Climate Change Science Institute

FY 2014 Annual Report

Climate Change Science Institute
Oak Ridge National Laboratory

Table of Contents

Letter from the Director

The issues facing our planet's citizens from a changing climate—such as rising global surface temperatures and more frequent extreme weather events—remain a major challenge. There continues to be a pressing need for tools and information that individuals and leaders can use to ensure their communities have reliable and resilient access to needed services, such as energy, water, food, health, and transportation. In response, the Climate Change Science Institute (CCSI) at Oak Ridge National Laboratory (ORNL) remains focused on advancing the knowledge of climate change and understanding its consequences, making the best scientific investments to ensure the tools and information for resilient communities are available and working with stakeholders to ensure they are delivered in a useful form.

One of the main reasons I came to CCSI is access to the broad range of expertise and tools available here at ORNL to attack the issues related to a changing climate, along with the unique features of CCSI itself. I hope this annual report provides you with a meaningful sense of what CCSI is doing and, more importantly, how we might partner together to tackle the significant challenge of climate change and its effects.

A major accomplishment for CCSI in 2014 was the development of the *Climate Change Science Institute 2014–2020 Strategic Plan*. All CCSI staff and the CCSI Scientific Advisory Board members played an invaluable role in the development of this plan, and I'm grateful for their partnership and participation in its development. This report outlines how the plan is guiding both ongoing and future CCSI research efforts.

On a personal note, I celebrated my first anniversary at CCSI in October 2014. My time here continues to be an enriching experience. Tennessee has proven to be a wonderful place to live, and I can't say enough about the warmth and generosity of its people.

I want to take this opportunity to also thank the ORNL leadership for their incredible support of CCSI, in particular Laboratory Director Thom Mason and Associate Laboratory Directors Jeff Nichols and Martin Keller. I also want to thank CCSI's many sponsoring agencies, including

Climate Change Science Institute Director Jack Fellows.

the US Department of Energy (DOE), National Aeronautics and Space Administration, US Geological Survey, and US Environmental Protection Agency. Without this support from ORNL 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. They have welcomed me warmly, and 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.—
Jack Fellows

Production Team

Team Leader: John Sanseverino
Publication Director: Katie Elyce Jones
Editors: Vj Ewing, Katie Elyce Jones
Contributing Science Writers: Katie Elyce Jones, Vj Ewing, Justin Kaffka
Graphic Designer: Brett Hopwood
Photography: Jason Richards
Additional Images: iStockphoto, Energy.gov
Reviewers: Jack Fellows, Benjamin Preston, John Sanseverino

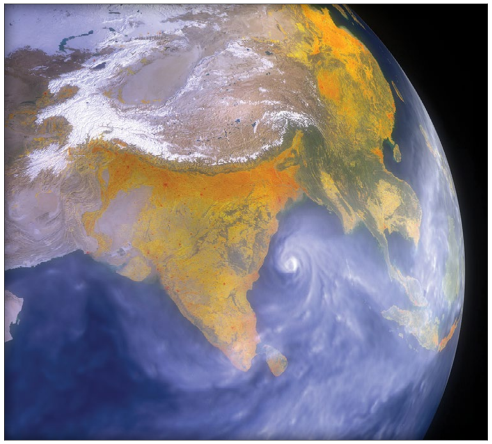
Institute Management

Director: Jack Fellows
Deputy Director: Benjamin Preston
Operations and Business Manager: John Sanseverino

Oak Ridge National Laboratory conducts basic and applied research and development to create scientific knowledge and technological solutions that strengthen the nation's leadership in key areas of science; increase the availability of clean, abundant energy; restore and protect the environment; and contribute to national security.

Oak Ridge National Laboratory is managed by UT-Battelle for the US Department of Energy.

What Is the Climate Change Science Institute?



Earth System Modeling.

Researchers at the Climate Change Science Institute (CCSI) at the Department of Energy's (DOE's) Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, have a mission to advance the knowledge of climate change and its consequences.

Why is climate change research a pressing national science and energy priority?

The Earth's climate has changed radically over its history but has been relatively stable the last 10,000 years. Today, that stability is threatened by human activities that emit roughly 36 billion tons of heat-trapping carbon dioxide (CO_2) into the atmosphere annually. That rate is increasing by roughly 1 billion tons per year, and CO_2 is building up in the atmosphere faster than nature can remove it. Recently, atmospheric CO_2 concentrations reached 400 parts per million for the first time in human history.

According to the 2014 US National Climate Assessment report, *Climate Change Impacts in the United States*, this is a 43% increase since the beginning of the Industrial Revolution. This increase has resulted in Earth's surface warming 1.5°F (0.8°C), with most of this warming occurring over the past 50 years. This warming rate is roughly 10 times the rate over the past 800,000 years and is evident in all climate change indicators, including melting sea ice and glaciers, dying ocean corals, plant and animal migrations, ocean and atmospheric temperature increases, and sea level rise. These changes are not uniform around the globe. If global CO_2 emissions continue to increase at current rates, the world will be 3–5°F (1.7–2.8°C) warmer over the next few decades and 6–9°F (3.4–5°C) warmer by the end of the century—warmer than the Earth has been in more than 50 million years.

How does CCSI approach climate change research to gain knowledge and develop strategies and tools for mitigating or adapting to climate change?

CCSI researchers work closely together to integrate modeling, observational, and experimental research in the following areas.

Earth System Modeling (ESM)

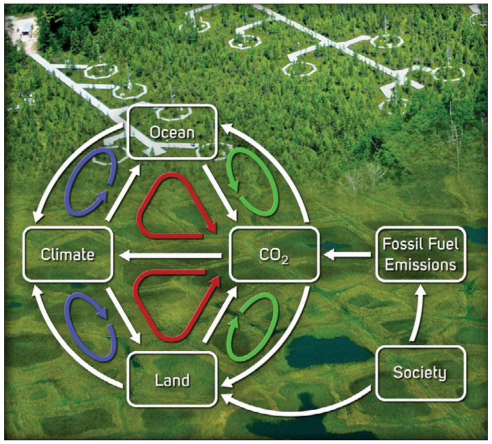
ESM researchers use high-performance computing—including the world's second-fastest supercomputer, Titan, located at ORNL—to develop tools and techniques for next-generation global Earth models that operate at unprecedented resolutions. More precise regional models are in high demand by decision makers around the nation and the world who are planning for potential climate change impacts, such as increased local and regional drought, weather extremes, wildfires, and sea level rise.

Terrestrial Ecosystem and Carbon Cycle Science (TECCS)

TECCS researchers primarily study carbon cycle processes and feedbacks, or the influence of rising CO_2 concentrations on land ecosystems. Researchers estimate that 50% of the world's carbon is stored in soil and vegetation, which humans have a unique ability to manipulate through land use (e.g., agriculture and deforestation). In addition to conducting fieldwork in several key ecosystems undergoing change, TECCS researchers work closely with model developers to integrate new information related to nutrient cycles, photosynthesis, and other ecosystem processes important to Earth System Models.

Impacts, Adaptation, and Vulnerability (IAV) Science

IAV Science researchers develop analysis tools and methods for assessing adaptation strategies for stakeholders who must prepare people and infrastructure for the risks associated with climate change. Many of these methods span multiple scales, from local to global, and rely on advanced computer models and diverse data sets that include social, political, and economic, as well as environmental, assessments. The IAV group



Terrestrial Ecosystem and Carbon Cycle Science.

Impacts, Adaptation, and Vulnerability Science.

Data Integration, Dissemination, and Informatics.

works with local governments at home and abroad on climate change assessments, analyzes the resilience of the nation's energy infrastructures to climate risks, and aids in the development of regional climate models needed by local decision makers.

Data Integration, Dissemination, and Informatics (DIDI)

The DIDI group hosts a number of large Earth science data sets that inform climate model developers and projects aimed at merging data from separate archives into single portals geared toward developers, scientists, and stakeholders interested in climate change information. DIDI team members also create data management tools so that contributing researchers retain credit and users can easily adapt data sets to their own scientific needs.

2014 Scientific Advisory Board

Earth System Modeling

Jean-Francois Lamarque is a senior scientist of the Atmospheric Chemistry and Climate and Global Dynamics Divisions at the National Center for Atmospheric Research.

Christiane Jablonowski is an associate professor in the Department of Atmospheric, Oceanic and Space Sciences at the University of Michigan.

Wayne Higgins is the director of the Climate Program Office at the National Oceanic and Atmospheric Administration.

Terrestrial Ecosystem and Carbon Cycle Science

Peter S. Curtis is a professor and department chair of the Department of Evolution, Ecology, and Organismal Biology at The Ohio State University.

Anna Michalak is a faculty member in the Department of Global Ecology in the Carnegie Institution of Washington at Stanford University.

Sasha Reed is a research ecologist with the US Geological Survey (USGS) and a member of the Southwest Biological Science Center.

Impacts, Adaptation, and Vulnerability Science

Virginia Burkett (SAB Chair) is USGS Chief Scientist for Climate and Land Use Change.

Noah Diffenbaugh is an associate professor in the Department of Environmental Earth System Science at Stanford University and a senior fellow in the Stanford Woods Institute for the Environment.

Anthony Janetos is the director of the Frederick S. Pardee Center for the Study of the Longer-Range Future and professor of Earth and Environment at Boston University.

Data Integration, Dissemination, and Informatics

Robert S. Chen is the director of the Center for International Earth Science Information Network at Columbia University's Earth Institute.

Sara James Graves is the director of the Information Technology and Systems Center at the University of Alabama in Huntsville (UAH), a University of Alabama System Board of Trustees University Professor, and a professor of computer science at UAH.

Mike Frame is USGS Chief of Scientific Data Integration and Visualization.

A Strategic Plan for the Future of the Climate Change Science Institute

Mission

By 2020, CCSI will be recognized as a premier research organization, partner, and source of knowledge for understanding climate change, evaluating its interactions with human and natural systems, and informing adaptation and mitigation policy and strategies.

CCSI researchers understand it is important that society adapts to climate-related changes but also prospers with reduced carbon use and emissions. Public- and private-sector leaders will need information and tools to help their communities and customers have reliable and resilient access to food, water, housing, transportation, health, and energy services. Stakeholders in the financial, risk, and relief sectors will also need tools to ensure these changes don't exceed recovery capabilities.

There are many climate change centers and institutes. However, CCSI is uniquely positioned to address the challenges posed by climate change. The institute is distinct based on the following organizational features and high-level priorities that inform its values, mission, and goals.

Collocation. CCSI's multidisciplinary research staff are collocated to work closely within a diverse national laboratory with world-class supercomputers, measurement and analysis tools, and scientific expertise.

Model-Data-Experiment Integration. CCSI researchers are improving multiscale climate and biogeochemical models and reducing uncertainty by integrating models, data, and long-term experiments.

Mission-Inspired Science. CCSI science objectives are driven by the need to better understand the impacts and consequences of climate change on human and natural land-energy-water systems.

To reaffirm its commitment and maintain focus, CCSI developed a strategic plan in 2014 to guide the institute through the next 5 years. CCSI is prioritizing its science goals based on societal needs as communities are confronted with the effects of climate change, and the strategic plan outlines clear organizational goals to help researchers, staff, and leadership meet their science goals in an efficient and impactful manner.

More than 80% of institute staff, from ORNL corporate fellows to administrative assistants to students and postdocs, participated in the development of this actionable document.

To view the strategic plan, please visit climatechangescience.ornl.gov

FY 2014 Metrics

124	Scientific publications
223	Scientific presentations and seminars
85	National and international leadership activities
55	Community outreach, committee service, and service-to-the-profession activities

Long-Term Field Experiment and Modeling Projects

Aerial view of SPRUCE plots at northern Minnesota site.

SPRUCE chamber under construction.

SPRUCE: Using controlled experiments to heat up one of Earth's most vulnerable carbon sinks

Initiated in 2012, SPRUCE, which stands for Spruce and Peatland Responses Under Climatic and Environmental Change, is the first whole-ecosystem, forest-scale experiment to increase temperature and CO_2 concentrations by enclosing forest plots, from belowground soil to tree canopies.

SPRUCE is a collaboration between CCSI at ORNL, the US Department of Agriculture Forest Service, and partnering universities. The decade-long experiment is being carried out in the black spruce peatland ecosystem of northern Minnesota and consists of 10 specially designed chambers that are 12 meters (m) in diameter and outfitted with heating infrastructures for air and deep soil warming, as well as a range of biological and environmental monitoring sensors.

A cold vault of carbon

Climate scientists are interested in studying all of Earth's ecosystems but especially regions expected to be vulnerable to climate change in the coming decades. Peatland ecosystems—found across the globe's northern latitudes—are of particular interest because cold, damp peatland bogs sit atop massive stores of carbon that biodegrade into CO_2 and CH_4 (methane). Though shorter lived in the atmosphere than CO_2, CH_4 is a potent greenhouse gas, estimated to trap about 20 times more heat than atmospheric CO_2.

Through large-scale field manipulations and carbon cycle observations, the SPRUCE team will study the response of the peatland plots to manipulated climate conditions, including the growth and dynamics of vegetation and microbial communities, changes in soil chemistry, and the breakdown of organic matter into CO_2 and CH_4.

By manipulating temperature and carbon concentrations, researchers will evaluate changes in ecosystem processes and the vulnerability of organisms, including the important peatland *Sphagnum* moss that dominates much of the bog moss cover. The data and analyses gained from the project over the coming years will be integrated into a number of Earth System Modeling efforts to better inform climate projections.

Turning up the heat in 2014

The SPRUCE experimental chambers include belowground and aboveground warming infrastructures. In the summer of 2014, belowground heating (known as deep peat heating) was initiated in eight plots at four warming levels and a target depth of 2 m. Researchers controlled temperature increases to 2.25, 4.5, 6.75, and 9.0°C, which meets and exceeds predicted temperature increases of 1.65–2.75°C based on current CO_2 emissions rates over the next century. Belowground processes and microbial communities are now being monitored as part of the ongoing study.

The team will finish installing the aboveground air-warming infrastructure in the winter of 2015. Then air-warming and increased CO_2 manipulation experiments will begin.

Learn more at mnspruce.ornl.gov

Research contact: Paul Hanson, hansonpj@ornl.gov

CCSI's Colleen Iversen displays a soil core taken during NGEE–Arctic fieldwork.

Polygon formations in Alaska created from permafrost freezing and thawing over hundreds of years.

Automated tram built in 2014 for extended spatial and temporal monitoring of the NGEE–Arctic site.

NGEE–Arctic: Enriching our knowledge of the Arctic ecosystem year by year

Since 2010, CCSI researchers have led a team of national laboratories and universities in a large-scale observation and modeling project known as the Next-Generation Ecosystem Experiments (NGEE)–Arctic. The goal of NGEE–Arctic is to quantify the physical, chemical, and biological characteristics of the Arctic ecosystem to inform next-generation climate models. CCSI scientists travel to the Barrow Environmental Observatory (BEO) in Barrow, Alaska, many times each year to conduct fieldwork, much of which investigates the impact of permafrost thaw on carbon release.

Simulating the Arctic's one-of-a-kind topography

If you fly over Barrow, you might notice the unique landscape: a pattern like polygon tiles. From the ground, these ice-rich geomorphological formations are 15 to 20 m in diameter and sloped or sunken at the center. These polygonal formations are created as seasonal permafrost freezes and thaws repeatedly over hundreds of years because snow melt and soil temperature can vary across a single polygon. In 2014, NGEE–Arctic researchers used high-performance computing to simulate the present and future energy balance and near-surface hydrology of the polygons at submeter resolutions, including snow distribution and the temperatures and depths of frozen and actively thawing polygonal layers. These simulations are giving researchers insight into how the topography and hydrology of these features will affect carbon release in the coming century.

A fast track to energy balance measurements

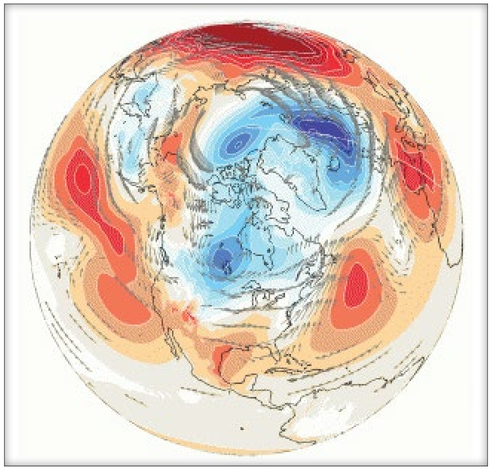
To collect data on the energy balance of the site's polygons, the team designed and deployed an automated tram in 2014 for extended spatial and temporal monitoring of the site. The tram, installed at the BEO, is a 65 m elevated track containing a digital camera and radiation and remote sensing instrumentation. With the ability to access measurements from the tram at their home laboratories, researchers can study the radiation that bounces off the polygon formations, as well as surface temperature, snow depth, and vegetation characteristics. Using this information to compare the radiative energy bouncing back to the atmosphere with the solar energy that initially reached the surface, scientists can estimate the impact of greenhouse gas warming and other energy-related imbalances in the climate system on Arctic ecosystem processes.

Thawing permafrost in the laboratory

To carry out controlled experiments on CO_2 and CH_4 (methane) release from thawing permafrost, ORNL and CCSI researchers brought core samples back from Alaska, keeping them frozen on the 4,000-mile journey. In the lab, the team gradually warmed the samples using controlled-temperature chambers, emulating permafrost thaw at temperatures between 8°C and −2°C. In this study, CO_2 production occurred rapidly during thaw while CH_4 production via methanogenesis (a part of microbial metabolism) lagged behind, only occurring at higher temperatures. Based on these results, researchers suggest the constant temperature coefficient (Q10)—the rate of change of biochemical systems used in many climate models—does not accurately reflect the rate of methanogenesis in permafrost soils. The results are available for future carbon cycle and Earth System Models.

Learn more at ngee-arctic.ornl.gov

Research contact: Stan Wullschleger, wullschlegsd@ornl.gov



A mapping of sea level pressure (increasing from blue to red) overlaid with lower free atmosphere wind direction from a DOE and National Center for Atmospheric Research climate simulation. Image credit: Tianyu Jiang, ORNL.

ACME: Getting ahead of the computing curve with major, next-generation climate model

CCSI researchers are collaborating with eight other DOE laboratories, the National Center for Atmospheric Research, four academic institutions, and one private-sector company on a 10-year project known as Accelerated Climate Modeling for Energy (ACME). The goal of ACME is to use DOE high-performance computing (HPC) resources to develop the most sophisticated Earth System Model for climate change research and energy applications.

The ACME project plan was approved in spring 2014, and the project commenced on July 1. CCSI researchers have been instrumental in developing and defending the project plan and leading or coleading several project teams, including the teams responsible for new land model development, assessing and improving model performance on HPC platforms, and developing and evaluating simulation workflow tools.

New era of computing, new era of climate modeling

ACME will provide scientists tasked with solving the nation's energy challenges with new computing capabilities. HPC architectures in the twenty-first century will support computing power at hundreds of petaflops followed by exaflops (a thousand petaflops). And with more computing power, expectations for scientific discovery will increase significantly. The ACME project leverages DOE science investments to include new process understanding in climate models—such as phosphorous cycling in tropical ecosystems, the influence of mountain ranges on temperature and precipitation, and soil microbial processes. ACME will also make it easier for a broad cross section of domain science experts to participate in model development and application.

Exploring key science questions in greater depth, finer resolution

The ACME team will develop model codes that address key climate science questions, including those related to the water cycle, biogeochemistry, and cryosphere. In the near term, researchers will simulate changes in river flow and other parts of the hydrological cycle by modeling interactions between precipitation and landscape within high-resolution, fully coupled atmosphere and land surface models to help determine how the water cycle will evolve in a warmer climate and change land and water use.

Likewise, ACME models will explore fundamental questions about the impact of carbon, nitrogen, and phosphorus cycles on the climate system. Simulations of the cryosphere, or surface ice, including the continental Antarctic Ice Sheet, will gain new depth and resolution, and researchers will study its stability in the climate system and the potential effects of sea level rise due to melting.

To contribute to this advanced model development, CCSI experts in terrestrial biogeochemistry and atmospheric chemistry will work with computational scientists to optimize workflow and engineer new software tools for calculating an increased number of scientific variables at higher resolutions on HPC resources.

Throughout 2015 CCSI researchers will play critical roles in the construction of the ACME Version 1 model, which will be deployed in 2016 to address critical science questions concerning hydrology, biogeochemistry, and the cyrosphere based on a suite of fully coupled high-resolution simulations.

Research contact: Peter Thornton, thorntonpe@ornl.gov

New Initiatives for 2015

El Yunque National Forest in Puerto Rico will serve as the first NGEE–Tropics research site in 2015.

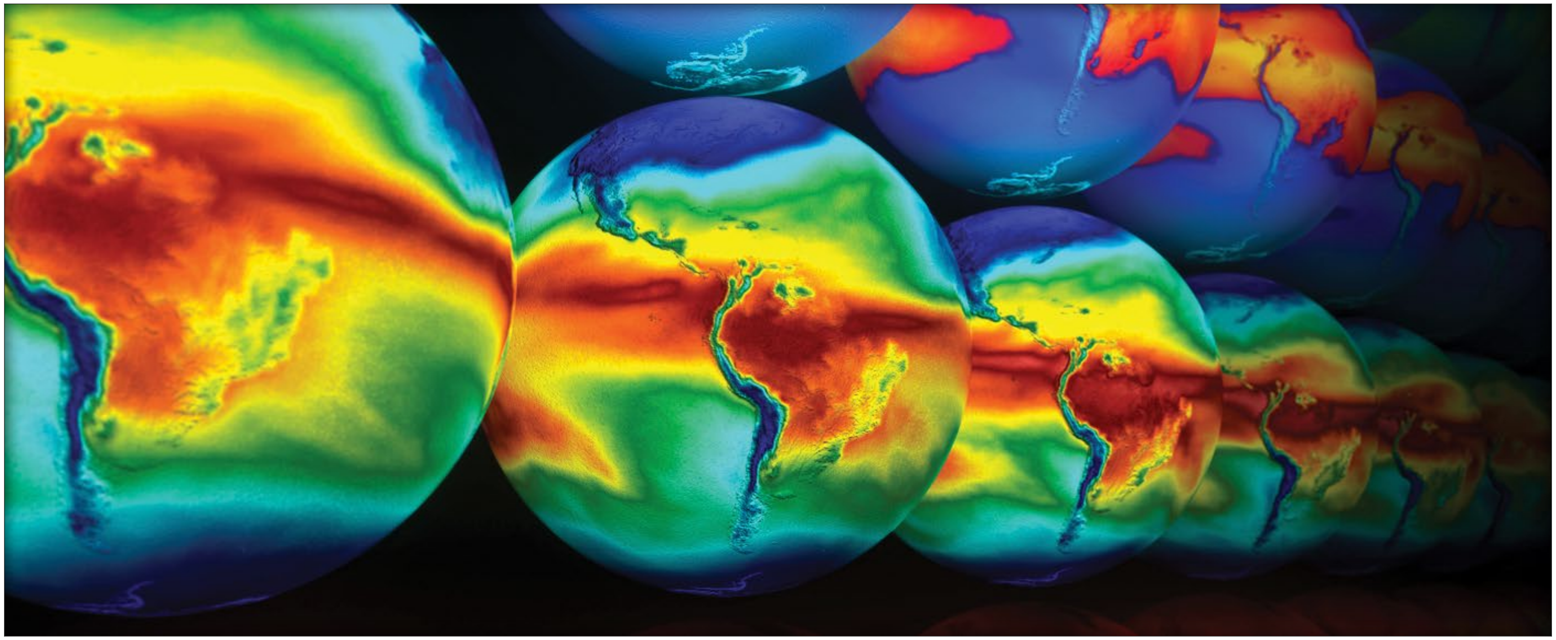
NGEE–Tropics: A decade of tropical expeditions will gather data for climate models

A new Next-Generation Ecosystem Experiments (NGEE) initiative focused on the tropics is beginning. In 2015, a team of CCSI scientists will officially begin a decade-long collaboration between DOE national laboratories and research institutions to develop a model structure that can determine whether tropical forests will act as net carbon sinks (absorbing more carbon than they release) through the twenty-first century. Measurements guided by model uncertainties will commence at the El Yunque National Forest in Puerto Rico in 2015 and eventually expand to multiple sites in the Americas, Africa, and Southeast Asia.

While researchers with the ongoing NGEE–Arctic project may brave subzero temperatures, the tropics come with their own challenges—extremely humid conditions, dense forests with difficult road access, and insect-borne diseases. But despite these challenges, understanding the tropical ecosystems that cover 40% of Earth's land surface is crucial to developing more advanced climate models. The tropics, and particularly vegetation-rich rainforests, are the globe's most powerful CO_2 regulators—taking in the gas through photosynthesis and releasing oxygen into to the atmosphere in large volumes, thereby serving an important role in the global carbon budget, as well as in global water and energy cycles.

Yet climate models rely heavily on data from temperate regions, where records are more substantial. To accurately predict how tropical regions will respond to increasing temperatures, changes in rainfall, drought and fire, increased atmospheric CO_2 concentrations, and land-use changes caused by human activity, models must account for the tropics' unique physical, ecological, and biogeochemical profiles. For instance, a significant role for CCSI researchers will be collecting new data on the phosphorus cycle between tropical plants and soil, an important nutrient cycle underrepresented in current models.

Research contact: Richard Norby, norbyrj@ornl.gov



These images show the distribution of water vapor, averaged monthly, from a high-resolution simulation of the Community Atmosphere Model.

Biogeochemistry Feedbacks Science Focus Area: Creating an open-source tool for model evaluation

As the complexity of Earth System Models increases, comprehensive evaluation of model predictions is needed by those who use them to make decisions—a diverse group that includes farmers, city planners, and other policy makers.

In 2015, a new Science Focus Area (SFA), sponsored by the DOE Regional and Global Climate Modeling Program, will begin to develop tools that systematically assess model accuracy and reduce uncertainties associated with predictions. The Biogeochemistry (BGC) Feedbacks SFA follows on the heels of the successful Carbon–Climate Feedbacks project (http://climatemodeling.science.energy.gov/projects/quantification-and-reduction-critical-uncertainties-associated-carbon-cycle-climate-system). Planned to be longer term and broader in scope, the BGC Feedbacks SFA will include not only terrestrial systems, like the Carbon–Climate Feedbacks project, but also marine ecosystems and will focus on quantifying feedbacks. The ultimate goal is to create an open-source benchmarking tool for use by the climate science community to routinely evaluate how models compare to observational data.

To meet this goal, the BGC Feedbacks team incorporates field and laboratory measurements to inform future model development and observational approaches, which uniquely positions the project between the measurement and modeling communities.

Most members of the project team, which includes researchers from four DOE national laboratories and two universities, have contributed to the Community Earth System Model and the DOE Accelerated Climate Model for Energy, both of which will be used to develop and test evaluation metrics. Through CCSI, the project team will have access to a combination of field, lab, and modeling expertise; internationally recognized environmental data centers; and large supercomputers.

Learn more at bgc-feedbacks.org

Research contact: Forrest Hoffman, hoffmanfm@ornl.gov

Earth System Modeling

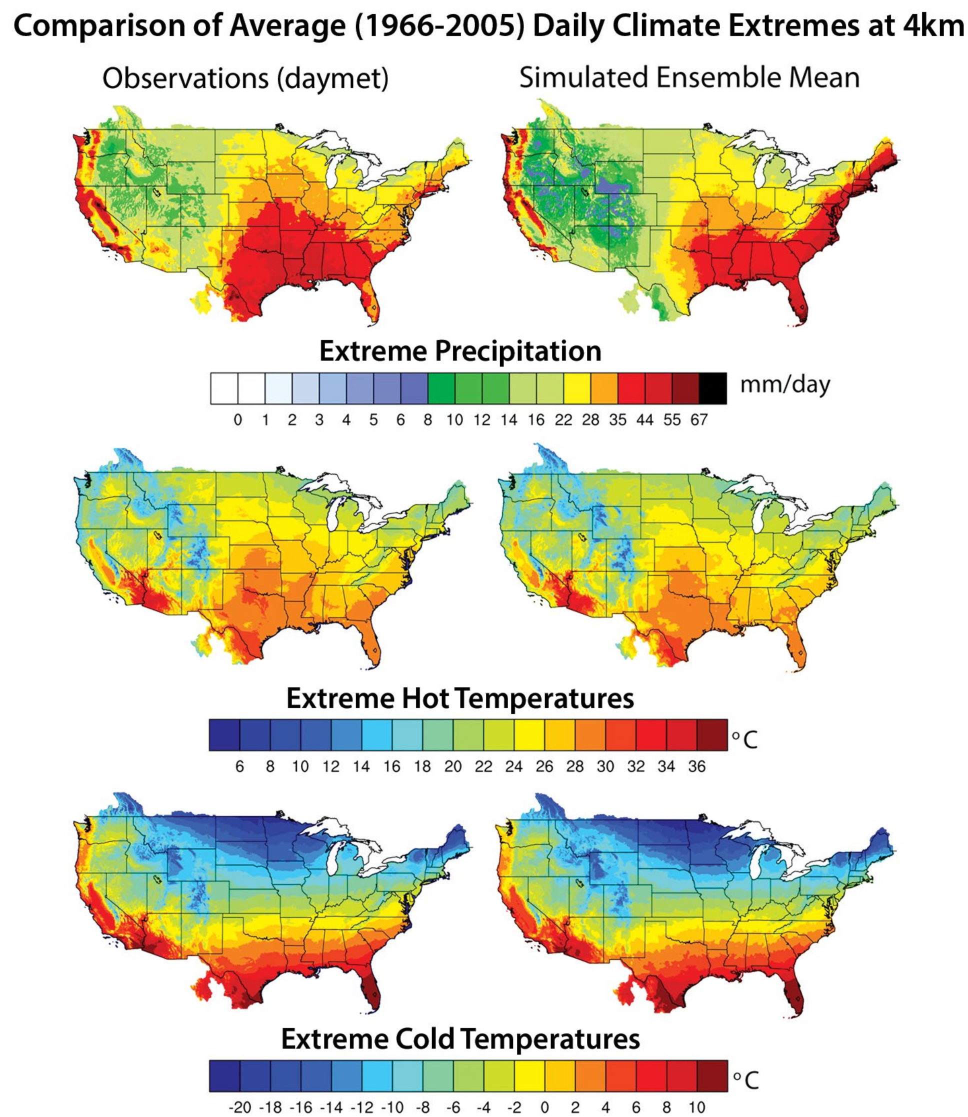
Simulating climate change at two and a half miles

A typical global climate model cited by the Intergovernmental Panel on Climate Change (IPCC) has a resolution of about 150 kilometers (km), which is not unimpressive considering the Earth's surface is about 40,000 km in circumference. But for governments, businesses, and agencies that are planning for climate change locally, 150 km resolution doesn't provide the topographical, hydrological, or ecological details needed to best predict small-scale climate change impacts like local water scarcity, crop migrations, and more.

CCSI researchers used the same models that drive global IPCC climate change projections and applied them at finer resolutions over smaller regions of interest across the continental United States. During 2014, a CCSI team finished runs at 4 km resolution (about 2.5 miles) using an ensemble of 12 models and generating 200 terabytes (200 trillion bytes) of climate data—making their 2014 simulations the most detailed that have ever been produced for the United States covering the years 1965–2005 and into mid-century, 2010–2050.

In its initial analyses, the team has focused on precipitation and temperature extremes. The model ensemble's predictions are generally consistent with IPCC projections for the United States, which predict the southern United States will experience a decline in precipitation over the next 40 years and the northern United States will see spells of rain and snow for longer periods of time. Results also support an increasing number of heat waves for the Southeast and West, while the country as a whole isn't projected to see many changes in cold extremes.

Research contact: Moetasim Ashfaq, mashfaq@ornl.gov



Three US maps comparing average precipitation and extreme hot and cold temperatures for the average daily observed, left, and average daily simulated climate extremes from 1966 to 2005 at 4 km horizontal grid spacing. The comparable simulation results show the sophistication of regional climate modeling conducted by CCSI researchers.

Pairing supercomputing strength with smart climate modeling

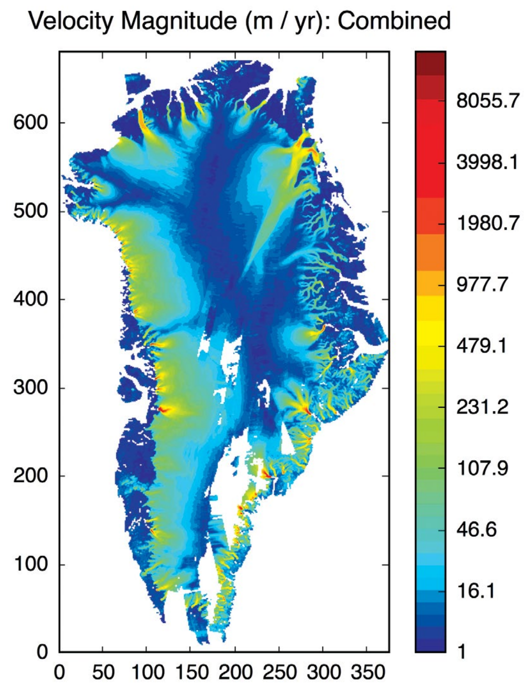
CCSI's computational climate scientists maintain several leadership roles among DOE Scientific Discovery through Advanced Computing (SciDAC) projects, which aim to accelerate scientific advances through high-performance computing (HPC). Global climate models are some of the most challenging applications in HPC due to their size and complexity, and researchers are constantly improving and validating model techniques. CCSI scientists are involved in three SciDAC projects: Applying Computationally Efficient Schemes for BioGeochemical Cycles (ACES4BGC), Multiscale: Accurate, Efficient, and Scale-Aware Models of the Earth System (MULTISCALE), and Predicting Ice Sheet and Climate Evolution at Extreme Scales (PISCEES).

In 2014, ACES4BGC sought to reduce the uncertainty of aerosols and biospheric feedbacks in models, including the development of a carbonyl sulfide parameterization and implementation and testing of a mesophyll diffusion mechanism. This project also carried out performance evaluations at several DOE HPC centers, including runs on the ORNL Titan supercomputer.

The MULTISCALE project develops multiscale atmospheric and oceanic parameterizations for the Community Earth System Model. CCSI contributors are developing advanced algorithms to address time-stepping limitations of high-resolution models and exploit the potential for acceleration using hybrid CPU–GPU supercomputing architectures.

The PISCEES project is simulating the melting of the Greenland and Antarctic Ice Sheets to improve sea level rise projections, as these events will be the main contributors to future sea level rise. This project is developing new tools and methods for validating ice sheet simulation results against observations and enabling the software to connect to estimates of the uncertainty surrounding future projections.

Research contacts: Kate Evans, evanskj@ornl.gov and Forrest Hoffman, hoffmanfm@ornl.gov



The PISCEES project builds models of the Greenland and Antarctic Ice Sheets to study sea level rise. One of the project's software packages, the Land Ice Verification and Validation package, which is tasked to evaluate the models as they are being developed, incorporates new data for model evaluation as it becomes available. This image shows a more complete view of velocity magnitude by combining 5 years of available data from the newly available MEaSUREs Greenland Ice Sheet Velocity Map from InSAR data (Joughin et al., 2010), which will be used to evaluate PISCEES model simulations. MEaSUREs is NASA's Making Earth System Data Records for Use in Research Environments program. Image credit: Matt Norman, ORNL.

Terrestrial Ecosystem and Carbon Cycle Science

Researchers measure the spectral reflectance of tundra vegetation near Nome, Alaska, on the Seward Peninsula, as part of larger mapping efforts to characterize climate-driven changes in Arctic landscapes. Left to right: Guido Grosse of the Alfred Wegener Institute in Germany, Santonu Goswami of CCSI, and Jennifer Liebig of the University of Tennessee.

Investigating landscape changes on Alaska's Seward Peninsula

Now in its third year, the CCSI Model-Data Fusion project (as it is called for short) consolidates data from satellite imaging, remote sensing, and fieldwork in Arctic Alaska to assess the thawing of permafrost, or frozen soil, and its impact on carbon release and uptake. After 2 years of surveying thaw across the pan-Arctic, in 2014, the team focused on a particular region undergoing a lot of change. The Seward Peninsula on the Alaskan west coast has previously been known for its large, crater-like maar lakes created from hot magma erupting through cold groundwater, as well as its history as part of the Bering land bridge that once connected Asia to North America. Today, CCSI researchers are interested in the peninsula for its vulnerability to climate change.

Using remote sensors to determine the density of vegetation, the team observed that some of the Seward Peninsula's trees, shrubs, and grasses are creeping northward and new lakes are appearing as permafrost thaws due to warming. Team members traveled to the peninsula several times in 2014 to corroborate satellite and sensing data with field observations. As they continue to monitor changes in the region's landscape ecology, they are also using the information they gain from the peninsula and other Arctic locations to improve the representation of ecological processes that drive the carbon cycle in climate models. In particular, they are developing specialized parameters for different types of Arctic vegetation to avoid "green sponges" in climate models, or the uniform modeling of diverse plant processes and their unique contributions to the carbon cycle, which can lead to over- or underestimating future greenhouse gas concentrations in the atmosphere.

The official title of the Model-Data Fusion project is "Model-data Fusion Approaches for Retrospective and Predictive Assessment of the Pan-Arctic Scale Permafrost Carbon Feedback in Global Climate."

Research contact: Daniel Hayes, hayesdj@ornl.gov

By connecting climate models with integrated assessment models, researchers can study the dynamic relationship between climate and human economies, such as changes in crop growth due to drought or shifting temperatures.

Modeling the influence of climate on economies and energy futures

To prepare for the impacts of climate change, governments, businesses, and decision makers are already choosing to implement climate mitigation strategies—whether it's growing new crops better suited for shifting temperatures and rainfall, choosing new energy infrastructures to reduce carbon emissions, or irrigating regions blighted by drought. Yet, today's Earth System Models (ESMs), which predict a handful of climate scenarios from a fixed set of assumptions, don't take into account the dynamic relationship between climate and human economies and societies.

CCSI scientists are part of an interdisciplinary team that is connecting climate models with integrated assessment models (IAMs). Intended to inform policymaking and strategy development, IAMs are used to understand how climate interacts with changes in human economies, land use, energy sectors, and water management. A multi-lab effort between ORNL, Pacific Northwest National Laboratory (PNNL), and Lawrence Berkeley National Laboratory to couple an ESM with an IAM has been under way since 2009.

By the end of 2014, the project "Improving the Representations of Human-Earth Interactions" succeeded in coupling the global Community Earth System Model (CESM) and PNNL's Global Change Assessment Model (GCAM), an IAM. Early results show that the coupled system eliminates significant biases in climate projections up to the year 2100, compared to the previous practice of operating the ESM and IAM models independently. This work is now being considered an extension to the Accelerated Climate Modeling for Energy project.

Using the information gained from coupled climate and impacts models, decision makers can better plan mitigation strategies to protect energy and building infrastructures and prepare for potential resource scarcity or rising food prices, among other impacts.

In particular, the CCSI team led the development of the coupling mechanism for the Community Land Model (CLM) that makes up part of CESM's four coupled models (land, ocean, atmosphere, and ice). The CLM coupled with GCAM will help researchers study the influence of past, present, and future land use on the carbon cycle and how climate feedbacks will influence energy consumption. In 2015, early users will have access to the coupled models for scientific research.

Research contact: Peter Thornton, thorntonpe@ornl.gov

Impacts, Adaptation, and Vulnerability Science

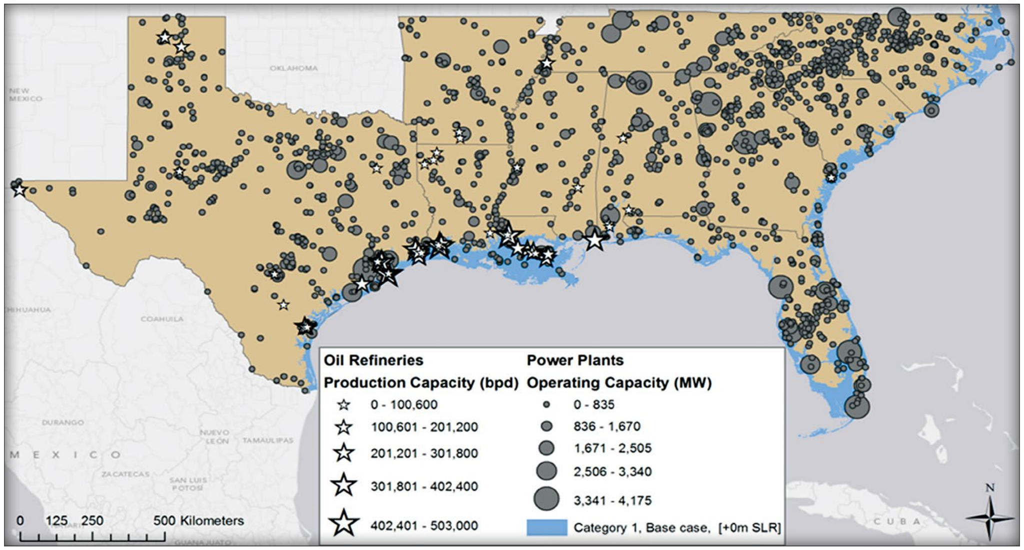
Sunlight shines on the Bering Sea. CCSI Deputy Director Benjamin Preston is assessing socioeconomic scenarios for the Bering-Chukchi-Beaufort region of Alaska for the Arctic Council. Image credit: NASA.

Finding adaptation options for Arctic region important to economy and wildlife

In 2014, CCSI Deputy Director Benjamin Preston joined the Adaptation Actions for a Changing Arctic (AACA) assessment led by the Arctic Council, an intergovernmental forum to coordinate cooperation and interaction among Arctic states, particularly on issues of sustainable development and environmental protection. The council established the AACA to create an integrated picture of the Arctic's ongoing environmental, social, and economic changes. For Part C of the three-part assessment, Preston will assess available socioeconomic scenarios for the Bering-Chukchi-Beaufort region, which is a site of oil and gas activities and home to Arctic wildlife such as polar bears and walrus seals, that is experiencing climate change impacts and other environmental, social, and economic stressors.

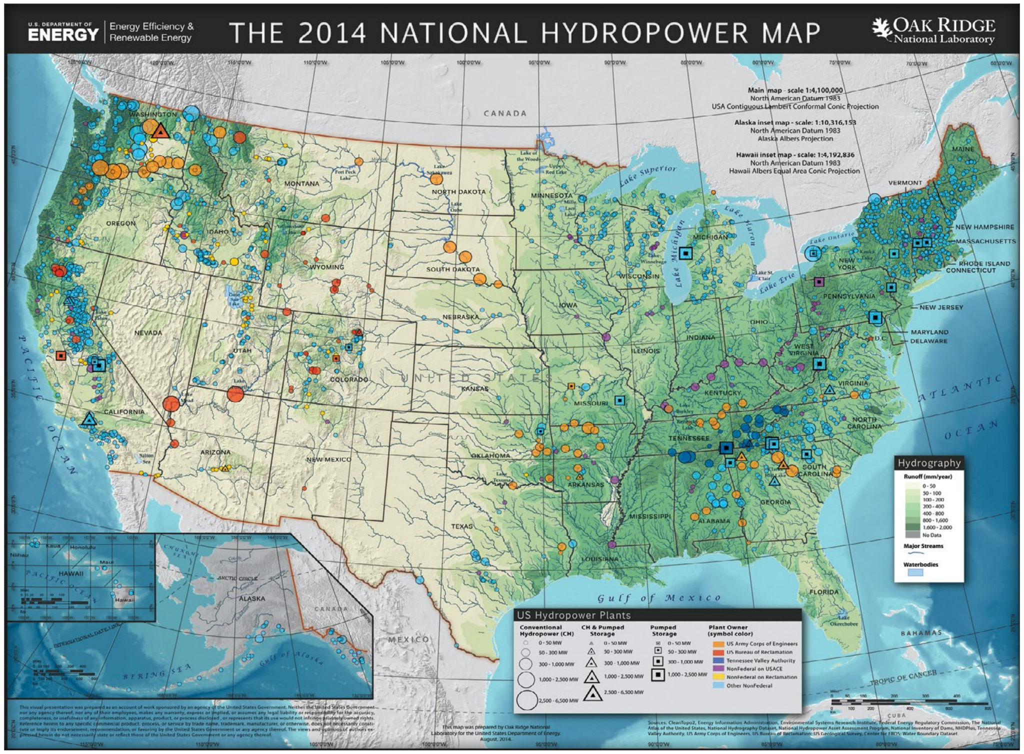
Assessing climate risks to Gulf Coast energy

As part of the ongoing collaboration with Pacific Northwest National Laboratory to develop capabilities for regional integrated assessment modeling, CCSI researchers published new studies during 2014 on the implications of climate change to energy systems. To better understand the vulnerability of US energy facilities to storm surge and sea level rise, CCSI researchers developed a new geospatial database of hurricane storm surge inundation risk for the United States. To identify power plants and oil refineries that could potentially be exposed to inundation, the IAV team worked with ORNL's Geographic Information Science (GIS) team to integrate this database with the GIS team's high-resolution energy facility database. Results of this work appear in Volume 2 of the journal *Climate Risk Management.* Addressing possible climate risks to the Gulf Coast energy infrastructure, Preston coauthored an *Environmental Science & Policy* paper (see Select Publications, de Bremond A, Preston B, and Rice J) that investigated the mechanisms by which integrated assessment model development can be enhanced for use by decision makers.



This map shows the geographic distribution of electricity generation facilities (gray circles) and oil refineries (white stars) in the southeast region, as well as the coastal area that is potentially exposed to inundation from Category 1 storms (blue).

For the paper, authors spoke with a number of energy utilities in the Gulf Coast region to better understand how utilities approach climate risk management and investment decisions.



There are more than 2,000 hydropower plants in the United States, which annually produce 6% of the nation's energy. Understanding how climate change may affect hydropower generation has great importance to future US energy security.

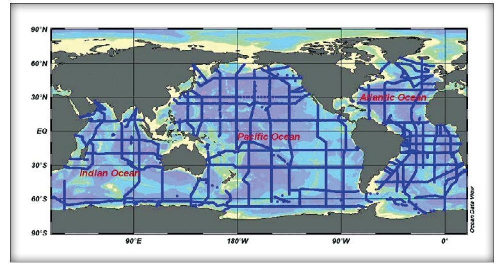
Protecting US hydropower through climate modeling

As part of its ongoing research on climate change implications for hydropower, ORNL convened a workshop "Methods to Evaluate the Effects of Climate Change on Federal Hydropower, SECURE Water Act Section 9505–2014 Workshop" on September 16–17 in Oak Ridge. The workshop was designed to kick-start planning for the second iteration of a report to Congress on the effects of climate change on federal hydropower. Led by CCSI researcher Shih-Chieh Kao, the workshop shared ORNL's proposed modeling approaches for estimating impacts of climate change on federal hydropower electricity generation with key stakeholders. The workshop also provided an opportunity to obtain feedback from stakeholders and learn about the work of other federal partners on climate modeling, which ORNL will use to help guide the 9505 Assessment due to Congress in March 2016.

Research contact: Shih-Chieh Kao, kaos@ornl.gov

Data Integration, Dissemination, and Informatics

Delivering user-friendly carbon data



Carbon Dioxide and Information Analysis Center users can find data for oceanic carbon distributions in the Global Ocean Data Analysis Project atlas.

The Carbon Dioxide Information Analysis Center (CDIAC) is DOE's primary climate change data repository. CDIAC manages 1,500 data sets, including CO_2 emissions from fossil-fuel consumption and land-use changes, atmospheric greenhouse gas concentrations, and long-term global and regional climate records.

In 2014, CDIAC strove to make three popular data sets more user-friendly than ever before. Released in January 2015, CDIAC's time-lapse visualization of a 1° by 1° global grid of CO_2 emissions data spanning the years 1751–2010 enables researchers to see and evaluate historical patterns in fossil-fuel CO_2 emissions.

Users can also access CDIAC's AmeriFlux data collection. AmeriFlux is a network of more than 100 sites across North and South America collecting continuous CO_2 and water vapor measurements useful for investigating carbon cycling between the terrestrial biosphere and atmosphere. The AmeriFlux database became CDIAC's most popular product in 2014 with more than 50,000 downloads.

CDIAC is also home to the world's largest ocean carbonate chemistry data collection. The Global Ocean Data Analysis Project (GLODAP) is merging data collected via research vessels, cruise ships, and buoys from the past two decades. In 2014, CDIAC standardized these synthesized GLODAP measurements in a new iteration of its Ocean CO_2 product that is more reliable and easier to use.

Learn more at cdiac.ornl.gov

Research contact: Thomas Boden, bodenta@ornl.gov

Gathering Earth science data from a bird's-eye view

The NASA AirMOSS plane, which is equipped to measure microwaves indicating soil moisture.

As part of its mission, the Distributed Active Archive Center (DAAC) archives data produced by the National Aeronautics and Space Administration (NASA) Terrestrial Ecology Program. In 2014, DAAC began building the data archive and distribution infrastructure for two new NASA airborne remote-sensing campaigns that are monitoring carbon uptake and release and other climate influencers across large and diverse ecosystems.

Using radar equipment, a spectrometer, and gas analyzers attached to a high-altitude aircraft, the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) is taking the pulse of carbon cycling in Alaska's Arctic territory. DAAC is building the infrastructure to take the CARVE data from the sky to the web by archiving and creating visualizations that will allow researchers to find and analyze information related to greenhouse gas concentrations, carbon emissions, soil moisture, surface temperatures, and more.

Sometimes you don't have to dig to understand what's going on belowground. In the case of Airborne Microwave Observatory of Subcanopy and Subsurface, or AirMOSS, researchers are using radar emitted from a NASA aircraft to map the landscape of 10 areas of North and Central America, from boreal to tropical forests. The energy that bounces back in the form of microwaves provides scientists with data to estimate soil moisture—an important ingredient in photosynthesis and carbon cycling that will help researchers better understand where and how climate change is happening. DAAC will be making AirMOSS radar maps and derived scientific data products available through a searchable web interface useful to scientists and climate modelers who are developing more robust and accurate climate models.

CARVE and AirMOSS data are expected to be available in late 2015.

Learn more at daac.ornl.gov

Research contact: Suresh SanthanVannan, santhanvans@ornl.gov

Making atmospheric data searches easy for different research and modeling needs

For more than two decades, the Atmospheric Radiation Measurement (ARM) Climate Research Facility, a DOE Office of Science User Facility, has collected and archived data from its fixed, mobile, and aerial facilities. This atmospheric research data, provided through open access to researchers and model developers, is related to cloud formation and radiative transfer processes in the atmosphere that lead to warming or cooling of Earth's surface. CCSI data scientists manage ARM's data archives, develop user interfaces and search tools, and store the project's hundreds of terabytes of data.

In 2014, CCSI data scientists introduced several advanced services for the ARM database. They led the release of the Online Metadata Editor (OME), which gathers more complete and consistent documentation about data products submitted to ARM by researchers. Metadata make it easier for other researchers to interpret and reuse data, and the CCSI team provided tutorial sessions on OME throughout 2014 to frequent or potential ARM data users at DOE Atmospheric System Research meetings. They also launched the Data Discovery browser, which simplifies scientific searches with faceted search categories like "Cloud Properties" and "Surface Properties" and expedites searches for model developers through "Modeling Best Estimates." These new data discovery tools contributed to a 30% increase in ARM's scientific users in 2014.

Giri Palanisamy, Atmospheric Radiation Measurement (ARM) Data Service and Operations manager, presents a tutorial on how to use ARM data resources.

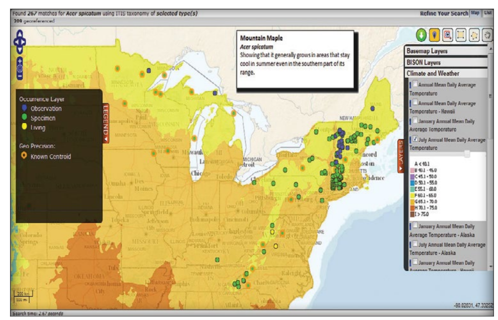
Learn more at archive.arm.gov

Research contact: Giri Palanisamy, palanisamyg@ornl.gov

Creating easy-to-search portals for wealth of US Geological Survey data

Locating plant and animal species and fossil specimens across the United States may only require an Internet connection for researchers using the Biodiversity Information Serving Our Nation (BISON) portal provided by the US Geological Survey (USGS) and developed by CCSI data scientists. Released in 2014, BISON allows users to search and download species occurrence records from hundreds of data sources including natural history museums, monitoring programs, research studies, citizen science programs, and peer-reviewed literature. BISON includes more than 100 million records and is growing. The data index and web viewer designed by CCSI and USGS collaborators is a US map that allows visual searches for species occurrences. A suite of web services enables users to access species occurrence data from BISON in custom applications and tools.

USGS also released the Science Data Catalog, jointly developed by USGS and CCSI data scientists, in 2014. CCSI worked on the database index, search engine, and user interface for the project, which began in November 2013 under an interagency agreement between the two organizations. The catalog service allows users to efficiently browse and discover USGS data sets through searches by keyword, data source, scientist name, or geographic information system. The catalog's records describe data sets, data collections, and observational or remotely sensed data stored in national systems. Some collections in the catalog contain information dating as early as the seventeenth century.



The data index and web viewer for the Biodiversity Information Serving Our Nation portal was designed by CCSI and USGS collaborators to allow visual searches of more than 100 million records for species occurrences across the United States.

Learn more at bison.usgs.ornl.gov and data.usgs.gov

Research contact: Giri Palanisamy, palanisamyg@ornl.gov

Leadership Highlights

CCSI researchers contribute to national and international assessments

During 2014, CCSI staff played key roles in finalizing and releasing two important scientific assessments of climate change and its consequences. Working Group II of the Intergovernmental Panel on Climate Change released its Fifth Assessment Report (AR5) in March 2014. CCSI researchers Benjamin Preston and Thomas Wilbanks made significant contributions to AR5. Preston was a coordinating lead author for Chapter 16, "Adaptation Opportunities, Constraints, and Limits," and Wilbanks was a coordinating lead author for Chapter 20, "Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development." Released in May 2014, the third US National Climate Assessment reported the potential implications of climate change for the nation, and CCSI's Wilbanks, Preston, Steve Fernandez, Peter Thornton, Virginia Dale, and Jay Gulledge were among the 240 authors who contributed to the report.

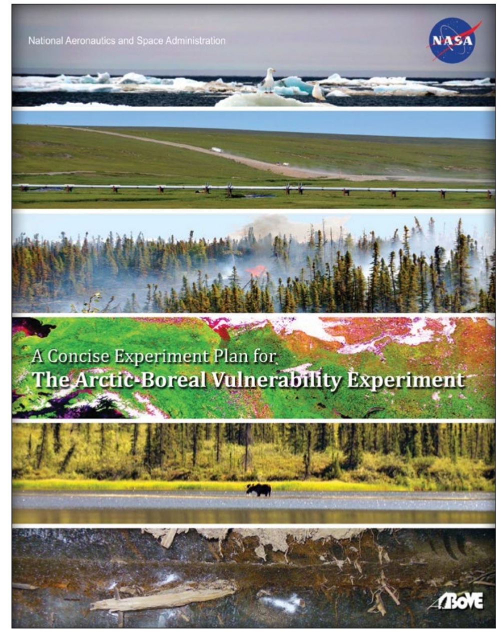
A strategy ABoVE the rest: Planning for the Arctic-Boreal Vulnerability Experiment

Daniel Hayes, CCSI research scientist, along with Eric Kasischke of the National Aeronautics and Space Administration (NASA) and the University of Maryland, cochaired the science definition team charged with formulating the research plan for the Arctic-Boreal Vulnerability Experiment (ABoVE). Stan Wullschleger, CCSI scientist and lead principal investigator for the Next-Generation Ecosystem Experiments–Arctic, also served on the ABoVE science definition team. ABoVE is a large-scale study of environmental change in the Arctic and boreal region of western North America and its implications for ecological and societal systems.

The Arctic and boreal region is experiencing the effects of climate change—such as shrinking sea ice, warming and thawing of permafrost, and increased frequency and severity of climate-driven disturbances—faster than other parts of the globe. Aimed at improving the analysis and modeling capabilities needed to understand and predict ecosystem responses and societal implications of climate change, research for ABoVE will link field-based studies with geospatial data products derived from airborne and satellite sensors. For more information, visit above.nasa.gov.

Photosynthesis research leads to finding that current models may underestimate global CO_2 uptake

In 2013, CCSI's Lianhong Gu, Anthony Walker, Richard Norby, David Weston, Jeffrey Warren, and Anna Jensen journeyed to the Parque Natural Metropolitano rainforest reserve in the heart of Panama City. They



were on a 2-week scientific expedition to measure photosynthesis in various tree species to provide climate models with more accurate input data. This expedition, as well as similar field experiments and a web tool developed by Gu, would later contribute to a 2014 *Proceedings of the National Academy of Sciences* (PNAS) paper that implies a significant 16% underestimation of global CO_2 uptake by plants over the last century.

There are many unknowns in modeling photosynthesis for climate simulations, and accurately quantifying CO_2 fixation by plants and trees improves the input data used for such simulations. The lack of complete data makes it difficult to know how much plants help mitigate the effects of climate change.

In an effort to advance current scientific understanding of photosynthesis, CCSI researchers wanted to manually take measurements of as many different plant species as possible. The team's main goal was to learn more about mesophyll conductance, or the resistance that CO_2 molecules encounter as they move through the interior of a leaf.

A plant's rate of mesophyll conductance affects the ratios between its key photosynthetic parameters. "Knowing these ratios conveys important information of the plant's photosynthetic machinery, sort of like telling us whether our car engine is a V-6 or a V-8. If we get these ratios incorrect, we get the wrong engine type," Gu said.

Mesophyll conductance varies widely across plants, so the jungle was a perfect place for the team to take measurements.

"Along the Panama Canal is a very large rainfall gradient—perfect for finding out how tropical rainforests conduct photosynthesis at different rainfall levels. It was like a natural laboratory," Gu said.

The problem is that climate models assume no resistance as the CO_2 molecules diffuse into the chloroplasts. To make matters more complicated, the variability among plants is staggering. About 1,500 different species were at the Panama site alone. The CCSI team managed to get about 100 measurements representing about 70 species in total. Researchers estimate there might be close to 300,000 plant species worldwide.

Rainforest canopy at the Parque Natural Metropolitano. Image credit: David Weston.

The team's work in Panama would support another one of Gu's expeditions—an online tool called LeafWeb. He developed LeafWeb (leafweb.ornl.gov) to allow other scientists to analyze their data easily and contribute to a global database on photosynthesis. The service lets scientists know the biology of the plant, its productivity, why it is so productive, and how it is affected by climate.

In exchange for providing the service, Gu is permitted to keep the data, which facilitates gathering CO_2 uptake data from a wide variety of different trees and plants. Quantifying these data across many species improves both the rate and magnitude of CO_2 uptake in climate models, making them more accurate.

In the November 2014 issue of PNAS, Gu, Ying Sun of the University of Texas at Austin (UT-Austin), and coauthors from CCSI, UT-Austin, and the University of Missouri published results of their research in mesophyll conductance across plant species. The authors conclude that plants have taken up 16% more CO_2 between 1901 and 2010 than previously estimated by the Community Land Model.

The study drew international media interest and was reported by BBC News, ABC Online, the *Daily Mail*, and others.—*written by Justin Kaffka and edited by Katie Elyce Jones*

Honors and Awards

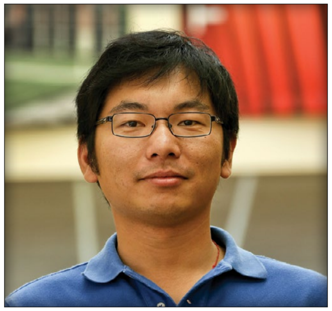
Jack Fellows, CCSI director

Fellows received the National Council for Science and the Environment (NCSE) Lifetime Achievement Award for his part in cofounding the US Global Change Research Program (USGCRP). USGCRP consolidates global change research across 13 federal departments and agencies to advance research on climate change in the United States and uses that knowledge to inform policy and the public. The program cooperates with organizations such as the Intergovernmental Panel on Climate Change. The awards ceremony took place in Washington, DC, at NCSE's 14th National Conference and Global Forum on Science, Policy, and the Environment in January 2014.

Jack Fellows.

Tianyu Jiang, CCSI postdoctoral research associate

Jiang achieved third place in the Chinese-American Oceanic and Atmospheric Association's "best dissertation" competition. Jiang, a member of CCSI's Earth System Modeling group, received the award February 5 in Atlanta during the 94th American Meteorological Society Annual Meeting. Jiang's dissertation, "Understanding the Scale Interaction of Atmospheric Transient Disturbances and Its Coupling with the Hydrological Cycle over the Pacific-North American Regions," focused on the connection between climate over the North Pacific and extreme weather, such as freezing temperatures, high-impact precipitation, droughts, and other severe events.



Tianyu Jiang.

Xiaofeng Xu, CCSI postdoctoral research associate

Xu was one of two winners of the Early Career Ecologist Award from the Ecological Society of America's (ESA's) Asian Ecology Section. Xu's research focuses on understanding and quantifying terrestrial ecosystem responses and feedback within the climate system for the purpose of improving computational Earth System Models. The award was established by ESA to promote the recognition of young ecologists who make substantial contributions to Asian ecological research development. Xu's research on land–atmosphere exchanges of greenhouse gases, particularly methane and nitrous oxide across North America and China, has significantly enriched the field of Asian ecology and provided fundamental information for the scientific community and decision makers. He began a position as assistant professor of ecology at the University of Texas at El Paso in September.

Xiaofeng Xu.

Forrest Hoffman, Jitendra Kumar, and Richard Mills, CCSI research scientists

"Representativeness-based sampling network design for the State of Alaska" was named the Outstanding Paper by the US Regional Association of the International Association of Landscape Ecology (US-IALE). The paper was coauthored by three CCSI researchers—Forrest Hoffman, Jitendra Kumar, and Richard Mills—and William Hargrove of the US Department of Agriculture Forest Service. The paper presents a quantitative method that establishes an optimal sampling strategy for collecting environmental data by classifying spatial areas based on their environmental characteristics. This method provides a framework for using sparse field measurements to best represent entire ecoregions and an approach for integrating models and data. The authors received the award at the US-IALE annual symposium held in Anchorage, Alaska, in May 2014.

From left to right, Jitendra Kumar, William Hargrove, and Forrest Hoffman.

Select Publications

Andres RJ, Boden TA, Higdon D, "A new evaluation of the uncertainty associated with CDIAC estimates of fossil fuel carbon dioxide emission," *Tellus B*, **66**, 23616 (2014).

Ashfaq M, Ghosh S, Kao S-C, Bowling LC, Mote P, Touma D, Rauscher SA, Diffenbaugh NS, "Near-term acceleration of hydroclimatic change in the western US," *Journal of Geophysical Research: Atmospheres*, 118(19), 10676–10693 (2013).

de Bremond A, Preston B, Rice J, "Improving the usability of integrated assessment for adaptation practice: Insights from the U.S. Southeast energy sector," *Environmental Science & Policy*, **42**, 45–55 (2014).

De Kauwe MG, Medlyn BE, Zaehle S, Walker Ap, Dietze MC, Hickler T, Wang Y-P, Luo Y, Jain AK, El-Masri B, Wårlind D, Weng ES, Parton WJ, Thornton PE, Wang S, Prentice IC, Asao S, Smith B, McCarthy HR, Iversen CM, Hanson PJ, Warren JM, Oren R, Norby RJ, "Where does the carbon go? A model-data intercomparison of vegetation carbon allocation and turnover processes at two temperate forest free-air CO_2 enrichment sites," *New Phytologist*, **203**(3), 883–899 (2014).

Evans KJ, Mahajan S, Branstetter ML, McClean JL, Caron JM, Maltrud ME, Hack JJ, Bader DC, Neale R, Leifeld JK, "A spectral transform dynamical core option within the Community Atmosphere Model (CAM4)," *Journal of Advances in Modeling Earth Systems*, **6**(3), 902–922 (2014).

Gu L and Sun Y, "Artefactual responses of mesophyll conductance to CO_2 and irradiance estimated with the variable J and online isotope discrimination methods," *Plant, Cell, & Environment*, **37**(5), 1231–1249 (2014).

Hoffman FM, Kumar J, Mills RT, Hargrove WW, "Representativeness-based sampling network design for the State of Alaska," *Landscape Ecology* **28**(8), 1567–1586 (2013).

Hoffman FM, Randerson JT, Arora VK, Bao Q, Cadule P, Ji D, Jones CD, Kawamiya M, Khatiwala S, Lindsay K, Obata A, Shevliakova E, Six KD, Tjiputra JF, Volodin EM, Wu T, "Causes and implications of persistent atmospheric carbon dioxide biases in Earth System Models," *Journal of Geophysical Research: Biogeosciences*, **119**(2),141–162 (2014).

Iversen CM, Sloan VL, Sullivan PF, Euskirchen E, McGuire AD, Norby RJ, Walker AP, Warren JM, Wullschleger SD, "The unseen iceberg: plant roots in arctic tundra," *New Phytologist* **205**(1), 34–58 (2015).

Kang S, Nair SS, Kline KL, Nichols JA, Wang D, Post WM, Brandt CC, Wullschleger SD, Singh N, Wei Y, "Global simulation of bioenergy crop productivity: analytical framework and case study for switchgrass," *Global Change Biology Bioenergy*, **6**(1), 14–25 (2014).

Langan R, Archibald R, Plumlee M, Mahajan S, Ricciuto D, Yang C, Mei R, Mao J, Shi X, Fu JS, "Stochastic parameterization to represent variability and extremes in climate modeling," *Procedia Computer Science*, **29**, 1146–1155 (2014).

Liu S, Wei Y, Post WM, Cook RB, Schaefer K, Thornton MM, "The Unified North American Soil Map and its implication on the soil organic carbon stock in North America," *Biogeosciences*, **10**, 2915–2930 (2013).

Oubeidillah AA, Kao S-C, Ashfaq M, Naz BS, Tootle G, "A large-scale, high-resolution hydrological model parameter data set for climate change impact assessment for the conterminous US," *Hydrology and Earth System Sciences*, **18**(1), 67–84 (2014).

Steed CA, Ricciuto DM, Shipman G, Smith B, Thornton PE, Wang D, Shi X, Williams DN, "Big data visual analytics for exploratory Earth system simulation analysis," *Computers & Geosciences*, **61**, 71–82 (2013).

Walker AP, Hanson PJ, De Kauwe MG, Medlyn BE, Zaehle S, Asao S, Dietze M, Hickler T, Huntingford C, Iversen C, Jain A, Lomas M, Luo Y, McCarthy H, Parton WJ, Prentice IC, Thornton PE, Wang S, Wang YP, Warlind D, Weng E, Warren JM, Woodward FI, Oren R, Norby RJ, "Comprehensive ecosystem model-data synthesis using multiple data sets at two temperate forest free-air CO_2 enrichment experiments: Model performance at ambient CO_2 concentration," *Journal of Geophysical Research: Biogeosciences*, **119**(5), 937–964 (2014).

Wilbanks TJ and Ebi KL, "SSPs from an impact and adaptation perspective," *Climatic Change*, **122**(3), 473–479 (2014).

Wullschleger SD, Epstein HE, Box EO, Euskirchen ES, Goswami S, Iversen CM, Kattge J, Norby RJ, van Bodegom PM, Xu X, "Plant functional types in Earth system models: past experiences and future directions for application of dynamic vegetation models in high-latitude ecosystems," *Annals of Botany*, **114**(1), 1–16 (2014).

Zaehle S, Medlyn BE, De Kauwe NG, Walker AP, Dietze MC, Hickler T, Luo Y, Wang Y-P, El-Masri B, Thornton P, Jain A, Wang S, Warlind D, Weng E, Parton W, Iversen CM, Gallet-Budynek A, McCarthy H, Finzi A, Hanson PJ, Prentice IC, Oren R, Norby RJ, "Evaluation of 11 terrestrial carbon-nitrogen cycle models against observations from two temperate Free-Air CO_2 Enrichment studies," *New Phytologist*, **202**(3), 803–822 (2014).

Zscheischler J, Michalak AM, Schwalm CR, Mahecha MD, Huntzinger DN, Reichstein M, Berthier G, Ciais P, Cook RB, El-Masri B, Huang M, Ito A, Jain A, King A, Lei H, Lu C, Mao J, Peng S, Poulter B, Ricciuto D, Shi X, Tao B, Tian H, Viovy N, Wang W, Wei Y, Yang J, Zeng N, "Impact of large-scale climate extremes on biospheric carbon fluxes: An intercomparison based on MsTMIP data,"*Global Biogeochemical Cycles*, **28**(6), 585–600 (2014).

Climate Change Science Institute at Oak Ridge National Laboratory
One Bethel Valley Road
PO Box 2800, MS-6301
Oak Ridge, TN 37831-6301
Phone: (865) 576-9093
climatechangescience@ornl.gov

CLIMATE CHANGE SCIENCE INSTITUTE
OAK RIDGE NATIONAL LABORATORY