with how this agreement will be implemented. Thus, our ability to advance the science and develop useful tools and information remains critical. All of us at CCSI are proud to be part of this effort. In this report, you will be able to get a glimpse of this year's efforts to advance climate models, understand critical processes in human and natural ecosystems, archive and use key data sets, and explore ways society can deal with a changing climate. In addition to this report, I encourage you to look at the recent YouTube video describing the CCSI research and outreach activities (available on the CCSI website or by searching YouTube).

This year also marked the first anniversary of the CCSI 2014–2020 Strategic Plan. Toward the end of the year, we made important adjustments to the strategic plan to reflect changes in funding sponsors and our own priorities. These adjustments have helped us maintain a strong commitment to critical ongoing science projects and identify new areas of emphasis. Many of these adjustments are in response to excellent advice provided by the CCSI Science Advisory Board (SAB), including key strategic hires and redoubling our efforts to mentor and promote the professional development of the CCSI early career scientists.

Our commitment to the ongoing science projects described in this annual report remains strong; however, adjustments have been made to the strategic plan to reflect increasing interest in how climate change influences and is impacted by urban environments and the food-energy-water nexus. Several CCSI members have spent the past year working with cities in Tennessee on how to better incorporate climate change in their planning, including the Urban-CAT project described in this report. On many of these projects we are working very closely with our sister organization, the Urban Dynamics Institute, led by my great colleague Budhu Bhaduri. These are critical efforts to better understand what science is needed to provide individuals and leaders the tools and information needed to make wise decisions about reliable and resilient community services like energy, water, food, health, and transportation. Here at CCSI, we believe user engagement can lead to better science investments.

On a personal note, I have just finished my second year at CCSI and continue to feel gratified by the support CCSI receives and its collection of outstanding researchers and staff, many of whom will be highlighted in this report. I want to particularly thank the ORNL leadership team for their incredible support of CCSI, including Lab Director Thom Mason, Deputy Lab Director Thomas Zacharia, Associate Lab Director Jeff Nichols, former Associate Lab Director Martin Keller, and Interim Associate Lab Director Gary Jacobs.

Many thanks also to the CCSI SAB members and our many sponsors, including DOE, NASA, USGS, and EPA. Without this support from ORNL, the CCSI SAB, and agency sponsors, CCSI would not have been able to make the accomplishments highlighted in this report or dream about the future.

My last thank you is to the gifted and dedicated men and women who make up CCSI. I highly value their talents and friendship and am impressed by their dedication to equipping this nation with the scientific tools and information it needs for planning in the face of a changing climate.

I hope this annual report provides you with a meaningful sense of what CCSI is doing and, more important, how we might partner to tackle the significant challenge of climate change and its effects.

Jack Fellows

CCSI—Advancing knowledge of climate change and understanding its consequences

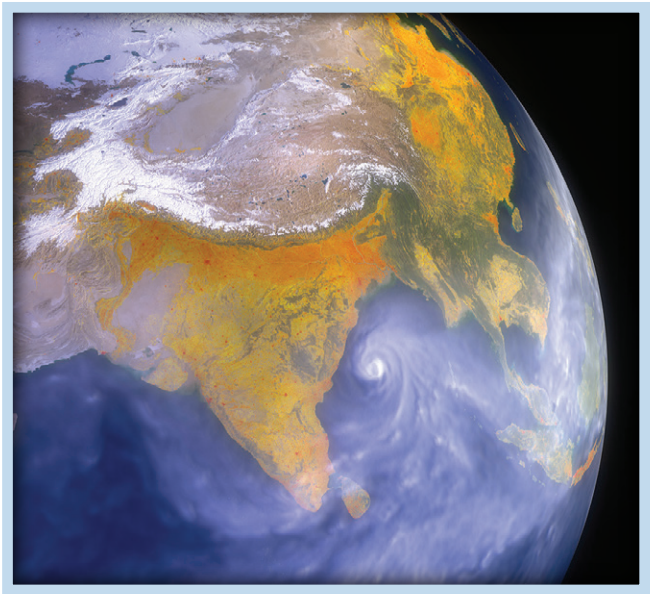
While most scientists are now in agreement about the reality of human-induced climate change, it is still difficult to predict with certainty what the long-term impacts will be and hence to develop relevant solutions to address them. Among the factors that contribute to this uncertainty are inconsistencies among the results of various Earth system models; the need for more precise models on regional and local scales; the need for more comprehensive observational data from remote field sites; uncertainties associated with how various carbon sources and sinks will respond not only to future warming, but also to increased levels of atmospheric carbon; uncertainties associated with ice sheet melting; and uncertainties associated with the response of various ecosystems to warming, especially those in sensitive regions of the Earth, such as the tropics and the Arctic.

Since its inception in 2009, CCSI has been addressing these and other climate-related issues through four research theme areas: Earth System Modeling (ESM); Data Integration, Dissemination, and Informatics (DIDI); Terrestrial Ecosystem and Carbon Cycle Science (TECCS); and Impacts, Adaptation, and Vulnerability (IAV) Science.

These four groups are collocated and work synergistically across multiple projects. Modelers (ESM) work with field experimentalists (TECCS) to develop lab and field experiments; field experimentalists collect and analyze data that in turn improve the models. Other research collaborators (IAV) use the climate change scenarios from the modeling group to determine impacts on various stakeholders and to develop tools to help decision and policy makers address those impacts. At the same time, CCSI data experts (DIDI) work with researchers in all of the theme areas to provide innovative data storage, access, and visualization tools and best practices to expand access to relevant data and information, as well as track and document the use of data products resulting from research.

There are many climate change centers and institutes, not only in the United States but also around the world. CCSI is unique among these because of its multidisciplinary staff collocated within a diverse national science laboratory, with world-class supercomputers, measurement and analysis tools, and scientific expertise; its model-data-experiment approach, which integrates models, long-term experiments, and data; and its mission-inspired research, driven by the need to better understand the impacts and consequences of climate change on human and natural land-energy-water systems.

Earth System Modeling



ACME—Scaling the heights of Earth system modeling

The Accelerated Climate Modeling for Energy (ACME) project, now in its second year, has already racked up numerous awards, most recently "best video" at Supercomputing 2015 in Austin, Texas. More important, the team, which consists of eight national laboratories, the National Center for Atmospheric Research, four academic institutions, and one private-sector company, is on schedule for release of Version 1 of the ACME model in June 2016.

The major activity this past year was completion of Version 1 of the model, based on the Community Earth System Model or CESM. The team ran tests on the model throughout fall 2015 and early 2016. After the release in June, the team will start a series of science experiments, in the works for 2 years, that will run from July 2016 through July 2017.

The CCSI ACME team—which includes Peter Thornton, ACME council member and Land Model Task Team colead; Valentine Anantharaj, Workflow Task Team colead; and Patrick Worley, Performance Task Team colead—has been concentrating on land model development, atmospheric model development, and software engineering aspects of the project such as workflow and performance analysis.

Land model development

On the land model side, the most significant advance made this past year was integrating the phosphorus cycle. In the past, Thornton points out, CESM was unique in the community of global ESMs for including both a nitrogen cycle and a carbon cycle. No model to date, however, has included phosphorus. ACME Version 1 will include carbon, nitrogen, and phosphorus cycles, based on work by Xiaojuan Yang, a CCSI early career scientist. "This is world class new science that no other coupled model has," says Thornton. "We're really excited about that."

Another innovation the team has introduced is what's called "reactive transport modeling capability." This is a new, more sophisticated way to solve the coupled hydrology-temperature (freeze-thaw) dynamics and biogeochemistry reactions in the soil and between the soil and vegetation. Thornton says the approach more consistently integrates the mass, energy, and biological components of the model, including the phosphorus cycle work.

Atmospheric model development

Achievements by the ACME Atmospheric Model team have been no less impressive, but perhaps the most exciting have been in the area of high-resolution simulation. Most global models today don't represent the impacts of climate change on water resources very well in mountainous regions or other regions with complex terrain. To address this, the team has developed a topography-based subgrid system based on high-resolution global elevation data from various sources. This results in a greater number of subgrid units over regions of complex terrain, such as mountains, leading to better representation of precipitation and surface water flow in such regions. For consistency, the same high-resolution subgrid system is also being used for the ACME Land Model.

Performance—to the exascale and, perhaps, beyond

Pat Worley, is leading the performance evaluation effort, both for ORNL aspects of the project and for the project

as a whole. Up to this point, that's mainly been a matter of ensuring all the subcomponents of the system run as quickly as possible on Titan and other leadership computing resources and then ensuring that when they are coupled they continue to run quickly. The performance target they are aiming for is 5 simulation years per day for the highest resolution simulations.

Workflow

Workflow is the final piece being worked on in CCSI. The goal is to have a robust system that domain scientists can use efficiently and effectively without a lot of tedious work up front. The workflow tool under construction is really a set of tools operating under a web-based user interface that will be in place when Version 1 is rolled out in June—available to the whole world. Not having a workflow tool such as the one being designed restricts the science that can be done and the use of the model to that very small population of computer programmers/modelers/software engineers who are also domain scientists. "So by looking at workflow, we really hope to open it up to a larger community," Thornton says.

Learn more at http://climatemodeling.science.energy.gov/projects/accelerated-climate-modeling-energy

Contact: Peter Thornton, thorntonpe@ornl.gov

LIVVkit awakens—a toolkit for land ice verification and validation

PISCEES (Predicting Ice Sheet and Climate Evolution at Extreme Scales) hit another milestone in July 2015 with the public release of the Land Ice Verification and Validation toolkit or LIVVkit, the first automated tool to evaluate ice-sheet models both in a stand-alone configuration and coupled to earth system models (ESMs).

Developers and users of scientific models are interested in determining how well the models work for their intended purposes. They must show that the software runs correctly (software verification), that the mathematical algorithms are solved correctly (numerical verification), that the software is capable of being used reasonably well for its intended task (software validation), and that it reproduces the physical world reasonably well (physical validation). CCSI's Joe Kennedy, a postdoctoral research associate and one of the LIVVkit developers, says that there are a variety of observations with which LIVVkit can compare simulations for model validation. But to have the validation tests mean anything, users also have to ensure that the math is right, so verification and validation go hand in hand. "Verification makes sure that we are taking the right path," he says, "and validation makes sure that we're getting to the right place."

Getting to Know Our Early Career Scientists—Moetasim Ashfaq

Dr. Moetasim Ashfaq (Moet), an atmospheric physicist in the Computing and Computational Sciences Directorate and Climate Change Science Institute (CCSI), spent his early years in Kashmir, Pakistan, a country widely regarded as extremely vulnerable to climate change.

Moet uses high-resolution climate models to study the impacts of climate variability and change on natural and human systems—particularly at fine (regional and subregional) scales. Two areas he specifically focuses on are the continental United States and south Asia.

Moet was part of the groundbreaking team that solved the puzzle of the Karakoram glaciers. Globally, glaciers have been retreating due to warmer temperatures—except for one area, the Karakoram (in the Himalayas), where they not only aren't retreating, but are actually growing. Through high-resolution modeling Moet and his colleagues found this to be the result of the unique seasonality of precipitation in the region. The research also indicated that this trend would continue through the 21st century—a finding of great importance to the more than 1 billion people dependent on meltwater from glaciers in the Himalayas as a freshwater resource.

In the United States, his focus has been on future climate change up to about the middle of the 21st century. As part of this work, Moet and his colleagues have developed one of the highest resolution climate models covering the United States, and they are using it to address issues such as the impact of climate change on hydroelectric plants and the collateral effects of extreme weather events.

The resources at the lab may not be what one typically thinks of as inspirational, but Moet says "they are magical," allowing scientists to do things here that wouldn't be possible anywhere else. And the lab is a big supporter of the "think outside the box" ethos, which he says will be needed to address the climate challenges we are facing.

To learn more about Moet and his work, please go to the CCSI website.

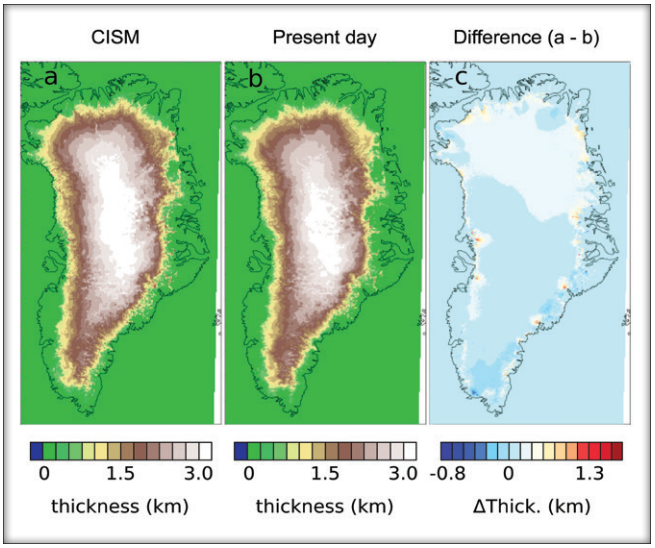
LIVVkit, a lightweight, Python-based toolkit, allows users and developers to automatically run a comprehensive set of verification and validation tests and easily integrates into a user's or developer's workflow. LIVVkit runs on different platforms, from regular laptops to supercomputers like ORNL's Titan.

Over the next few years, climate and computational scientists will be developing new versions of various ice-sheet models and their dynamic cores (dycores), the backbone of the ice-sheet models that solves the fluid and thermodynamic equations governing ice-sheet behavior. LIVVkit was developed to support this development and maintain confidence in the models.

Currently LIVVkit is being used to compare newer versions of individual ice-sheet models with older versions that have already been benchmarked, a good way to ensure that changes haven't adversely affected the models, but the ultimate goal is to use it to cross compare the various ice-sheet models and how they affect ESM results.

LIVVkit is available on GitHub, a web-based host with Git source code management and collaboration features.

Contact: Joseph H. Kennedy, kennedyjh@ornl.gov, or Katherine J. Evans, evanskj@ornl.gov



Example validation output from LIVVkit: (a) shows the ice thickness that was simulated in CISM (the Community Ice Sheet Model), (b) shows present-day ice thickness observations, and (c) shows the difference between the model output and observations (a − b).

2015 CCSI Science Advisory Board

The Science Advisory Board (SAB) was chartered in 2012 to provide advice, guidance, and counsel on CCSI strategic science objectives. Membership consists of 12 external (non-ORNL, non-UT-Battelle) advisers with knowledge of and influence in the major research areas of CCSI. Members are appointed for staggered 3-year terms by the CCSI director through consultation with the deputy director, operations and business manager, and theme leaders to ensure the membership has broad experience in science and technology in areas relevant to CCSI. SAB meets annually at ORNL to gain in-depth knowledge of relevant activities, and conference calls are conducted to provide updates to the board in between the site visits.

The following members rotated off the board this year: Virginia Burchett (outgoing chair), USGS; Peter Curtis, The Ohio State University; Noah Diffenbaugh, Stanford; and Sara Graves, University of Alabama, Huntsville. We would like to thank them for their many years of service to CCSI. Their input was invaluable during the formative years of the institute.

The following new members were appointed to the board in 2015.

Jeff Arnold—senior climate scientist with the US Army Corps of Engineers Institute for Water Resources.

David Hollinger—director of the USDA Northeast Climate Hub and project leader at the US Forest Service Northern Research Station.

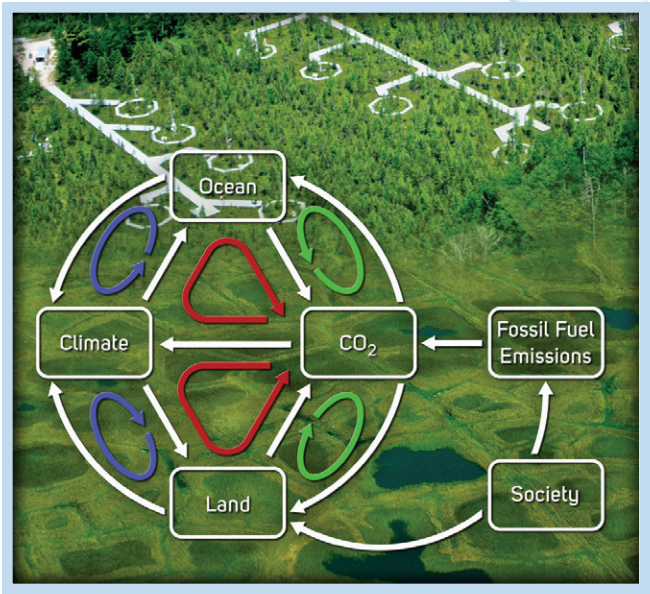
Brian O'Neill—leader of the Integrated Assessment Modeling group within the Terrestrial Sciences Section at the National Center for Atmospheric Research (NCAR), leader of the Climate and Human Systems Project, and cochair of the Community Earth System Model Societal Dimensions Working Group.

Curt Tilmes—computer scientist with the NASA Goddard Space Flight Center.

They joined current SAB members Robert S. Chen, director of the Center for International Earth Science Information Network; Mike Frame, chief of Scientific Data Integration and Visualization, USGS; Wayne Higgins, director of the Climate Program Office at NOAA; Christiane Jablonski, associate professor of atmospheric, oceanic, and space sciences, College of Engineering, University of Michigan; Anthony Janetos, director of the Frederick S. Pardee Center for the Study of the Longer-Range Future; Jean Francois Lamarque, senior scientist and section head of the Global Chemistry Modeling group at NCAR; and Anna Michalak, faculty member in the Department of Global Ecology, Carnegie Institution of Washington at Stanford University.

CCSI extends a warm welcome to the new SAB members and a special thanks to those already serving, including incoming SAB chair, Sasha Reed (research ecologist with USGS).

Terrestrial Ecosystem and Carbon Cycle Science



TES SFA—Lessons to be learned

For CCSI's Terrestrial Ecosystem Science Scientific Focus Area (TES SFA), 2015 was a year of scientific achievements and milestones in its continuing mission to understand and predict the global terrestrial ecosystem forcing of Earth's climate, to assess vulnerability of terrestrial ecological systems to projected changes, and to integrate empirical data to improve model structures and processes. TES SFA principal investigators completed the second successful triennial review of the project, including a progress report covering FY 2012–FY 2015 research tasks and a science plan for the next triennial research period (FY 2016–FY 2018).

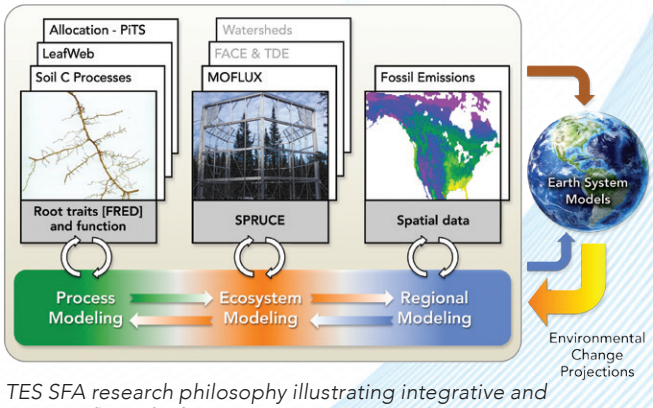
The second triennial review was held in late June 2015. A committee of eight reviewers and three DOE Biological and Environmental Research (BER) program managers reviewed the progress report and 3-year project proposal for fiscal years 2016–2018. The TES SFA science plan and proposal for research funding over the next 3 fiscal years were accepted as written. Reviewers provided some helpful comments on the projected strategy that were also addressed by the team, says Paul Hanson, TES SFA principal investigator and ORNL Corporate Fellow.

Integrating short- and long-term tasks

The basic science plan addresses standing challenges in climate research, covering tasks such as large-scale and long-term experiments, carbon-cycle (C-cycle) observations, database development, and terrestrial studies integrated with modeling activities.

Science goals during the previous triennium (FY 2012–FY 2015) were focused on establishing long-term peatland warming studies and the collection of preliminary data to serve as baseline reference material as the treatments come online. The team brought SPRUCE (Spruce and Peatland Responses Under Climatic and Environmental Change) to full operational status in August 2015; says Hanson, "We've transitioned from construction to full investment in science."

Though SPRUCE is a major component of the TES SFA, it is only one of several tasks funded for the 2016–2018 triennial period. Work continues on the refinement of subsoil-carbon mechanisms within terrestrial ecosystem



TES SFA research philosophy illustrating integrative and iterative flow of information between model projections, hypothesis development, and executed experiments.

models, and two new tasks were established to characterize and understand the role of roots in driving the ecosystem C-cycle. A dedicated TES SFA team also takes advantage of experimental and process studies to improve mechanisms for C-cycle models.

From root to canopy, a decade of measurements at the Missouri Ozark AmeriFlux (MOFLUX) forest site bridged experiments with predictive models of future climate conditions. Under the approved science plan, MOFLUX site work will continue to inform data sets and characterize drought responsiveness of eastern forests.

The recently established LeafWeb, a web-based tool for automated analyses of leaf-gas exchange measurements and data sharing, is another new task for the next triennium. Starting in FY 2016, DOE BER is fully funding this effort to analyze photosynthetic traits that Hanson calls a "necessary and crucial move" to sustain the long-term investment necessary to drive high-resolution C-cycle models of global terrestrial ecosystems.

Functional philosophy

Central to the triennial proposal is an organizational philosophy aimed at gaining important climate information through successful incorporation of experimental data within global ecosystem models. Whether short-term or long-term, TES SFA research impacts other DOE programs such as ACME, Earth systems modeling around the globe, and climate science across CCSI. "Our research is being done in the context of modeling, with a key objective to translate lessons learned from experimental work into an enhanced predictive model capacity," Hanson says.

Learn more at http://tes-sfa.ornl.gov/

Contact: Paul Hanson, hansonpj@ornl.gov

SPRUCE marks beginning of landmark ecosystem experiment

SPRUCE, which stands for Spruce and Peatland Responses Under Climatic and Environmental Change, marked another milestone this year. After 3 years of planning, collecting background data, and construction, 10 open-topped transparent enclosures—12 m in diameter by 8 m in height (about 39 by 26 ft)—went "live." The enclosures, which are the laboratories for experiments to assess the ecological responses of peatland flora and fauna to increased temperatures and CO_2 concentrations, are superimposed on a belowground corral that isolates the peatland. By controlling the temperature and the amount of CO_2 in the test chambers, scientists hope to learn how microbial communities, moss populations, various higher plant types, and some insect groups respond.

The atmosphere and soil within the enclosures, to a depth of about 3 m (roughly 10 ft), will be maintained at a range of temperatures up to 9°C (16°F) above temperatures outside the enclosures (mimicking projected temperature increases by the end of the 21st century), and CO_2 levels will be increased in half the enclosures, again emulating potential increases by the end of the century. Soil heating began in 2014, atmospheric heating within the enclosures began in July 2015, and CO_2 increases will begin in 2016. To celebrate completion of the aboveground enclosures and the start of atmospheric heating, a commissioning ceremony was held in August 2015.

"The SPRUCE experiment continues ORNL's involvement in environmental change studies that are conducted in the real world at scales relevant to an ecosystem's stature, biodiversity, and biogeochemistry," said Paul Hanson, who leads the project and is a member of ORNL's Environmental Sciences Division and CCSI.

Although peatlands cover only about 3% of the Earth, they contain up to 33% of the global soil carbon pool. That carbon has been trapped in the cold, oxygen-poor environment since the end of the last ice age, 10,000 years ago; however, warming conditions could cause peatlands to release large amounts of carbon, as either CO_2 or CH_4 (methane), further impacting Earth's climate. Currently scientists have a poor

SPRUCE test chamber, September 8, 2015.

understanding of the potential impacts of a warming, more CO_2-rich environment on carbon stored in soils, which impacts the accuracy of ESMs and climate projections.

"SPRUCE is the first experiment to test the combination of warming and elevated CO_2 on carbon-rich peatland ecosystems," said Randy Kolka, team leader and research soil scientist with the US Forest Service, a partner in the project.

Learn more at http://mnspruce.ornl.gov/

Contact: Paul Hanson, hansonpj@ornl.gov

NGEE-Arctic—Putting a face on climate change

For the Next Generation Ecosystem Experiments–Arctic (NGEE-Arctic), 2015 was a watershed year: Phase 1 (2012–2015) was completed, a combined summary report–Phase 2 proposal was submitted, a very successful project review was completed, and work on Phase 2 (2016–2018) was started.

During Phase 1, the NGEE-Arctic team perfected approaches to measurements, site selection, and team integration, as well as interactions with the project modelers. To advance the goal of more reliable Earth system models (ESMs), team members developed new model structures to take into account microbial processes, surface-subsurface interactions, and hydrology at high latitudes (above 60° north or south latitude), as well as benchmarking strategies for model testing. Along the way, they determined that Arctic tundra must be studied from a holistic perspective. Pieces cannot be studied in isolation, but rather the many questions being asked need to be examined in an integrated manner. All of this paid off when it came time for the Phase 2 proposal, an expanded scope of research for continuing work at Barrow, on Alaska's North Slope, and initiating work to the south, on the Seward Peninsula.

The review, which took place in early September, included DOE Biological and Environmental Research program managers and 11 outside reviewers, including scientists from the international community. Reviewer comments and the official letter from DOE recognized in very positive terms the team's commitment to the project, integrated approach, presentations and documentation at the review, and "progress on the project and delivery and defense of a well-developed proposal," which was accepted with only moderate revision. NGEE-Arctic Program Director and Principal Investigator Stan Wullschleger has high praise for the review process and review team, as well as the NGEE Arctic team itself, whose constructive suggestions, he says, have made the project stronger.

Gearing up for Phase 2

Phase 1 was heavily slanted toward data gathering, and the field team has gotten adept at handing off data to

Getting to Know Our Early Career Scientists—Colleen Iversen

Colleen Iversen, a member of CCSI's Terrestrial Ecosystem and Carbon Cycling Science group, grew up on a farm in rural Michigan. She says she's always wanted to understand the way the world works, the "why" of things. "I think this is what makes science so much fun for me . . . there is always a question that you get to answer, so you always have something new or interesting on the horizon. I also like being on the cutting edge of new technology and science, and what better place for this than a national laboratory?"

Colleen believes ORNL and the other national labs bring next-generation technologies and ways of thinking to bear on scientific questions. "Along with that comes multidisciplinary teams—multiple investigators with multiple skills, multiple ideas, and multiple ways of looking at things. And that's part of what makes a national laboratory great."

Colleen's time currently is spread over three main CCSI projects: SPRUCE; NGEE-Arctic; and NGEE-Tropics, the last in more of an advisory role. For SPRUCE she is investigating the effects of warming and elevated CO_2 on the root growth of bog tree and shrub species, as well as how changes in the availability of nutrients could influence both root growth and responses to warming. For Phase 2 of the NGEE-Arctic project, Colleen is assuming a task leader role in some areas, including a new task on plant traits that examines how they enable plants to adapt and how they are used in models. And along with CCSI's Jeffrey Warren, she is leading a new task to develop a global root trait database, currently called "FRED" for "Fine-Root Ecology Database."

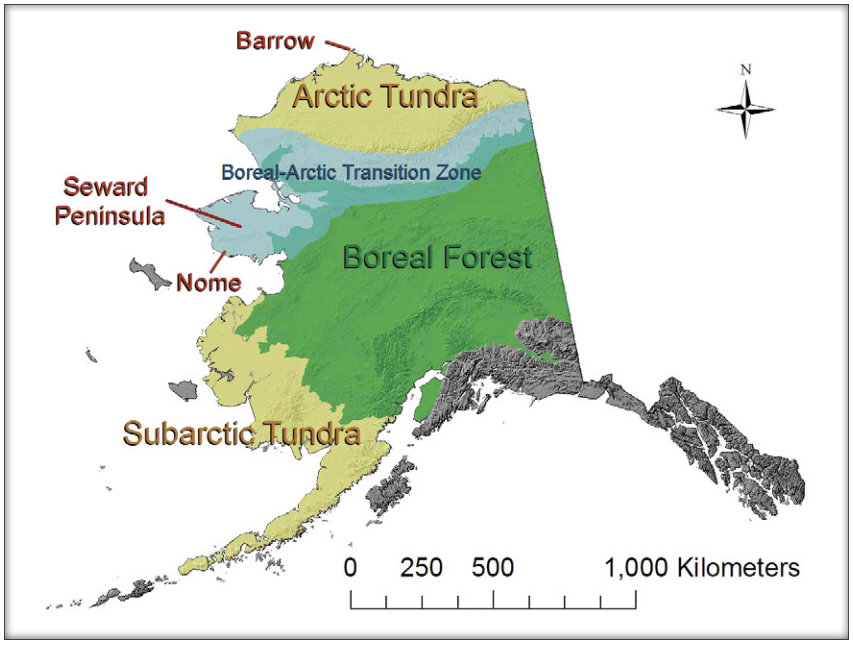
A common element in these new tasks is filling in knowledge gaps. For years, Colleen says, the impact of the belowground sector has been missing in models. Hopefully the work she and others are doing in this area will better inform the models that are predicting the climate future.

To learn more about Colleen and her work, please visit Colleen's website.

the modelers. Based on what they have seen, the modelers are already making suggestions for Phase 2.

There is a notable difference between the North Slope site, above the Arctic Circle, which is very cold and very stable, and the Seward Peninsula, which is comparatively very warm, very dynamic, very transitional . . . already undergoing rapid change. Working on the Seward Peninsula will enable the team, in Wullschleger's words, "to study today's environment superimposed on tomorrow's climate."

From late July to early August 2015, 18 team members went to the Seward Peninsula to begin identifying potential field sites. Wullschleger says these efforts benefited from having a site visualization tool developed by data management team members that enables them to tag photos taken in the field with GPS coordinates for later comparison and evaluation. As a result, they have been able to complete the selection process. While they were there, they were also able to start the research process by taking preliminary measurements; setting up instruments for monitoring temperature, precipitation, and permafrost conditions; and taking water samples.



Transition zone between boreal forest and Arctic and subarctic tundra in Alaska. (Adapted from USGS, http://alaska.usgs.gov/science/interdisciplinary_science/cae/boreal_arctic.php)

Back at the lab, the team is developing specific field work plans for conducting research in 2016.

Communicate, communicate, communicate

Communication is a big part of the NGEE-Arctic paradigm: communication among team members, communication between the onsite research team and the modelers, communication with the broader scientific community, and communication with local communities. This last, according to Wullschleger, has really put a face on climate change for him. Local populations in Alaska, many of whom are dependent on fishing, hunting, and foraging, are already feeling the effects of climate change.

Learn more at http://ngee-arctic.ornl.gov/

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NGEE-Tropics—Tropical forest responses to a changing climate

The $100M, 10-year, NGEE-Tropics project was initiated to answer critical questions related to gaps in our knowledge of tropical forests and determine whether they will continue to function as carbon sinks if temperatures continue to rise. Following the ModEx "formula," gaps in current models are identified, and experiments and fieldwork are then designed to provide the missing data. The results are used to develop more precise models, which in turn influence the direction of future research.

Three main sites have been selected for Phase 1 fieldwork: Manaus, Brazil; El Yunque National Forest in Puerto Rico; and several sites across Panama, where project researchers from the Smithsonian Tropical Research Institute will join the team. Work at all three sites has been jumpstarted by the need to get equipment in the field to record the effects of this year's El Niño.

The roles of soil moisture and nutrients

CCSI's Rich Norby, who is on the project's executive committee, leads the Nutrient Biogeochemistry research area. A key task for that research, led by CCSI's Xiaojuan Yang, involves the phosphorus nutrient cycle in the tropics and efforts to improve the "phosphorus model"—the phosphorus cycle is one of the critical gaps in knowledge that NGEE-Tropics is designed to address. Yang's research suggests that if there is not enough phosphorus, plants can't be as productive as they might otherwise be; and therefore, they don't draw down as much CO_2 from the atmosphere. CCSI's Melanie Mayes is interested in linking the hydrologic information from the project with the soil biogeochemistry findings. She says moisture is the key to everything. "If it's really, really wet, you have fluctuating

redox reactions that cause soil minerals to dissolve, liberating phosphorus.

At the Manaus site, currently experiencing extreme drought, researchers want to develop a mechanistic model of H_2O fluxes and resistances from the soil through to the canopy and atmosphere. As part of the fieldwork for this task, they will apply resistances to H_2O uptake and thresholds to investigate cavitation of the soil-root system, which happens when the xylem is damaged (cavitated) by stressors such as drought. At other project sites, NGEE-Tropics personnel are installing sap flowmeters and dendrometers to assess drought stress and correlate it with tree growth.

Measurements of water potential in the leaves at the top of the forest canopy are also necessary, and this is a challenge in the rainforest. To resolve this challenge, sensors are being placed in towers adjacent to the trees where possible. In other cases (e.g., Panama), cranes are being used. And where neither of these alternatives is available, in some cases researchers may have to resort to climbing trees to obtain samples.

Collaboration and leverage

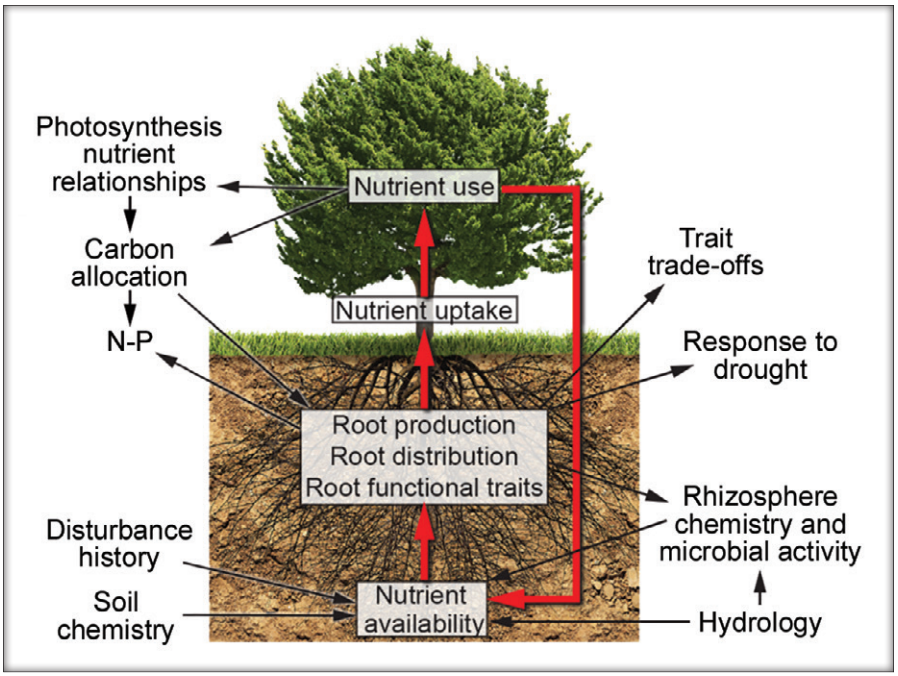
NGEE-Tropics researchers are collaborating with researchers on other tropical research projects and making use of data from prior or simultaneous research projects to leverage NGEE-Tropics goals.

Jeff Warren, a CCSI environmental scientist, points out that one of the sites in Panama, Barra Colorado Island, has been heavily studied for nearly 100 years, and that information will definitely be leveraged for the project. Norby says he also expects to leverage photosynthesis-phosphorus data from a previous Oak Ridge National Laboratory–funded project in Panama geared toward deepening understanding of tropical research conditions.

So while a lot of original research is being conducted for NGEE-Tropics, people aren't forgetting that there's a lot of excellent existing data and new ways of combining and looking at the data sets to improve models and guide NGEE-Tropics. "It's really about building partnerships," says Mayes, "and that's a good model for all research."

Learn more at http://esd.lbl.gov/ngee-tropics/

Contact: Rich Norby, norbyrj@ornl.gov



Graphical representation of nutrient–plant productivity relationships being probed as part of NGEE-Tropics.

FACE data continue to enrich climate research

The ORNL free-air CO_2 enrichment (FACE) experiment ended in 2009, followed by a flurry of publishing activity made possible by the experiment's data gathering over 12 years of operation. However, more than 6 years later, the impacts of DOE's FACE experiments are still being felt.

After the ORNL FACE experiment measurements were completed in 2009, CCSI ecologist Rich Norby and project colleagues integrated the mounds of observational data into computer models. "We can't do experiments directly to address all the questions related to global forest response over many decades," he said. "So we have to make use of models to get at these questions. An important reason for intensive experiments is to inform and improve our models."

Recently Norby and an international team of researchers set out to assess how the results from the ORNL FACE and Duke University Forest FACE experiments compared to 11 vegetation models that simulate various ecological processes. The team summarized its work in an article, "Using ecosystem experiments to improve vegetation models," published this year in *Nature Climate Change*.

Using a unique "assumption-centered" approach, the researchers evaluated why certain models performed better

than others. "We wanted to understand why the models were doing what they were doing, rather than just compare them to the data in a superficial fashion," said CCSI's Anthony Walker, one of the study participants and coauthors. "We evaluated the models based on how well they represented underlying biological mechanisms."

Comparing the models with the FACE data sets allowed the team to identify missing elements or incorrect assumptions in the models and pinpoint processes for which additional understanding is needed. "By understanding the processes that are responsible for what's going on in the models, we're connecting them with the experiments in a common language," Walker said.

The team's study is helping to evaluate current understanding and model representation of forest ecosystem responses to future climates. It will also help guide new FACE experiments that are under way or planned in different biomes and climates, such as the Amazon, Australia, England, and Sweden.

According to Norby, this type of collaborative approach is increasingly important in climate change science, where field researchers and modeling experts are working together more closely than ever before.

Learn more at http://facedata.ornl.gov/

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Aerial view of open-air FACE chambers at the Oak Ridge National Environmental Research Park, Oak Ridge, Tennessee.

Impacts, Adaptation, and Vulnerability Science

The year in review

Over the past year, CCSI's Impacts, Adaptation, and Vulnerability (IAV) Science researchers have worked diligently to leverage various capabilities across CCSI to enhance understanding of the consequences of climate change in ways that represent scientific excellence but that also have practical implications for vulnerable societal systems. This emphasis on generating social impact from science investments is reflected within CCSI's strategic plan, and the institute's IAV Science research is a key mechanism by which this objective is achieved.

During the year, IAV Science staff continued to support the mission of DOE with work for the Offices of Energy Policy and Systems Analysis, Science, and Energy Efficiency and Renewable Energy. Projects ranged from developing methods for the cost/benefit analysis of climate change impacts to energy utilities, evaluating the sustainability of bioenergy, and developing socioeconomic scenarios to inform integrated assessment of climate change impacts and adaptation responses.

Through the Laboratory Directed Research and Development program (LDRD), IAV Science researchers have sought to develop new capabilities to assess climate change risks and design interventions to reduce those risks. For example, Earth system models, regional climate models, and hydrological models were used in the assessment of climate change impacts on probable maximum precipitation and flooding—critical design criteria for infrastructure such as dams and for the siting of nuclear power plants. Meanwhile, two ORNL institutes, CCSI and the Urban Dynamics Institute, have partnered to bring the broad range of modeling and data analysis capabilities at ORNL together to inform green infrastructure investment and siting to reduce urban storm water runoff in the city of Knoxville. Such projects position CCSI to address not only scientific challenges, but also practical decision challenges regarding climate adaptation and the realization of a more resilient nation.

IAV Science staff continued to play important roles in scientific assessment activities. The *Adaptation Actions for a Changing Arctic* assessment is due for release in 2017, and IAV staff have been leading efforts to assess alternative socioeconomic futures that will shape the consequences of climate change in the Arctic. IAV Science is also leading the second assessment of the impacts of climate change on hydropower, with a report to Congress due in the spring of 2016. CCSI staff across the four themes, including IAV Science, also participated in different expert workshops sponsored by the Intergovernmental Panel on Climate Change that helped to lay the foundation for the *Sixth Assessment Report*.

Looking ahead, CCSI's IAV Science researchers are looking forward to supporting DOE's new emphasis on data and modeling to enhance understanding of the energy-water nexus. Given the energy sector is a significant user of water and given the widespread concern about the impacts of climate change and population growth on the sustainability of US water resources, investigating interactions between water and energy is fundamental to DOE's mission. In addition, CCSI is looking forward to opportunities to support the sustained assessment efforts of the US Global Change Research Program.

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Evaluating the most extreme rainfall and flood events for energy-water security

Characterization of hydrometeorological extreme events at scales relevant to decision making is one of the core research objectives of CCSI's IAV Science theme. Because of the catastrophic consequences associated with such events (e.g., dam failures), this past year CCSI's Shih-Chieh Kao led an LDRD-funded project to reexamine extreme hydrometeorological events and critical energy-water infrastructure.

The project team focused on the most extreme hydrometeorological events: probable maximum precipitation (PMP) and probable maximum flood (PMF). A PMF is theoretically the largest flood event that could occur under a series of adverse hydrometeorological conditions triggered by a physically possible PMP event. What makes PMP-PMF special is that, taken together, they are the theoretical physical upper bounds under a series of worst-case atmospheric and land surface conditions. As such, they are used as the strictest design/evaluation standards for critical energy-water infrastructure such as dams, reservoirs, and nuclear power plants.

Aerial view of Fort Calhoun Nuclear Reactor during the 2011 Missouri River flood. (Courtesy US Army Corps of Engineers)

The problem is, the last time PMP was examined was the late 1970s and early 1980s, when NOAA issued a series of hydrometeorological reports. Since then there has been no national initiative to update them.

There is renewed interest in PMP-PMF, including questions about how valid current methods are in light of new atmospheric and climatic information since the 1980s. The frequency and intensity of extreme meteorological events are increasing, and there have been extensive land use/land cover (LULC) changes since the 1980s that could impact PMP-

Getting to Know Our Early Career Scientists—Shih-Chieh Kao

CCSI scientist Shih-Chieh Kao, team leader of the Hydrologic Systems Analysis Team in the Environmental Science Division, was born and raised on Taiwan, an island nation in the extreme western Pacific. The eastern two-thirds of Taiwan is very mountainous, and only about 20% of the land is "usable." Not only is it subject to three or four hurricanes per year, but because it is situated in a complex seismic zone, it is also subject to earthquakes.

All of this makes for some very interesting hydrologic features, says Shih-Chieh, and while it didn't predetermine a career in hydrology, it certainly made him interested in hydrology-related issues.

After obtaining undergraduate and master's degrees in civil engineering, specializing in hydraulics, from the National Taiwan University, in 2004 he came to the United States to pursue a PhD in civil engineering, again specializing in hydraulic and hydrologic engineering.

Shih-Chieh says his first projects at ORNL, analyzing climate data, left him feeling "a little horrified." Analyzing the frequency of extreme weather events simulated by climate models, he realized that if the climate data he was seeing were indeed accurate, "we needed to start thinking about extreme events in new ways."

And that has set the tone for much of his later climate-related research, including a recent ORNL LDRD project in which his team developed a new modeling framework to evaluate the potential impacts of extreme events on critical energy-water infrastructures.

Currently Shih-Chieh is the principal investigator for the National Hydropower Asset Assessment Program (NHAAP), which ORNL runs for the DOE Water Power Program. As part of NHAAP, ORNL hosts and maintains the national hydropower database for DOE and also collects a comprehensive set of observation data to support analysis of hydropower trends in the United States. "Because this is an energy lab, I've been very fortunate in getting involved with this type of work," he says. "Scientists here have the opportunity to directly work on 'national-scale questions,' and the research outcomes may directly inform national policy. This makes working here a very unique experience that you don't typically have in other venues."

To learn more about Shih-Chieh and his work, please visit his website.

PMF. Finally, the advanced computing resources available today are better able to handle demanding high-resolution flood simulations than what was available in the 1980s.

Kao's project team, which included collaborators from Tennessee Technological University, was able to (1) develop an integrated modeling framework to simulate PMP and PMF using ORNL high-performance computing resources, (2) quantify how PMP responds to climate changes based on multiple future scenarios, (3) test the sensitivity of PMF to LULC changes, and (4) develop an integrated PMP/PMF risk assessment framework to evaluate the potential impacts of extreme events on energy-water infrastructure.

The LDRD project ended in 2015, and the team is currently working with the Nuclear Regulatory Commission on review of site-specific PMP and PMF estimates for multiple US nuclear power plants.

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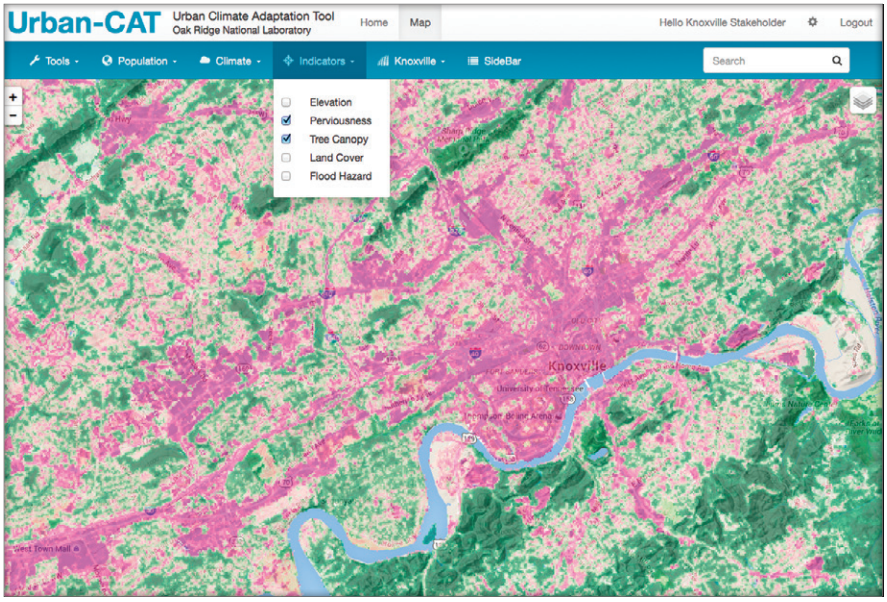
Urban-CAT—Improving resiliency one community at a time

Two ORNL institutes, CCSI and the Urban Dynamics Institute (UDI), have joined forces to address one of the most pressing problems facing midsize cities today: how best to allocate scarce resources to deal with climate change. The solution they have come up with is a unique web-based decision support tool, the Urban Climate Adaptation Tool or Urban-CAT.



To ensure that Urban-CAT will be useful and accessible to urban decision makers, the project team, which includes Olufemi Omitaomu, Esther Parish, and Phil Nugent, is collaborating with the City of Knoxville. "As scientists we can perform all kinds of calculations, but in the end, if they are not comprehensible by decision makers or don't result in something that people can use, then we have failed," says Omitaomu.

Nearly 50% of the world's population lives in midsize cities like Knoxville, with populations around 250,000. And the World Health Organization projects more than 60% of the world's population will live in midsize cities by 2030. Big cities such as Chicago or New York have more resources to deal with climate change scenarios says Omitaomu. Midsize cities need tools to develop adaptation strategies they can integrate into their policies gradually, to be ready when change comes.

The challenge in helping cities plan for this type of change, according to Omitaomu, who works for both CCSI and UDI, is that most climate models don't provide enough information at a usable scale for local planners to make decisions, to understand what adaptation measures they need to put in place to alleviate repercussions from some of the impending climate changes such as rising sea levels, increased rainfall, or drought.

The Urban-CAT platform addresses this by coupling climate projections with socioeconomic and infrastructure data at scales useful for urban planning. The platform also provides connectivity to multiple data sources for comparison and assessment of local project scenarios under different climate conditions. Finally, the project team has developed a set of urban resilience indicators to be used in assessing resilience and in monitoring and evaluating the effectiveness of selected adaptation actions in reducing risk.

Funded through ORNL's Laboratory Directed Research and Development program, the project is a direct response to the President's Climate Data Initiative, a broad effort to leverage open government data resources with tools to help communities become more resilient to climate change.

At the end of FY 2016, the second year of the project, Omitaomu says they will have a tangible product for Knoxville to test and start using. The ultimate goal is a full-suite climate adaptation toolkit, which will be widely available through the US Climate Resilience Toolkit.

"Different cities will face different challenges," Omitaomu says. "If we can develop a useful tool for the City of Knoxville, we can customize it for other cities."

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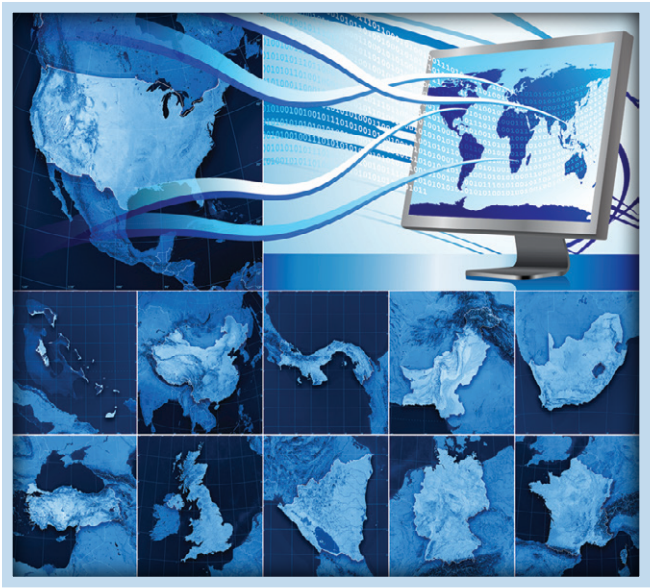
Data Integration, Dissemination, and Informatics



ARM Decadal Vision signals new roles for Palanisamy

Giri Palanisamy.

CCSI's Giri Palanisamy is assuming the new roles of ARM Data Services and Operations manager and ARM Data Architecture and Services Strategy Team (ASST) manager to meet next-generation data needs within the Atmospheric Radiation Measurement (ARM) Climate Research Facility (the ARM facility). Nine DOE national laboratories share the responsibility of managing and operating the ARM facility. ORNL traditionally was responsible for hosting the ARM Data Center; operating the Data Archive; and providing web-based data product request services for the user community, including data reprocessing services and support. But all that is changing.

In October 2014, the ARM facility articulated a "decadal vision" calling for accelerating the application of ARM observations and data processing for model evaluation and development. The path to realizing the vision has required organizational changes, including redefining certain roles to provide improved clarification of responsibilities and foster greater cohesion throughout the multilaboratory system.

Among these changes was creation of the new role of ARM Data Services and Operations manager to better coordinate data services across the ARM facility. In this role Palanisamy will provide leadership and management to all ARM facility data services and operations, including the Site Data Systems Group (located at Argonne National Laboratory), the Data Management Facility (located at Pacific Northwest National Laboratory), the External Data Center (located at Brookhaven National Laboratory), and the ARM Data Center. (Note: Palanisamy assumed the role of ARM Data Center manager October 1, 2015).

ASST was put in place to craft a comprehensive, multiyear plan for ARM's current computational environment to accommodate the influx of very large data sets produced from new scanning-cloud and precipitation radars and vast amounts of quantitative information that will be generated from improved high-resolution model workflows. This strategy and implementation plan, referred to as the "ARM Adaptive Architecture" and currently under development, will enable the ARM facility to accommodate a much larger amount of data than ever before. As the manager of this group, Palanisamy will facilitate teamwork among its members and ensure the future computational framework possesses the capacity to efficiently respond to emerging operational demands. With the expected influx of very large data sets and the increases in data service demands already being seen, "this rearchitecture is more important than ever for successful product delivery," Palanisamy says.

According to an ARM facility news release, Palanisamy is "making a daily impact on the advancement of science through [his] unique, pivotal contributions to ARM and willingness to take on new challenges."

Learn more at http://www.arm.gov/

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CDIAC staff contribute to reassessment of China's carbon emissions

For more than 30 years the Carbon Dioxide Information Analysis Center (CDIAC) has functioned as DOE's primary repository and information analysis center for climate change data related to greenhouse gas emissions—especially CO_2—making the data more accessible and useful to scientists and researchers worldwide.

Recently CDIAC Director Tom Boden; CCSI's Bob Andres; and Appalachian State University's Gregg Marland, a former ORNL scientist, lent their emissions data expertise to a *Nature* study that reevaluated China's fossil-fuel carbon emissions from 2000 to 2013.

The growth in China's economy has made it both the world's largest fossil-fuel carbon emitter and the world's largest cement producer (another big carbon emitter). Thus there is considerable interest in China's contribution to the global CO_2 budget; however, past estimates by various organizations, including CDIAC, have varied by as much as 15%. "Differences of 15% become important at global and regional carbon cycle scales," Boden says. "For a country [like China] that's emitting something on the order of 2 gigatons of carbon per year, with growing energy demands and large reserves of coal, it's important to quantify fossil-fuel emissions well." In the study, estimates for China's fossil-fuel and cement CO_2 emissions were reevaluated and revised down by 10% to 14% through incorporation of updated, harmonized information; provincial-level fossil fuel data; and new, measured emissions factors for Chinese coal. Boden, Andres, and Marland helped verify the calculations based on their years of carbon-accounting experience.

Coal-burning power plant, China.

Even with this adjustment, China is still the world's largest carbon emitter, but the revised estimates will benefit climate models and projections of future climate.

Learn more at http://cdiac.ornl.gov/

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DAAC—Earth observations with NASA

Two 5-year NASA field campaigns wrapped up in late 2015. Both campaigns were part of the Earth Venture (EV) Suborbital Investigations program started in response to recommendations in the National Research Council's Decadal Survey for NASA, NOAA, and USGS. EV campaigns are stand-alone, using simple instruments and, in the case of the suborbital investigations, NASA aircraft.

Staff members at the ORNL Distributed Active Archive Center (DAAC) have been working with the NASA project teams on the data from these two campaigns for the last year and a half, according to ORNL DAAC Manager Suresh Vannan, and will be releasing tools to access and manipulate the data in 2016.

The Airborne Microwave Observatory of Subcanopy and Subsurface, or AirMOSS, campaign was aimed at providing information on root zone soil moisture (RZSM) over North America to improve model prediction of net ecosystem carbon exchange or NEE (the difference between the rate of carbon uptake during photosynthesis and release during respiration). Soil moisture, essential for photosynthesis, is an important determinant of NEE. The AirMOSS data will be used to validate similar satellite microwave observations, with additional ground measurements used to validate both.

The Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) was designed to determine the concentrations of various greenhouse gases (CO, CO_2, CH_4) at different

altitudes in the atmosphere in Alaska to (1) have baseline measurements for use in tracking changes over time and (2) validate similar satellite measurements. Vannan says it is crucial to have these types of measurements for a region as fragile as boreal and Arctic Alaska to better quantify the impacts of climate change.

The DAAC role in both of these cases is focused on the data sets produced in the campaigns. DAAC staff standardize and structure the data sets to provide them in a useful format, including providing visualizations, and archive them, providing search and retrieval capabilities.

The visualizations are particularly important, according to Vannan. They help researchers use the data quickly—rather than spending time in data transformations and manipulations, they can go directly to data analysis. The original data behind the visualizations are accessible, he says, and DAAC users can download the data sets and use them in their models. In the case of AirMOSS, DAAC is also capturing and archiving the algorithms used to extract the soil moisture information.

Learn more at https://daac.ornl.gov/

Contact: Suresh Vannan, santhanavans@ornl.gov

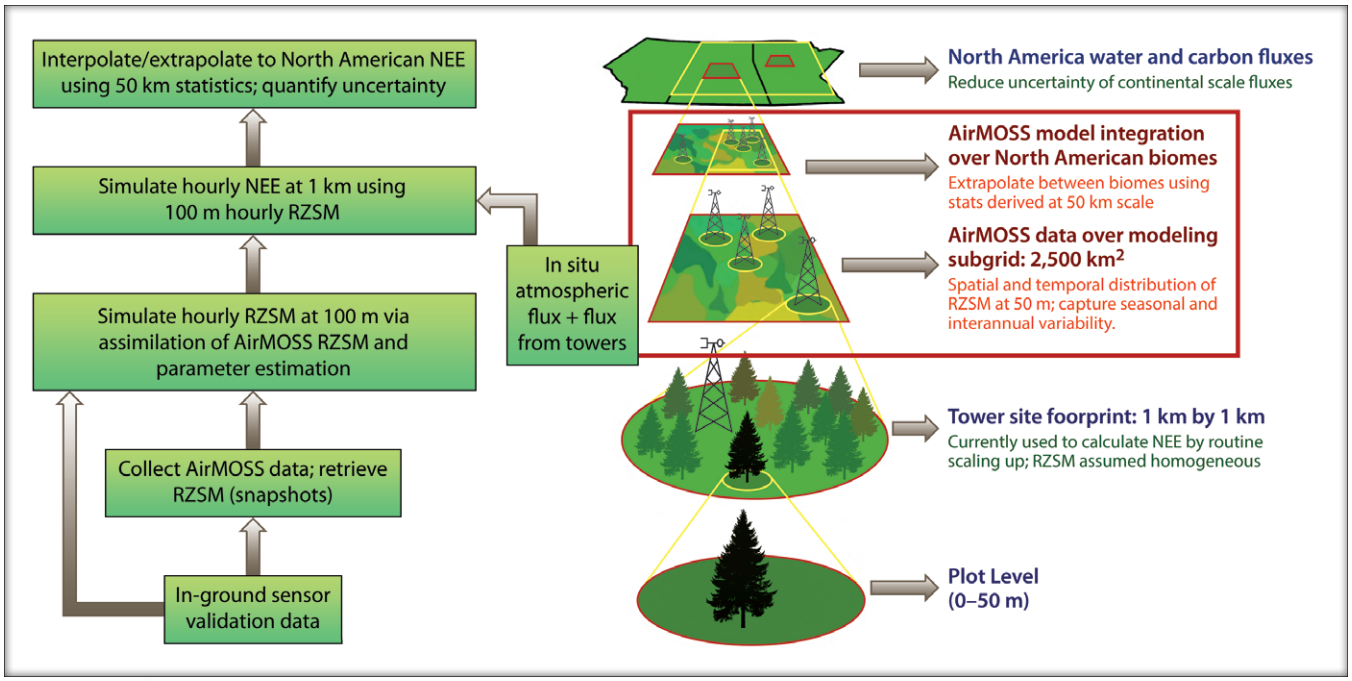

Diagram of AirMOSS bottom-up approach. (Adapted from Moghaddam and Lou, NASA AirMOSS workshop, March 26, 2013, http://uavsar.jpl.nasa.gov/science/workshops/presentations2013/UAVSAR_WorkShop2013_AirMOSS_Overview_(Moghaddam).pdf)

Honors and Awards

Tool developed by the CCSI team for SCCG shows risk of exposure to rising sea levels on a scale of very high (red) to very low (green) or unexposed (blue) for a Sydney suburb.

Preston and Maloney on award-winning Australian team

CCSI's Ben Preston was the principal researcher on the Sydney Coastal Councils Group's (SCCG's) award-winning project "Prioritising Coastal Adaptation and Development Options for Local Government." Australia's National Climate Change Adaptation Research Facility awarded the project "Highly Commended" status in the local government category of the 2014 Climate Adaptation Champions awards. As part of the project, Preston and CCSI staff research associate Meghan Maloney developed an evaluation tool for assessing protections to community infrastructure, health, and safety based on a risk management framework.

Hack elected AMS Fellow

James Hack, founding CCSI director and current director of the National Center for Computational Sciences, was elected a Fellow by the American Meteorological Society (AMS) in 2015. Hack was cited for his "outstanding contributions to advancing the atmospheric and related sciences, technologies, applications, and services for the benefit of society." AMS has a membership of more than 14,000, but the number of newly elected Fellows is limited to two-tenths of one percent of the membership, reflecting the high regard for those elected. He was honored at the organization's annual meeting in January 2015.

Homeland Security awarded ORNL team for highlighting climate change risks to vulnerable Maine bay

Members of CCSI and UDI, in collaboration with team members from the US Department of Homeland Security (DHS) and other DOE national laboratories, were awarded the DHS Office of Infrastructure Protection's Trailblazer Award for their contributions to a DHS project known as the Regional Resiliency Assessment Program (RRAP). The team's study of Casco Bay in Maine was the first RRAP to focus on the potential impacts of climate change. ORNL team members included Melissa Allen, Steve Fernandez, Benjamin Thomas, Thomas Wilbanks, Sherry Wright, Olufemi Omitaomu, Supriya Chinthavali, Daniel Koch, and Linda Sylvester.

UV-CDAT team awarded Federal Laboratory Consortium Interagency Partnership Award

CCSI and National Center for Computational Sciences staff were part of a team that won the prestigious Federal Laboratory Consortium (FLC) Interagency Partnership Award for 2015 for the Ultra-Scale Visualization Climate Data Analysis Tools (UV-CDAT) project. UV-CDAT combines a number of tools into one framework to enhance productivity and facilitate new discoveries. The award, which recognizes teams of agency and/or laboratory employees from at least two different agencies/organizations, is part of the FLC excellence in technology transfer family.

ORNL participants included John Harney; Marcia Branstetter; Brian Smith; Peter Thornton; Galen Shipman (formerly of ORNL); Chad Steed; Brian Jewell; and Kate Evans, the local project lead.

Preston awarded 2015 AGU Falkenberg Award

Ben Preston, senior research scientist and CCSI deputy director, was awarded the 2015 American Geophysical Union's (AGU's) Charles S. Falkenberg Award. Established in 2002 and jointly sponsored with the Federation of Earth Science Information Partners, the award is presented annually to a scientist under 45 years of age who "has contributed to the quality of life, economic opportunities, and stewardship of the planet through the use of Earth science information and to the public awareness of the importance of understanding our planet." Preston was cited "for his commitment to communicate climate change science and use that information to improve lives, economic opportunities, and planet stewardship."

Melanie Mayes honored at 2015 YWCA Tribute to Women celebration

In September, the Knoxville YWCA held its 31st Annual Tribute to Women celebration, and CCSI's Melanie Mayes, one of about 20 finalists in six categories, was recognized in the arts and innovation category. The Tribute to Women is East Tennessee's premier occasion for recognizing the accomplishments of women across the region. Mayes exemplifies the dedication to empowerment, equality, and transformation the award signifies, not only in her professional work but also in mentoring the next generation of scientists and in volunteerism.

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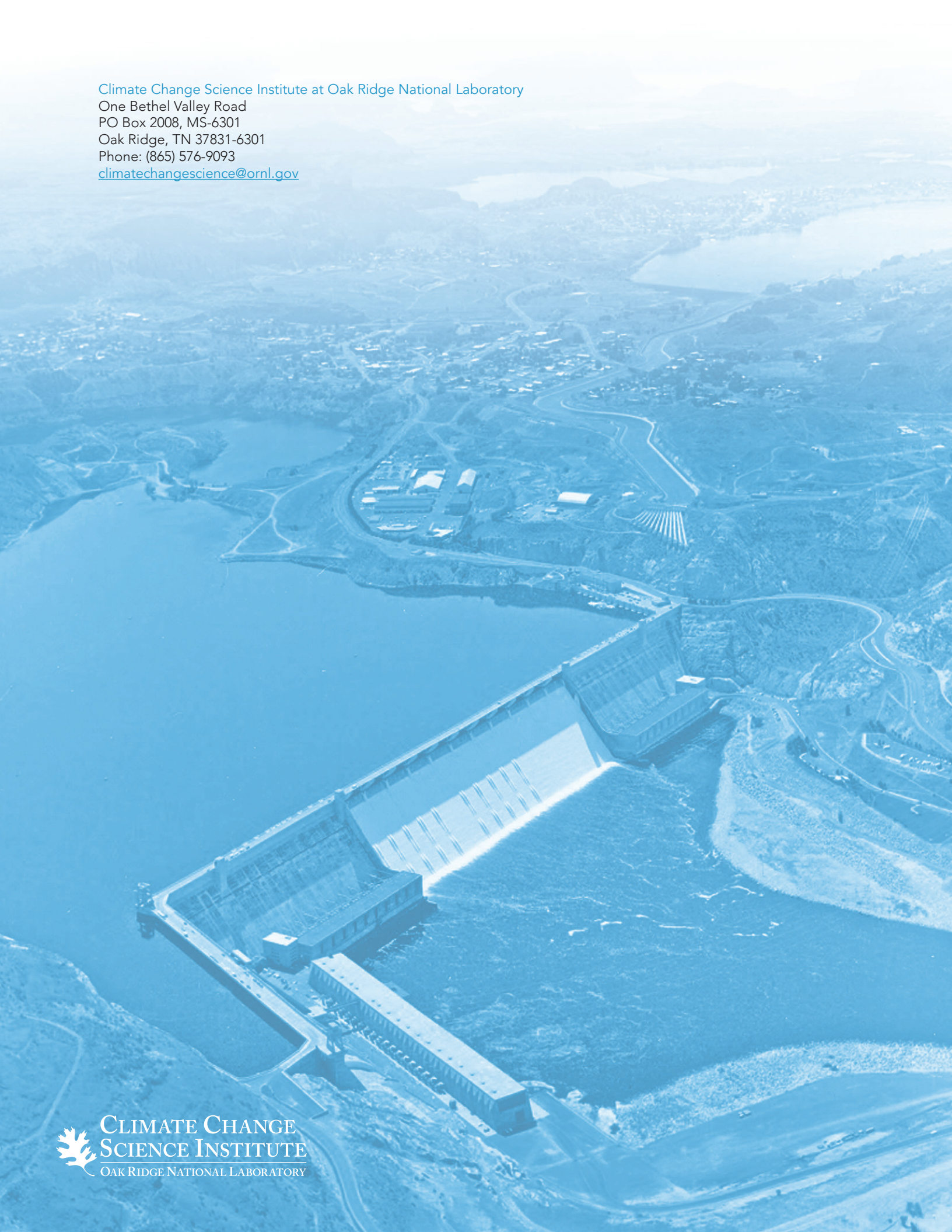

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