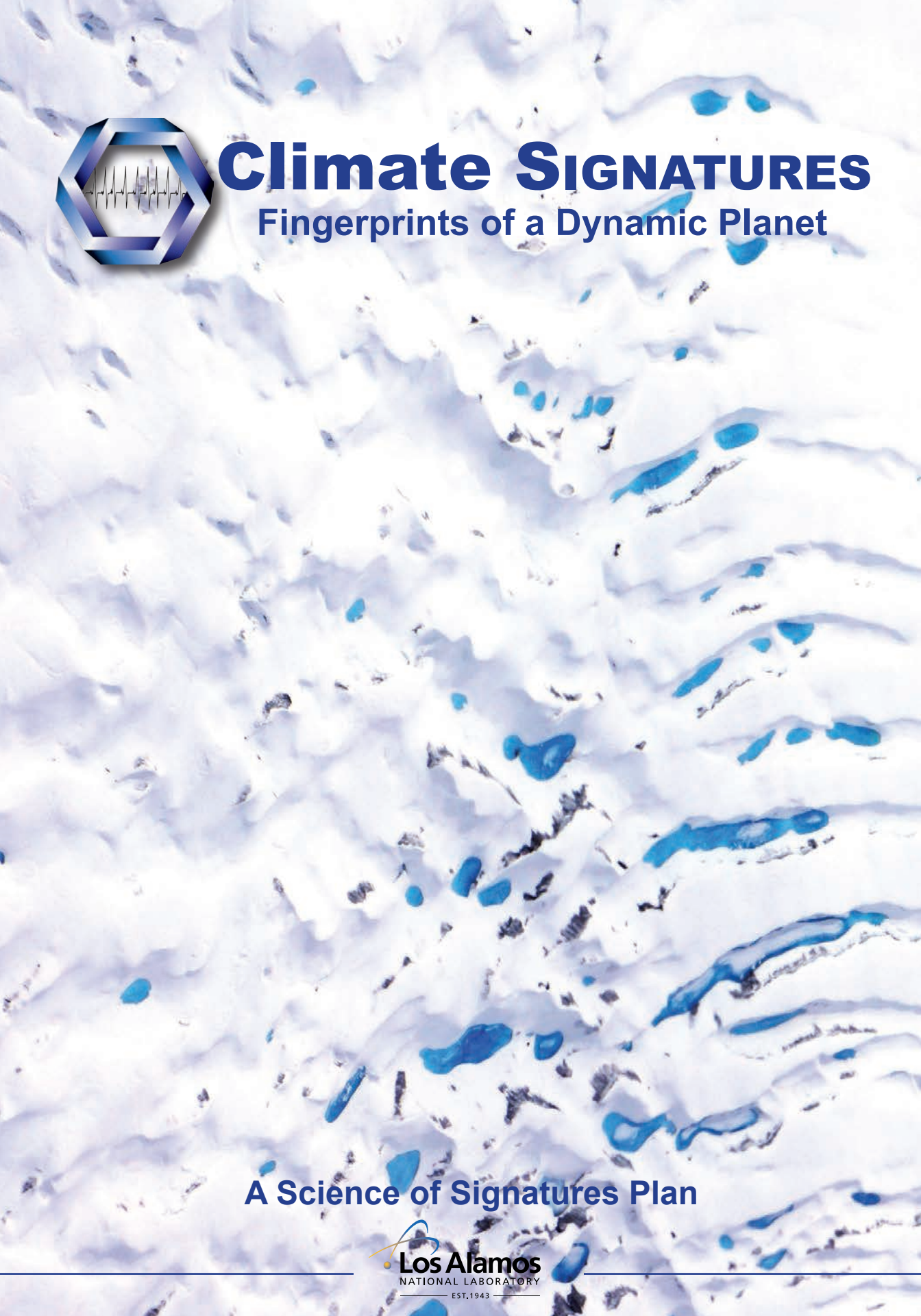
Climate Signatures

Fingerprints of a Dynamic Planet



A Science of Signatures Plan

Los Alamos
NATIONAL LABORATORY
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Century of Change

Los Alamos National Laboratory's charge is to develop science and technology that will make the Nation safer and enhance our global standing. This breadth of mission scope requires careful planning and effective cooperation with partners and other governmental agencies. The document you are holding is one of the products of ongoing efforts that are designed to both help us coordinate internally and communicate externally about how the Laboratory's unique capabilities are being applied to problems of the greatest significance. Climate change is one of those problems.

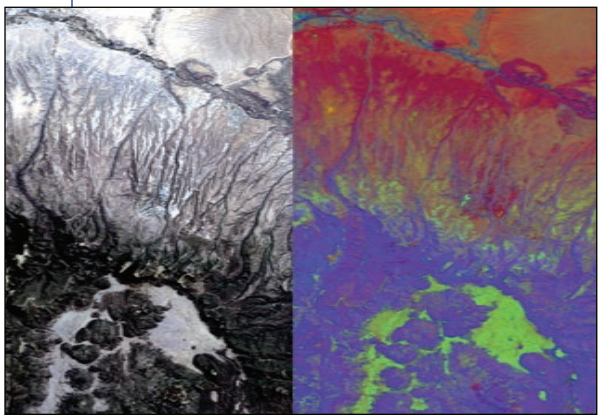
The story of climate change is told by the signatures it writes upon the environment, and its importance is effectively conveyed by the words of President Obama: "There's one issue that will define the contours of this century more dramatically than any other, and that is the urgent and growing threat of a changing climate." (September 2014).

The Laboratory's role in climate-change research, then, is one of identifying and interpreting the signatures of change. Our goal is to provide balanced and accurate information to national decision makers so that appropriate choices can be made based on the best possible knowledge. Applications range from providing information that might be used to verify climate treaties, to helping predict how rising ocean levels will affect low-lying metropolitan areas, to mapping the ways in which drought is changing our western and southwestern forests.

We are able to provide accurate information by taking advantage of the extraordinary breadth of multidisciplinary science at our Laboratory and because climate signatures are an aspect of climate research particularly well suited to our strengths in modeling, super-computing, and experimental science.

This Science of Signatures (SoS) plan provides a framework from which to view the breadth and depth of our work in this area. Additional resources on SoS or our climate work can be requested from the contacts listed on page 22. Planning for R&D is a living process, and we welcome your feedback and questions.

Nancy Sauer is the Associate Director for Chemistry, Life, and Earth Sciences, which oversees the Science of Signatures effort for the Laboratory.



Hyperspectral vision. A machine-learning technology called GENIE allows the use of hyperspectral techniques to analyze landforms. Categorization of this visible/infrared Landsat satellite image into forest, grasslands, bare ground, and farm lands is used for input to wildfire models.

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The Trinity supercomputer is one of the many resources that the Laboratory uses to solve some of the most complex modeling problems facing us today, including modeling various aspects of climate-change science.

The National Landscape

Climate research is an increasingly significant national imperative that is driven by a wide range of climate-related topics. The Laboratory's role is to understand those topics as articulated by national policy and to provide science-based solutions within the context of the Laboratory mission.

One important climate-related policy document is the **Executive Office of the President – The President's Climate Action Plan (June 2013)**, which has key objectives: 1) cut carbon pollution in America, 2) prepare the United States for the impacts of climate change, and 3) lead international efforts to combat global climate change and prepare for its impacts. The document acknowledges that sound science must be engaged for all three objectives, and as we will show, the Laboratory is already contributing in each.

These objectives are reflected in other documents produced by the U.S. government, including but not limited to the following.

The OSTP/DOE QER Quadrennial Energy Review Report, which is intended to identify the threats, risks, and opportunities for U.S. energy and climate security (2013).

National Science and Technology Council – The National Global Change Research Plan 2012-2021, which is charged with developing a "comprehensive and integrated United States research program to assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

The DOE Strategic Plan, which calls for a robust predictive understanding of Earth's climate and environmental systems and informs the development of sustainable solutions to the Nation's energy and environmental challenges.

DHS Climate Change Adaptation Roadmap (2012), which states that energy and climate change are key issues that shape the future security environment.

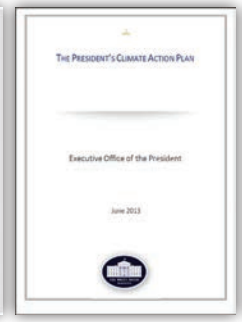
The DoD Quadrennial Defense Review (2014), which stresses the need to develop alternative energy sources and approaches for military applications and national security.

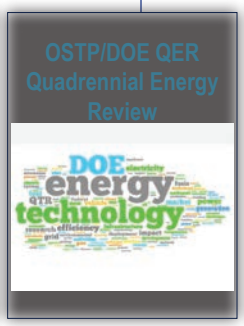
The picture that emerges from the large set of documents is that the concern for realistic solutions permeates every sector of government planning. The scale of participation extends from research and development to develop new ways of measuring the extent and impacts of climate change, to tools and techniques for climate treaty monitoring.

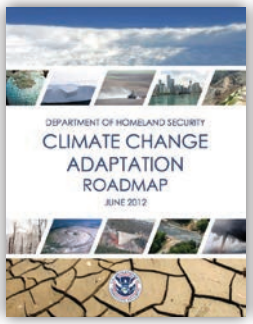
Why LANL?

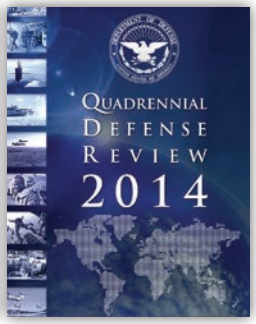
The Laboratory's mission is to serve the Nation by solving national security challenges through scientific excellence. Climate research touches on two of the four main major mission drivers that bound LANL's scope; energy security and emerging threats. Thus, climate research is core to our mission.

We work to achieve success in climate research by providing information and science-based solutions to policy makers and national agencies. Because efforts in climate touch upon many aspects of work at the Laboratory, there









are other institutional and organizational plans that impact our strategic planning in climate signatures. Many of these integrate climate and energy themes, particularly in the arena of energy-production induced climate change. The intersection of energy/climate is discussed in the next section.

The following documents help the Laboratory plan climate-related research. Collectively their intent is to coordinate and marshal people, equipment, and facilities behind important technological problems within the scope of our mission.

- **LANL Energy Security Strategy Refresh (2014).**
- **SoS Climate Impacts Plan (2013).**

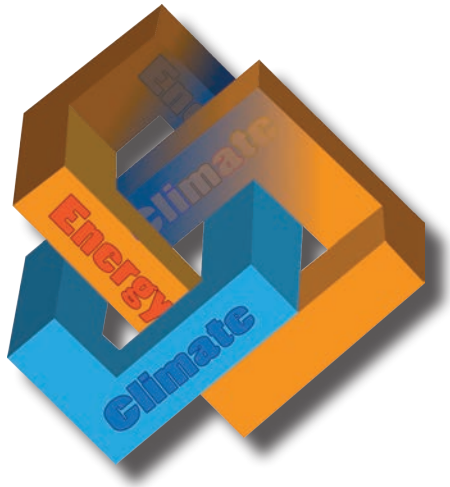
Energy & Climate

The Laboratory has chosen to separate energy signatures from climate signatures for the purposes of the Science of Signatures. Energy and climate research overlap, and in many ways the two topics do coevolve and reinforce each other. However, grouping the two together has the risk of overemphasizing what they have in common rather than cultivating those areas in which they are unique. By treating them separately, we can ensure that each receives full development and attention from Laboratory staff, managers, and external stakeholders.

Who Should Read This

This document was written with multiple audiences in mind.

Our staff: This document is the high-level Laboratory strategy for climate signatures. It is intended to unite Laboratory scientists behind a single strategic direction and to guide the



research and efforts of our staff. It will inform investments in hiring, facilities, equipment, as well as additional planning.

Our stakeholders: It is intended as a communications document for those outside the Laboratory who have current or potential programs that might benefit from the expertise available at LANL. With it, we hope to begin a dialog that will help us understand the technological and scientific requirements of our customers and to inform them of where we might be of assistance.

Our collaborators: Climate science is a cross-organizational and multidisciplinary endeavor. To be successful, we must collaborate with other science and technology organizations, local and national governmental bodies, and through them with the civilian population that we seek ultimately to serve. This document explains what we hope to achieve and where we will require partners to succeed.

What are climate signatures?
Signatures include both visibly detectable "signals" or changes such as melting polar ice or sea level rise; and physical, chemical, and biological data/characteristics that are tightly coupled to the machinery of the earth's climate system and reflect impacts of climate change and variability on human and natural environments. Changes in sensitive ecosystems such as in polar regions can be used as early warning systems and inform us about potential future changes in other parts of the earth. At LANL, scientists are integrating such observational data with analytical and computational models. Scientists then use such models to develop new observations and signatures to enhance the accuracy of climate predictions, assess climate impacts, and conduct infrastructure and policy analyses.

Science Pillars

The science pillar concept is a primary tool the Laboratory uses to plan how we will accomplish current and future missions, including the climate mission that is the focus of this document. There are four science pillars:

1-Materials for the Future (Materials),
2-Integrating Information Science and Technology for Prediction (IS&T),
3-Nuclear and Particle Futures (NPF), and
4-Science of Signatures (SoS).

Each of the pillars has discrete science goals that are fundamental to building the Laboratory's future science and technology base. These pillars support each other, and interfaces among the four pillars are leveraged for the benefit of all four.

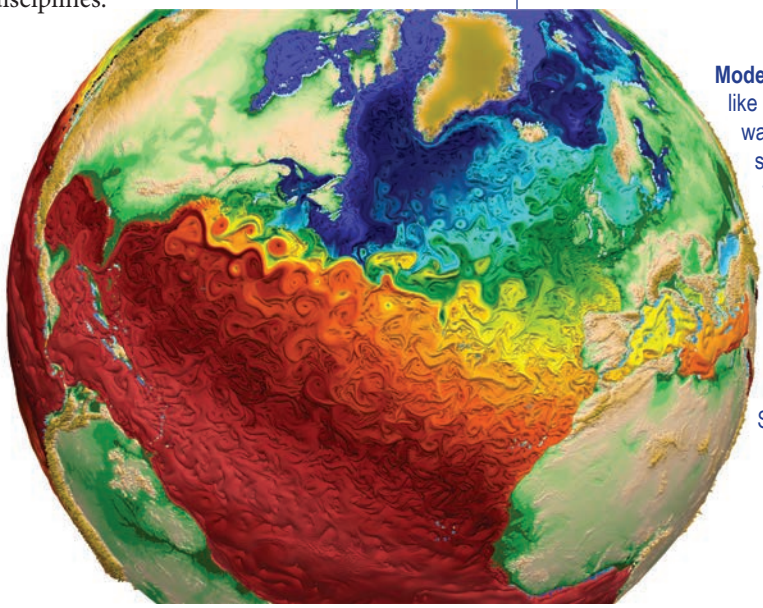
The fundamental precept of this approach is that the greatest science breakthroughs will come as we approach difficult problems in revolutionary ways. This multidisciplinary approach draws upon physicists, materials scientists, chemists, computer scientists, theoreticians, biologists, Earth scientists, space scientists, engineers, mathematicians, and numerous other disciplines to solve important national security science problems. The pillars approach gives these experts a framework for working together and allows them to apply their skills across the traditional boundaries of their disciplines.

The science pillars also inform our investments in science and engineering, guide recruitment and training strategies, and serve as a framework for our partnerships with other leading research institutions worldwide. Climate strategy incorporates a wide variety of signatures and thus responsibility for some of the associated strategic planning efforts fall under the Science of Signatures. However, there is a significant component of both IS&T and biosurvellience required in climate signatures. Laboratory planning efforts in climate have therefore included leadership from these pillars as well.

Science of Signatures

The Science of Signatures strategic plan (updated 2014) was chartered by the Principal Associate Directorate for Science, Technology, and Engineering (PADSTE) and written by a team of more than 35 managers and scientists from across the Laboratory following a two-year process. Its grounding principle is that we must be able to identify and characterize threats before we can understand them or take action to mitigate them. Signatures are the unique elements that allow us to locate threats within their environments and describe them.

The Science of Signatures pillar addresses emerging challenges by developing science and technology to detect these threats. Our complete technological toolbox is applied to



Modeling A Warming Ocean. The paint-like swirls of this visualization depict global water-surface temperatures, with the surface texture driven by vorticity. Cool temperatures are designated by blues and warmer temperatures by reds. Trapped regions of warmer water (red) adjacent to the Gulf Stream off the eastern coast of the U.S. indicate the model's capability to simulate eddy transport of heat within the ocean, a key component necessary to accurately simulate global climate change. See pages 14–15 for more.

signature science from across our mission areas of global security; nuclear defense; and energy, climate, and health. Critical components are the discovery and detection of signatures to enable understanding of component species or processes that have a major impact on a large, complex system.

Specifically, we characterize measures, signals, and properties in or of complex systems in order to detect or attribute change; predict systems behavior across scales in space (molecular to global) and time (near-term to geologic), and assess impacts to the system of change.

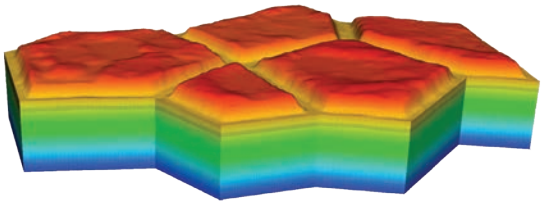
SoS Scientific Approach

Our scientific strategy is to *discover new signatures*, *revolutionize measurement of signatures,* and *deploy new technologies in the field*. Each of these three components has distinct characteristics.

Discover signatures: Identify signatures of chemical, biological, radiological, nuclear, and explosives threats, and of climate, energy and health security impacts. In essence, signature discovery is determining those measurable phenomena that uniquely identify and characterize properties within complex environments.

Revolutionize measurements: For threat-specific signatures, develop entirely new measurement technologies, methodologies, or strategies or develop transformational advances in the current state-of-the-art. In essence, how can sensitive and specific measurements be made in entirely new ways and/or how can new phenomena (signatures) be measured?

Forward technology deployment: Make measurement technologies and methodologies practical through engineering. This includes prototyping of sensors and instruments for field deployment and systems integration of sensor networks. In essence, how do we bring science advances to the real world in a way that provides feedback into signature discovery and/or revolutionary measurement technologies?



LANL computer models help explain why Arctic permafrost thaws in characteristic polygonal patterns and the impacts of that thawing on climate.

The strategy of Discover, Revolutionize, Deploy is applied to the Los Alamos SoS areas of scientific leadership:

- **Nuclear and Radiological**
- **Chemical and Materials**
- **Biological**
- **Energy**
- **Climate**
- **Space**

The other five areas of leadership are developing strategic plans similar to this biosurveillance plan. Each individual plan will nest with the larger SoS plan.

SoS is tightly integrated with the other pillars along the themes of Discover, Revolutionize, Deploy.

The Science of Signatures Pillar is

- **An Institutional effort led by the Associate Directorate for Chemistry, Life, and Earth Sciences.**
- **An organizing principle built on historical strengths and technical leadership.**
- **One of four science plans to shape and manage the future of science and technology at the Laboratory.**
- **Supported and mandated by DOE.**
- **Important to our immediate stakeholders and the Nation.**
- **Reshaping the way we think of multidisciplinary science.**

Climate Overview

Climate signatures involve the detection and prediction of changes in the earth's climate, and the impact those changes have on human and other systems. Climate signatures that are both credible and actionable require the integration of observational data (both in situ and remote) and controlled experiments, predictive modeling and simulation, uncertainty quantification, and vulnerability analysis of affected systems.

Climate change impacts ecosystems, public health, and infrastructure. National security issues include agricultural productivity, water availability, natural resources competition, energy sector vulnerabilities, and geopolitical instability. Good decisions on these issues require sound science, which LANL provides.

Los Alamos National Laboratory has developed world-class climate models for over 20 years, specializing in the simulation of ocean and cryospheric systems (e.g,. Arctic sea ice). We also lead significant modeling projects in terrestrial hydrology, and Arctic ecosystem dynamics. We have strong measurement capabilities in in situ and remote sensing of atmospheric constituents such as greenhouse gases, as well as field monitoring of ecosystems in the Arctic, South America, and the southwest region of the U.S.

LANL's National Infrastructure Simulation and Analysis Center provides key decision support to the Department of Homeland Security and other sponsors by analyzing the vulnerability of critical infrastructure to extreme weather events and other threats. Our strong capability in uncertainty quantification for stockpile stewardship is being applied to the predictions of complex climate models.

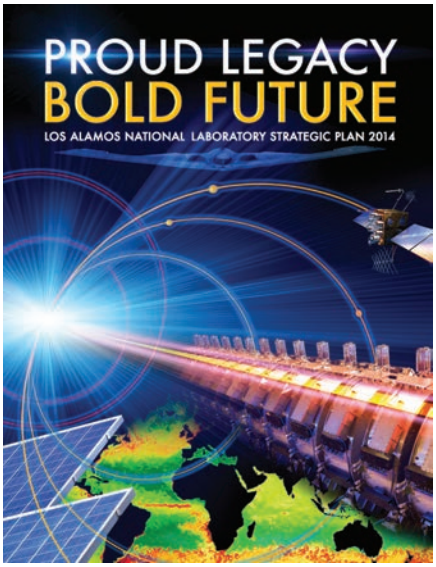
Climate science is expected to be a national and international priority in the next decade, and climate signatures will be of increasing importance to stakeholders at all levels from individual to national, with significant implications for national and global security.

As described in the President's 2013 report cited earlier, climate change affects decisions involving ecosystems, services, public health, infrastructure planning, and security issues including agricultural productivity, water availability, natural resources competition, energy sector vulnerabilities, and geopolitical instability. This implementation plan identifies the strengths and priorities that will allow LANL to become a leading and trusted science advisor for these problems.

LANL's Approach

LANL has a well-developed Energy Security strategy, first published in 2009 and substantially updated in 2014.

Climate impact verification is captured within the Mitigating Impacts of Global Energy Demand Growth component of the Energy Security strategy and within the recently announced "Proud Legacy Bold Future– Los Alamos National Laboratory Strategic Plan 2014." Addressing energy/climate security requires science-based decision and assessment tools to quantify uncertainty (risk) and to predict by integrated modeling and



The Laboratory's internal strategic plan describes the major mission areas that govern our activities and investments. Climate science is one of the major scientific challenges of the 21st Century and is thus a natural fit for our capabilities.

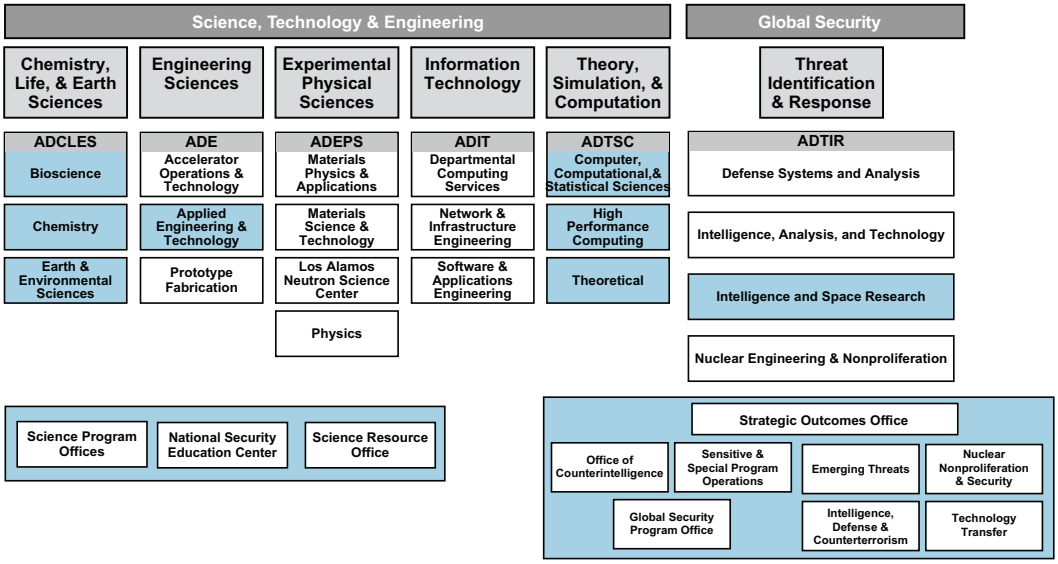
measurement the complex interactions of anthropogenic emissions with climate, natural, and engineered systems across multiple spatial and temporal scales.

Climate signatures that are both credible and actionable require the integration of observational data and controlled experiments, predictive modeling and simulation, uncertainty quantification, and vulnerability analysis of affected systems–all at multiple scales with global coverage. To contribute nationally LANL leverages and integrates capabilities primarily from the SoS and the Information Science and Technology (IS&T) pillars, with some contribution from the other two pillars.

The SoS pillar component is focused on measurement science and technology. Measurements for climate impact verification include the quantification and attribution of fluxes of greenhouse gases and other emissions from point to regional scales, the quantification of system response to anthropogenic and natural forcings in space and time at relevant resolution, and the confirmation of cause and effect through experiments. LANL and its partners have expertise in measuring emissions from ground to space that can encompass scales from meters to thousands of kilometers. These measurements enable the detection and quantification of climate impacts. One of LANL's major objectives for climate impact verification is the integration of multiscale measurements; natural, climate, and engineered systems modeling; and uncertainty quantification.

The IS&T pillar is focused on predictive modeling and simulation, uncertainty quantification, and decision support. The modeling and simulation goal is to predict change and effects on climate, natural, and engineered systems. Uncertainty quantification is focused on combining computational models (regional and global), physical data sources (top-down and bottom-up), and expertise. It allows us to make inferences about regional-scale change and effects. Decision support includes integration of energy and infrastructure with climate and natural models for planning, mitigation, and adaptation analysis and assessment. It also provides a basis for a greenhouse gas information system.

Three strategic goals are outlined later in this document. They cover the areas of measurement, predictive modeling, and integrated-impacts analysis and decision support.



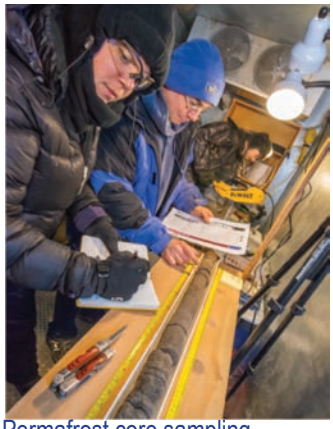
Laboratory organizational chart showing in blue the organizations that currently contribute to climate signatures development. The Laboratory as a whole has a budget of over $2B and more than 9000 employees, and while our "bench strength" is already great, it can clearly go much deeper should the science challenges demand it.

Understanding Climate Feedba

LANL is a major research partner in two large multi-lab/university partner climate research projects coordinated through the DOE ments" (NGEE) were developed based on the recognition that there are major uncertainties about how climate variability and cha large regional to global climate feedbacks. The Arctic and Tropics are two of the most climate sensitive terrestrial ecosystems, a

The Arctic

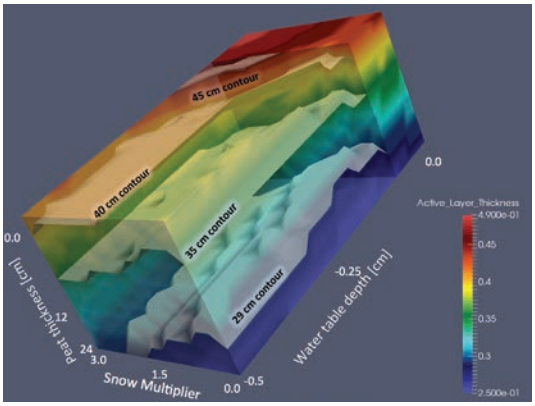
The Arctic may be the most climatically sensitive region on Earth. High latitudes have experienced the greatest regional warming in recent decades and are projected to warm twice as much as the rest of the globe by the end of the 21st century. They are uniquely characterized by the presence of permafrost, defined as ground that has been continuously frozen for 2 or more years. Observations suggest that permafrost degradation is now common in high-latitude ecosystems and is expected to drive changes in climate forcing through biogeochemical and biophysical feedbacks.



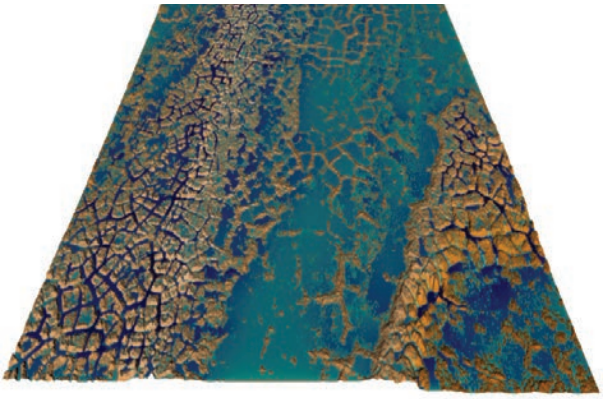
Permafrost core sampling.

Biogeochemical feedbacks are dominated by the potential to release a large amount of currently stored carbon back into the atmosphere as CO_2 and CH_4. These feedbacks will take place in an environment undergoing dramatic geomorphic change and landscape reorganization. Thawing of ice-rich permafrost can lead to subsidence and deformation of land surfaces that range from localized depressions to deep and extensive thermokarst events. These landscape features, along with thermal erosion, gully formation, and drainage network expansion, are dramatically changing topography, surface hydrology, and vegetation structure on time scales of years to decades.

Los Alamos National Laboratory leads the development of the Arctic Terrestrial Simulator (ATS), a fine-scale thermal hydrology model, and in understanding how hydrology and geomorphology control ecosystem processes and how these processes will be modified by permafrost degradation. LANL also contributes to NGEE biogeochemical studies through field investigations using isotopes and water chemistry. Recent focus has been on the patterned ground (see figure) near Barrow, Alaska, but activities will transition to the Seward Peninsula near Nome where permafrost degradation effects and vegetation changes are much more pronounced.



The Arctic Terrestrial Simulator model results show effects of snow depth and peat thickness on active layer (seasonal thaw zone) thickness.

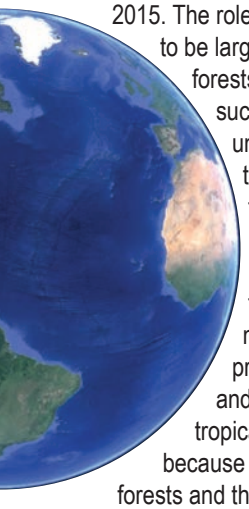


Thawing permafrost takes on a distinctive geometric pattern. Shown here is polygonal ground near Barrow, Alaska.

cks in Sensitive Ecosystems

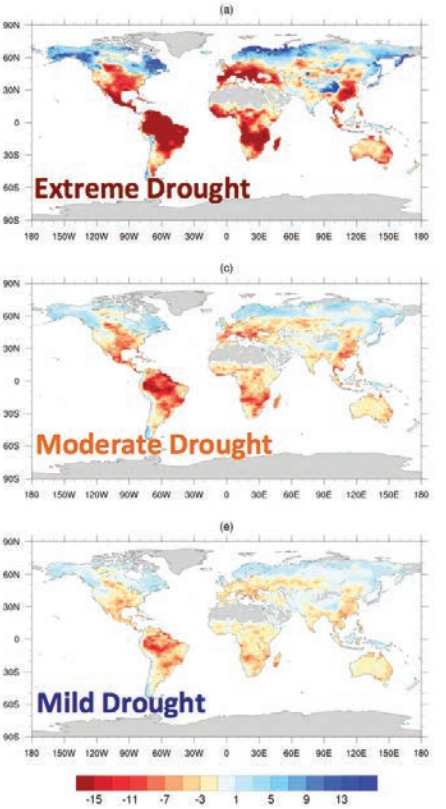
Office of Science, Office of Biological & Environmental Research (OBER). These "Next Generation Ecosystem Experi-
ange will alter carbon cycling and sequestration in terrestrial ecosystems, and that such changes have strong potential for
nd OBER has made NGEE-Arctic and NGEE-Tropics two of their top research priorities.

The Tropics

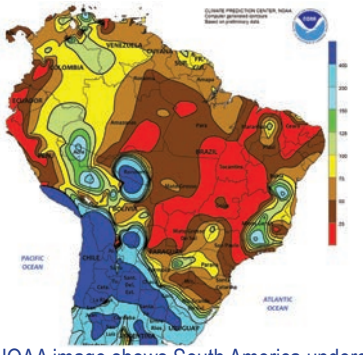


Because of the success of NGEE-Arctic, DOE initiated NGEE-Tropics in 2015. The role of tropical rain forests in the carbon cycle is understood to be large, but there are major uncertainties about how these forests will react under climate change and disturbances such as tree cutting and burning. NGEE-Tropics aims to understand how this delicate ecosystem functions, and the kinds of feedbacks to the carbon cycle and climate that may develop. Using an integrated modeling and observation strategy, NGEE-Tropics will develop a detailed Earth Systems Model that will describe how the tropical forests interact with Earth's climate. This model will help predict how rising temperatures, shifting precipitation patterns, increasing greenhouse gas levels, and other natural and human-induced changes affect tropical forests' influence on climate. The work is crucial because the flux of carbon, water, and energy between tropical forests and the atmosphere tend to be inadequately represented in climate models. Tropical forests are among the biggest sources of terrestrial uncertainty in projections of Earth's future climate. NGEE-Tropics plans to dramatically reduce this uncertainty and thus improve future climate projections.

The first phase of the project lasts 3 years and will assess current knowledge of tropical forest ecosystems and will define more the key uncertainties related to current models. Field studies of the current El Niño conditions will help drive modeling advances and prepare for phase 2. The second phase will have a greater pan-tropical focus and result in model refinements driven by the results of phase I. The effort includes collaborators from Berkeley, Brookhaven, Los Alamos, Oak Ridge, and Pacific Northwest national laboratories, as well as researchers from NASA, the National Center for Atmospheric Research, the Smithsonian Tropical Research Institute, the U.S. Forest Service, and several institutions from other nations, including Brazil's National Institute of Amazonian Research. Because of LANL's expertise in the study of drought-induced plant mortality, its scientists are leading the sub-component of NGEE-Tropics focused on quantifying, understanding, and modeling historical and future drought-impacts on pan-tropical forest stress and death. LANL also has a major role in understanding tropical hydrology and biogeochemical cycling within NGEE-Tropics using both modeling and multiscale field observation approaches.



Aggregated Earth System Model simulations conducted by LANL show the extreme sensitivity of tropical net primary productivity to future drought scenarios. The color bar at the bottom shows the % reduction in productivity.



This NOAA image shows South America undergoing a period of extraordinary environmental stress. August, 2015.

http://www.cpc.noaa.gov/products/analysis_monitoring/regional_monitoring/

Coastal Zone Impacts

The coastal zone is one of the most complex and dynamic regions of the earth. Eight of the ten largest cities on the planet, and forty-four percent of the world's population live within 150 km of the coast. While comprising only a small fraction of the earth's total area, this narrow band around our continents is where terrestrial, marine, atmospheric and human processes interact with the highest ecologic and economic consequences. Climate change driven processes such as sea level rise and tropical and extra-tropical storms have disproportional impacts in this region. Urbanization and human exploitation of resources within coastal environments leads to structural and ecological changes that degrade biologic productivity, leading to trillions of dollars of losses in ecosystem services per decade and causing feedbacks to the climate system through disruption of carbon sequestration in coastal wetlands and forests.

Costal zone impacts. The world's costal zones hold most of our population and are particularly vulnerable to the impacts of a changing climate.

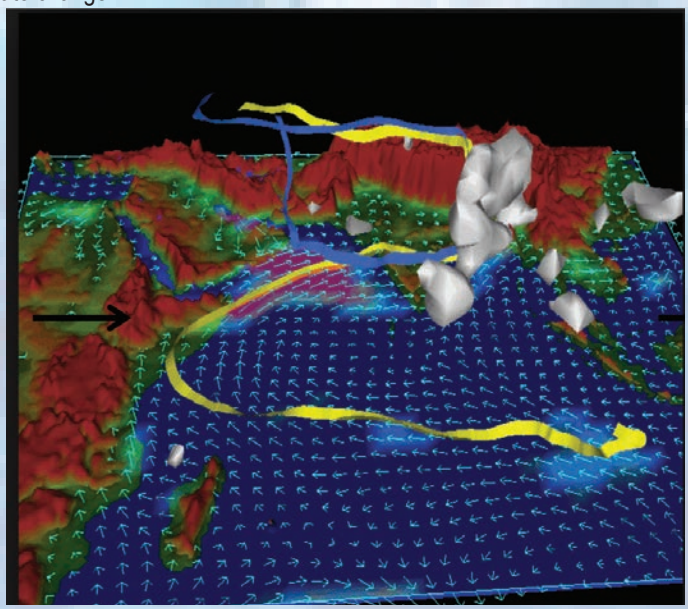
LANL's research touches on many aspects of coastal science. Our ocean, land, and sea ice modeling capabilities at high latitudes inform far-field drivers of the coastal zone in the form of sea level rise and biogeochemical changes in the ocean. Our ocean modeling capabilities can also be extended to coastal processes at high regional resolution. We are characterizing sea level rise uncertainties with respect to Greenland and Antarctic ice sheet dynamics and the Southern Ocean warming that can trigger rapid ice sheet retreat.

New modeling capabilities under development focus on the coastline directly, modeling the fluxes of water and nutrients from Arctic deltas into the Arctic Ocean, their biogeochemical impacts, and the effects of altered deltaic geomorphological structures. High-performance computing is needed to resolve the small-scale processes that take place in this geographically localized zone.

Our infrastructure modeling and analysis capabilities identify vulnerabilities in coastal populations and energy infrastructure to coastal inundation subject to climate change.

Better Models: The global coastal research at LANL is to produce a transformational modeling system which develops and adopts new approaches to:

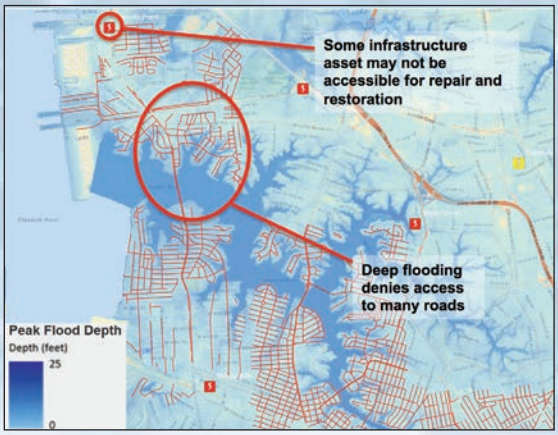
1) multiscale computational physics,
2) couple model components,
3) acquire coastal process observations, and
4) manage, manipulate, archive, and serve observational and modeling data sets.



Modeling to assess scale of impacts. Computational models such as this one of the Indian monsoon system help to bracket the extent of coastal impacts.

Infrastructure Impacts

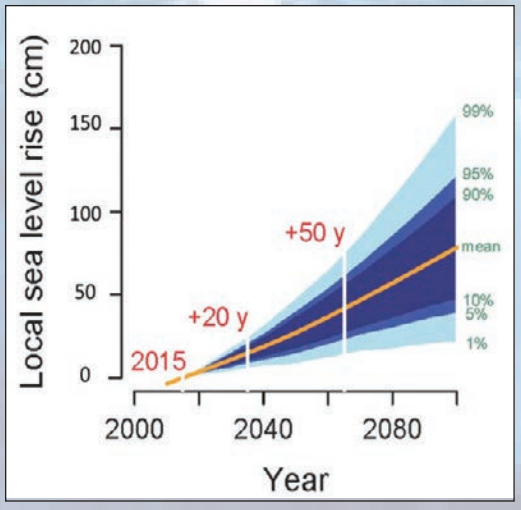
Much of the United States highway, electrical, and communications infrastructure is aging, and climate change threatens to damage it in the coming decades. Roadways and bridges are likely to become flooded by sea level rise and increasing storm intensity (see opposite page), and electrical generation and transmission are at risk from flooding and storms. Loss of electricity will cascade to other vital systems as well (for example, water supply and communications). In other regions, drought will also affect water supply to other infrastructures as well as populations. Our national security requires that we anticipate and plan for impacts to these vital components of our civilization. Understanding the extent of the potential problem is the first step, followed by strategies for ameliorating the damage caused by extreme weather events and sea level rise.



Local and national authorities will make decisions about how to prepare and when to act, and those authorities require reliable information. That information will only come from the correct combination of modeling and data. The problem is complex, both because climate itself is such a difficult modeling problem and because our infrastructure has vast numbers of interdependent parts. The solution is to identify and understand the key variables that couple infrastructure models to climate simulations in a meaningful way.

Research is needed to understand these couplings in both space and time. A vital aspect is to properly represent the interface variables and determine how best to calculate them from climate models, which may simulate processes on scales that differ from those that impact infrastructure. If we are to predict and optimize future infrastructure response and performance to changing climatic conditions, we must also thoroughly understand the uncertainties in order to develop adaptation strategies that are robust.

LANL has the technical capabilities in both climate and infrastructure modeling to make major contributions to this important problem. In infrastructure, we have spent decades providing energy and infrastructure analysis to the Department of Defense, Department of Homeland Security, the Department of Energy, and other sponsors. Over that time we have accrued knowledge and tools that allow us to begin to tackle this next great challenge. Our approach is well developed and uses physicists, engineers, mathematicians, statisticians, computer scientists, and economists, and it employs interdependency, optimization, and risk-assessment frameworks. In climate science, we have developed models for climate simulation that run on the fastest computers in the world and incorporate a sophisticated understanding of the challenges of uncertainty quantification in large and dynamic systems. Our contribution lies in combining these two skill sets.



LANL is studying

- Intermittency and uncertainty of renewable electrical generation
- Integrating wind and photovoltaics at low cost and high reliability
- The emerging strong interdependence of energy networks
- Natural gas and the electrical grid
- Water-for-energy, energy-for-water
- Increasing impacts of extreme weather
- Hurricanes, derecho, ice storms, polar vortex
- Decisions that bridge long and short time scales (day to decades)
- Decisions that bridge spatial scales (city blocks to national scale)

Integrated Disturbance

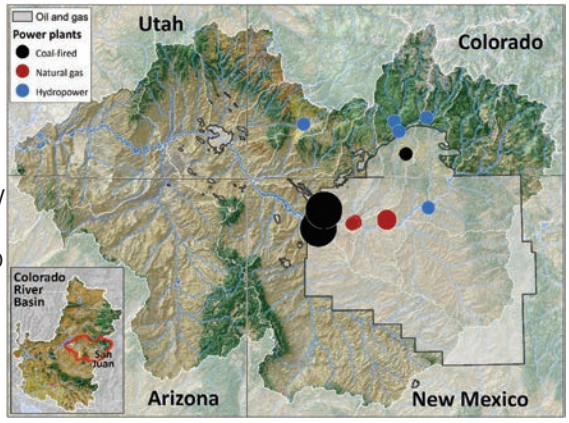
Climate-driven disturbances will have an increasing impact on natural ecosystems and hydrology. Of particular interest to LANL's scientists are vegetation mortality from drought, wildfire, insect infestation, and pathogens. These disturbances are projected to reduce global carbon uptake by as much as 50% over anthropogenic emissions. Likewise, our research is now predicting a similarly devastating impact on regional watersheds.

What is "Integrated Disturbance?"

Climate change impacts many aspects of the natural world, and these various impacts in turn affect each other. "Integrated disturbance" is a way of looking at these feedback loops holistically in order to more accurately predict trends in our environment.

Closely related is the interface called the energy-water nexus (EWN), which describes the complex way in which we require water for both energy and agriculture. Climate-driven disturbances will have a massive effect on both short- and long-term water supply. Ongoing research into some of our Nation's most critical watersheds has shown that climate-driven disturbances could lead to 20% reductions in annual river flows, compared to current climate projections without disturbance, in major sub-basins of the Colorado River basin. This finding will likely have a huge impact on how we understand the EWN. Scientists are also currently developing a prototype project, along with three other national laboratories, that demonstrates the impacts of "disturbed hydrology" on water operations.

LANL is a world-leader in the three key climate-driven disturbances: temperature/drought, wildfire, and insect infestation. Our work has demonstrated the massive impact that disturbances will have on forests, including widespread mortality and stress, leading to climate feedbacks larger than anthropogenic emissions. As part of a 3-year Critical Watersheds research project, LANL is working to understand and quantify the impact of disturbance on watersheds, ranging from fine-scale modeling of several-square-kilometer watersheds up to a regional-scale analysis of the entire Colorado River.

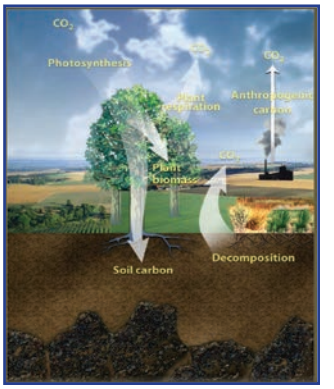


The San Juan River basin is host to a range of complex climate, disturbance, and energy-water challenges. The basin supplies water for multiple gas and coal-fired power plants and hydropower, vast oil and gas production, widespread irrigation, and urban areas.

Preliminary results suggest that climate-driven disturbances will have an increasingly catastrophic impact on regional water supplies. Presently, these disturbances are poorly represented (wildfire) or entirely missing (temperature-drought mortality, insect infestation) from earth system models (ESMs). Consequently, ESM-based water resource studies—at the heart of climate impacts and the EWN—are likely missing water impacts that are much more significant than climate change alone.

Drought and Tree Mortality. What are the exact physiological mechanisms that lead to tree death during prolonged drought and rising temperatures? These are the questions that scientists are trying to answer at a LANL research project called SUMO. SUMO stands for SUrvival/MOrtality study and it is the largest study of its kind in the world.

Carbon Cycling and Soil Metagenomics



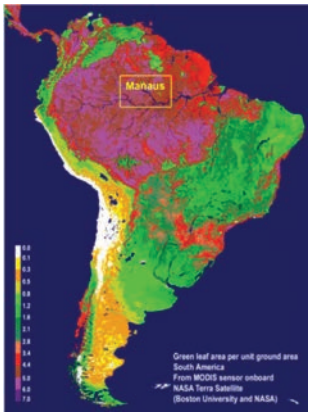
The DOE Office of Science's Biological and Environmental Research program addresses diverse and critical global challenges using Science Focus Area (SFA) teams. The team for Soil Metagenomics and Carbon Cycling is led by LANL and develops and uses community genomics approaches to link the biological processes controlling below-ground carbon storage and release to the community of microorganisms conducting those processes. The program's 10-year vision is to improve climate modeling and enable carbon management in terrestrial ecosystems by understanding the microbial and ecosystem factors that control carbon partitioning in soils. The collective studies span the molecular, cellular, microbial community, and ecosystem level scales. They look specifically at the roles that the microbial residents of soil play in northern temperate ecosystems, specifically comparing the drylands of the western U.S. to the hardwood and pine forests of the eastern U.S. Multiple environmental changes that may dramatically and permanently affect productivity and stability of temperate biomes are in play in the continental U.S. A major factor that is poised to alter dryland and forest biomes is anthropogenic nitrogen deposition to soils. The SFA is currently directed toward understanding the impacts of nitrogen deposition on cycling and retention of carbon in drylands and forest biomes.

Soil harbors an incredibly abundant (10^{10} cells per gram of soil) and diverse (over 100 thousand species per gram of soil) community of bacteria, fungi and other microbes, that are collectively responsible for nutrient uptake by plants and decomposition of plant biomass. The team has found that the resident microbial communities differ significantly in biomass and composition across shallow soil strata in both drylands and forests, where soil geochemistry changes across centimeter depth gradient. Microbial community activities in plant biomass decomposition, as well as carbon and nitrogen fixation, differ across these shallow depths, in response to nitrogen deposition, and in response to other climate change factors. The second research component of the SFA is to isolate and culture key fungal and bacterial members for intensive system-level study of metabolism and regulation, as single isolates and as members of defined mixed populations. In this way, we are able to gauge their carbon substrate preferences and relative contributions to carbon fixation and respiration under different soil nitrogen conditions.

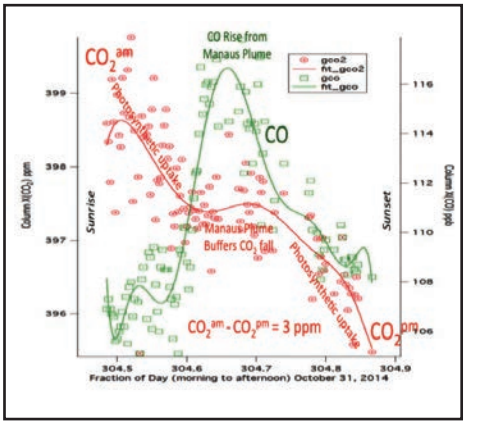
map of the continental U.S., showing two major biomes (western drylands and eastern forests). Dots indicate current field experiment locations.

Rainforest Response to Climate Change

As part of DOE's GOAmazon (Green Ocean Amazon) project, LANL is using a solar Fourier transform spectrometer (FTS) in Manaus, Brazil to measure atmospheric signatures of tropical rainforest photosynthesis (CO_2) and urban pollution (CO). The LANL FTS is p art of a global network & is the only station in the tropics. A key goal is to understand how pollutants are modifying photosynthetic CO_2 uptake by the Amazon rainforest.



Regional column CO_2 and CO daily variation. Photosynthetic draw-down by the Amazon and modulated by the Manaus plume.



Daily results show how CO from Manaus (green line) has reduced CO_2 uptake (red line) at the peak of the CO plume. Results are being used to test and improve models of how tropical rainforests will respond to climate change.

Goal 1: Develop and deploy hardware to collect novel and high-value observations

Identifying and interpreting climate signatures of value requires new signal detection hardware; computational and analytical techniques to extract information-rich signatures from complex multi-variable signal sets, and research, development, and application of prototype to mature signature assessment systems.

Los Alamos has a number of attributes that allow us to lead in this area, including strong capability in in situ and remote sensing technologies to measure climate-related signatures in the atmosphere, biosphere, and hydrosphere. We also have strong scientific capabilities that enable us to identify innovative climate signatures or indicators, and understand how climate signatures are processed or modified through earth systems, which will in turn establish LANL leadership in the identification of ecosystem tipping points and assessment of impacts for rare and extreme events.

Objective 1.1: In situ and remote sensing technologies for climate

Understanding the impact of human activities on climate in turn requires an understanding of how climate dynamics scale from the local level to the global. LANL can contribute to that understanding by building on our strong capability in remote sensing technologies to measure a broad spectrum of climate-related signatures. These techniques are necessary to understand fundamental climate processes as well as human activities and their impacts on climate.

Observations from in situ and remote sensors have distinct and complementary characteristics. Climate signatures may be unique to one or the other type of sensor; in other cases one sensor type can help to validate the other which can be important for upscaling or downscaling. In situ sensors provide direct measurements of quantities of interest at a point or on a fine local scale. LANL is at the forefront in developing field applications and analytical tools for this type of monitoring system with capabilities that include chemical, isotope, particulate, and microbial/genomic analyses.

Remote sensors offer aggregate measurements and can be available at scales of very fine to global. LANL is well known for its remote sensing hardware and data analysis tools primarily developed for defense and global security applications and more recently applied to environmental and climate applications. In conjunction with partners, we have established a series of test-beds and monitoring sites that are ideal for multiscale climate-related field measurements that facilitate full-cycle instrument/methods development, testing, and application.

Atmospheric samples and other measurements are being collected from research sites all over the world, like this one in the Chilean Andes, to better inform global climate science.

Objective 1.2: Climate signatures in earth systems

The core of the objective is to identify emerging signatures that will provide novel or unique climate information. Identifying innovative climate signatures and understanding how climate signatures are processed or modified through earth systems requires identifying the best multiscale climate state indicators. Examples include: identifying the most meaningful signatures of drought-induced tree mortality or shifts in atmospheric moisture sources and cycling, and monitoring key climate-related biogeochemical cycles such as carbon and nitrogen; and the relationship between soil moisture, biogeochemical processing, and vegetation growth. Novel isotopic, chemical, trace-gas, and microbial/genomic signatures offer great promise for addressing this objective and providing a detailed understanding of micro- to global-scale processes.

Measurements need to be made both in situ and remotely, and high-frequency sampling will often be

necessary to extract process-based knowledge of system behaviors. Extracting innovative climate signatures from multidata stream, high-resolution time series and remote sensing imagery data sets will require novel "big data" analysis methods. These methods include in situ data analysis, compression and transmission, as well as techniques to combine multivariable data streams and interrogate multidimensional data sets to find novel signatures of value to detect new processes, subtle changes in systems, tipping points, and ascribe emission attribution.

Objective 1.3: Identify tipping points and rare events

Among the most desirable and elusive capabilities is one that allows us to understand when a system is approaching a critical tipping point. Anticipating rare or extreme events and understanding their consequences allows preparation or mitigation in a manner not currently possible.

Three approaches are suggested to develop this capability. First, signatures can be extracted from a variety of paleoclimate records and analyzed to find past tipping points and the set of climate conditions leading to those transitions. The paleoclimate records may also be used to test the ability of ESMs to predict past tipping points.

Second, investigating signatures of rare or extreme events that have recently happened (e.g., large-scale mortality incidents) can help to identify precursor conditions or indicators that such events may be about to happen again. This approach will likely entail new ways of looking at signatures including combinations of different types of signatures. This objective is strongly linked to modeling described in Climate Goal 2, and thus will require integrated measurement and modeling approaches.

Third, sensitive and fast-responding ecosystems such as those in the Arctic and tropics may provide important insights on how other systems may shift as a result of new environmental forcings and change effects. Because of the relatively fast responses, these systems can also be used as test beds for developing and applying new climate signatures and models.

The Atmospheric Radiation Monitoring campaign deploys instrument packages around the world.

Novel instrumentation shows how trees react physiologically to stress.

Tree ring studies are one way the Laboratory studies seasonal variation and drought.

Goal 2: Integrate data, computation, and modeling

Climate science requires integrating observational data sets with analytic and computational models and then using these models to recommend observations and signatures that in turn increase the accuracy and reduce the uncertainty of analytical results. LANL has the opportunity to expand our leadership role in ocean, sea, and land ice; ecosystem and terrestrial dynamics; and hydrological modeling and computation; supporting related signatures of climate change. We can also explore the science of decadal prediction at global, regional, and local scales. Prediction requires understanding natural and anthropogenic variability and uncertainties. We should also be able to use climate model predictions to assist us in determining which observational data sets to pursue.

This model-driven experiments approach (ModEx) characterizes LANL. ModEx uses data from experiments and observations along with modeling results to iterate in two cycles. See figure. In the inner cycle, data (including parameters and their distributions and boundary and initial conditions) are used to drive simulations. The simulations are compared to data to verify that the models are correct and calibrate parameters provided to the model. Once complete, iterations of the outer cycle are taken, whereby the conceptual model is changed and the resulting predictions and implications of those changes are validated (or disqualified) by experiments and observations

Objective 2.1: Leadership in computational earth system models

Los Alamos will expand its leadership role in ocean, sea ice, land ice, ecosystem, and terrestrial dynamics, and hydrology modeling and computation. Models are required to understand the current state of the earth and to predict future changes. They can be empirical and model-specific phenomenology; or they can be advanced, computationally demanding, and physically based. Model development and computation is an enabling capability for understanding signatures of climate change in the past, present, and future.

Los Alamos has a key leadership role in several aspects of climate modeling. The Climate, Ocean, and Sea Ice Modeling (COSIM) program develops components of the DOE Accelerated Climate Model for Energy (ACME), and uses the predictive capabilities of this and the related U.S. Community Earth System Model to study the implications of climate change. Specific focus issues for predictive analysis include global and regional sea level rise; sea ice coverage in the polar regions; implications of changing climate to arid regions (including the southwestern U.S.) as well as tropical and Arctic regions; signatures of greenhouse gas (GHG) emissions and their implications; and ocean biogeochemistry components with emphasis on GHG exchange, ecosystem changes, and acidification. Other leadership modeling projects include the Amanzi model of terrestrial hydrology, and the Arctic Terrestrial Simulator supporting the study of tundra and high-latitude land dynamics.

Objective 2.2: Regional and decadal climate prediction

Decadal prediction at global, regional, and local scales requires understanding of natural and anthropogenic variability and prediction uncertainties. It is clear that the next frontiers of climate-change modeling and signatures analysis is moving to more refined scales, including predicting climate timescales spanning from seasonal to several decades, and at regional, 100-kilometers and smaller, spatial scales.

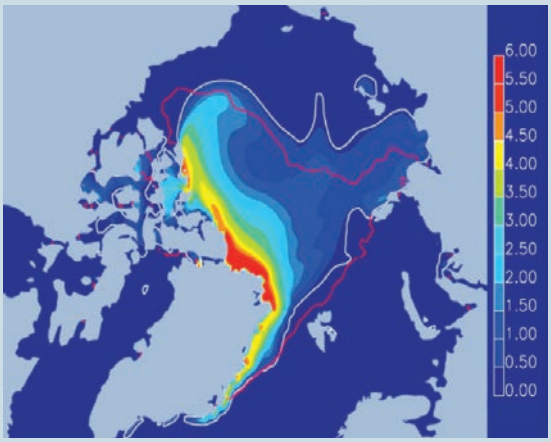
Decadal predictions are challenging because instead of capturing century-scale aggregate trends in the climate system, they must take into account short-term natural and anthropogenic forced variability. For components with a relatively long system memory such as ocean and land ice, a correct initial state is required. Regional spatial scales pose challenges to modeling, bridging relevant physical phenomenology and models at different characteristic scales. There are various strategies for making regional connections, including embedding regional models within the global model, forcing the regional model with the boundary conditions extracted from the global state, and developing models that use unstructured grids to “zoom in” on regional scales. The last is a main focus of the ACME model. A key aspect of producing predictions is

assessing and quantifying uncertainty. Decadal and regional prediction poses challenges in uncertainty quantification on top of those currently under study for global climate models.

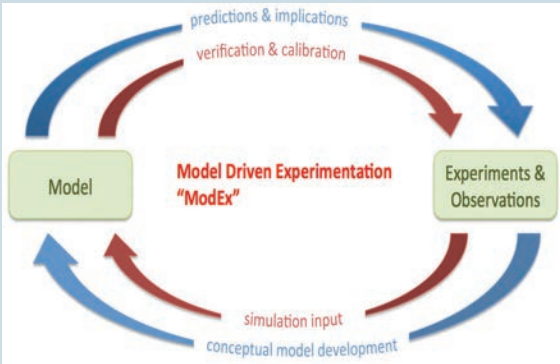
Capability in regional modeling and decadal-scale prediction are required to assess regional and local impacts. LANL has this scale capability in hydrology modeling. Most of the work has focused on Arctic and tundra hydrology, but the capability it is now being used to model tropical hydrology. We also lead development of the model prediction across scale (MPAS) next-generation ocean and ice models, which cross scales between global and regional modeling. Another focus area is modeling of sea level rise from melting land ice, which may interact with changing ocean circulation. LANL is also developing multiscale models with integrated observations of permafrost degradation and tropical tree mortality as part of the NGEE-Arctic and NGEE-Tropics projects that include coupled physical and biological processes to simulate large-scale shifts in carbon, water, and energy balances and their feedbacks to climate.

Objective 2.3: Apply model validation and uncertainty quantification

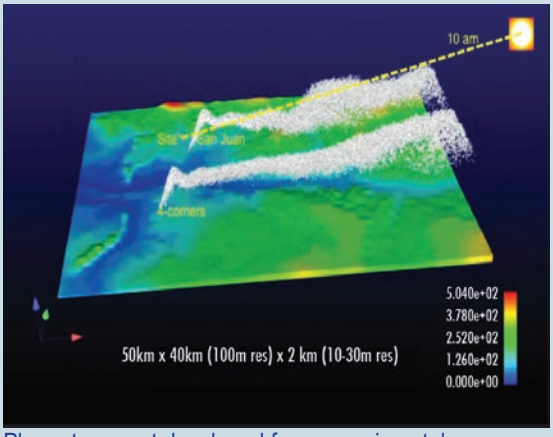
Techniques from model validation and uncertainty quantification indicate the reliability of model predictions and the value of observations to prediction accuracy. These results can then be used to establish the value of known and hypothetical observations, prioritize investment in model development, and guide the development of robust decisions. Particular focus areas include the quantification and propagation of uncertainties across scales, as well as the treatment of structural uncertainties within and between models. Uncertainty quantification is also important to the development of approximate models that can efficiently predict the response of the earth system under different scientific and socioeconomic assumptions, which is essential to translating complex simulation output into a form useful for the integrated assessment of climate change and its impacts to society. LANL is using uncertainty quantification to help identify sensitive ESM parameters for developing the observational framework of NGEE-Tropics as part of an integrated model/experiment (MODEX) approach.



Over the last 30 years, the area of thick multiyear Arctic sea ice in winter has declined by two-thirds as a result of climate change. The CICE model shows a minimum ice level.



ModEx uses an integrated, iterative approach that creates a feedback loop between models and experiments. Models improve experiments which are then used to improve models.



Plume transport developed from experimental measurements in the New Mexico Four Corners area.

Goal 3: Advise policy makers

Policy makers need decision support tools to help them decide the best way to develop sustainability and resilience plans for the next century. These tools and actions must be supported by robust measurements and validated models informed by measurements. Predictions of impacts on infrastructures and human populations may precipitate actions by regional, national, or international policy makers.

The overall goal of climate science and technology efforts within the national and international R&D communities is to model the Earth system, identify climate signatures, and actionably project future effects, particularly their impact on populations and infrastructure (e.g., energy). Comprehensive earth system models incorporate human activities including energy systems, land use, and feedbacks on changes in climate, water resources, and ecosystems. These efforts support the identification of policy options that are effective and robust with respect to system uncertainties.

Objective 3.1: Connect climate and impacts uncertainties across spatial and temporal scales

Climate change occurs globally but is experienced locally. Current-generation ESMs cannot resolve processes and impacts on scales smaller than about 100 kilometers, including the mesoscale weather systems that give rise to extreme climatic events such as storms and heat waves. The location of people and infrastructure can significantly affect vulnerability to climate change. For example, the future vulnerability of a coastal port to flooding during a hurricane or tropical depression depends on many phenomena at different scales, from local weather to global ocean and ice sheet dynamics. Likewise, the temporal scales of impacts (often days to months) and adaptation planning horizons (years to decades) are shorter than those targeted by climate models (decades to centuries). These issues challenge decision makers, but regional and multiscale climate modeling at scales at 10 kilometers and below, pioneered at LANL, can help to bridge the scale between climate and impacts. However, even with increased resolution, numerical model predictions have regional biases and errors in predictions of local extremes. Statistical downscaling methods incorporating historical site measurements are also needed to help compensate for model errors. Uncertainty quantification is required to apply global climate predictions to local impacts. These needs mandate new statistical methods to work with hierarchies of models and data.

Objective 3.2: Detect climate change vulnerabilities across spatial and temporal scales

Adaptation policies should be designed to strengthen resiliency, but we are currently unable to conduct stress tests to measure a local community's vulnerability to climate change. We do know that answers lie in the fact that local environmental, infrastructure and socioeconomic characteristics determine the degree of local vulnerability. LANL has unique capabilities in infrastructure modeling, economic analysis, and climate modeling that, if coupled with data collected by other agencies like NOAA and NASA, can effectively identify signatures of climate vulnerability across a wide spectrum of spatial areas, from cities to regions. Uncertainty quantification, furthermore, is essential in the measurement of the degree of vulnerability both because of the uncertainties derived from climate and of the ones derived by socioeconomic dynamics interacting with the infrastructure.

Objective 3.3: Apply Structural Health Modeling to climate-driven impacts

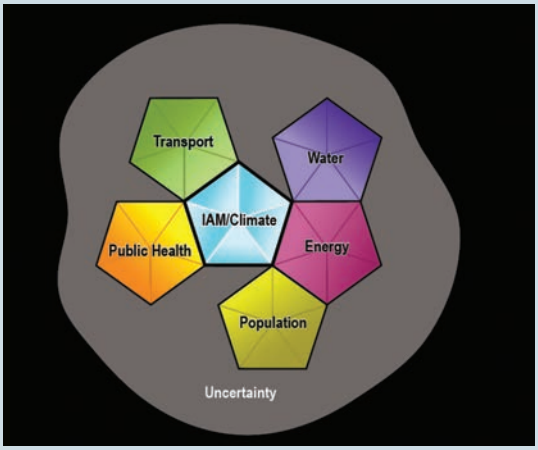
Infrastructure damage can be a climate-change-driven impact on economics and public health. Although there is considerable work occurring on how infrastructure impacts propagate to communities, there is less work on how shifts in local climate couple to infrastructure systems. Structural Health Monitoring could be used to generate the observational data needed to understand infrastructure system vulnerability

to the long-range effects of climate impacts on infrastructure components. Of particular interest are those systems that function in the potential mitigation of those impacts, such as flood walls, levees, and dams, and energy and transportation systems. LANL can leverage its expertise in Structural Health Monitoring and infrastructure analysis to provide a richer set of observational data and become a national leader in this area.

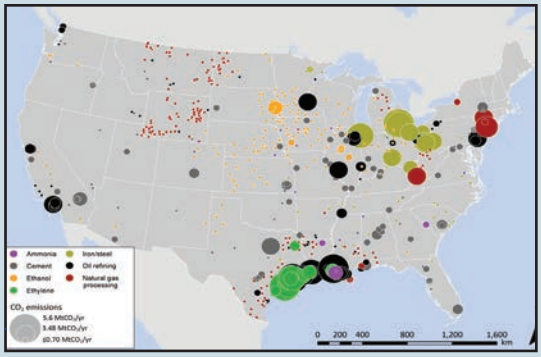
Objective 3.4: Develop integrated decision support capabilities

Integrated decision support capabilities developed in collaboration with stakeholders can greatly benefit problems of national and global security interest, such as coastal and energy critical infrastructure, hydrology and the energy-water nexus, Arctic issues, and climate/carbon geoengineering. Climate change has wide-ranging impacts cutting across many capabilities, including ecosystems and the environment, hydrology, energy security, and global security. LANL has expertise in Arctic, coastal, arid, and tropical environments. Many stakeholders invested in these environments could benefit from quantitative scientific-technical advice tailored to their particular decision problems. Problem domains include critical infrastructure vulnerability, Arctic transportation and resource competition, energy security; and global security risks associated with hydrologically vulnerable regions (e.g., transboundary water problems), and targeted interventions in the Earth system such as geoengineering capable of responding to impending dangerous 'tipping points'.

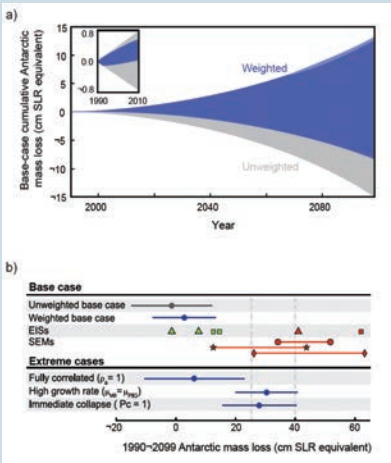
Integrated decision support capabilities for climate adaptation and resiliency planning are still in their infancy. Practical integrated impacts assessment will require the synthesis of advanced high-resolution ESM, uncertainty quantification and propagation from the earth system to impacts, robust decision analysis methods, and close interaction between earth science, decision science, engineering, and end-user communities.



Infrastructure simulations from Los Alamos help to determine economic and societal vulnerabilities of climate change.



Map of the contiguous U.S. shows the location of facilities that produce high-value chemicals/products and the amount of CO_2 emitted. (Middleton, et. al.,)



Quantifying uncertainty in sea level rise due to mass loss in the Antarctic ice sheet: (a) Uncertainty in future sea level rise over time due to ice loss from Antarctica in a warming climate. The analysis estimates the uncertainty in the acceleration of ice discharge to the ocean across different regions of the ice sheet. (b) Uncertainties calculated from an alternate set of assumptions and compared to other analyses.

Next Steps

Over the past two decades the scientific method has evolved from a close integration of experimental and theoretical sciences to include the computational and information sciences. In large measure this evolution has been driven by complexity of the science enterprise and by the sheer volume, velocity, and variety of data we now have the tools to acquire.

Making sense of this expanded scope in data requires sophisticated integration of computational sciences, simulation, and visualization with theory, modeling, and experiment. This powerful approach has been applied with great success in areas such as cosmology, nuclear physics, energy, and climate change. On a concrete level, our next steps as an organization will be to refine our internal strategy, build partnerships, and invest in the people, equipment, and capabilities required to make our plan a reality. The goals articulated in the previous sections will provide the framework for this process.

The Laboratory welcomes participation from internal groups, teams, and individuals and we are constantly seeking to build new partnerships with external organizations. Should you wish details on the various aspects of the plan mentioned here, please contact us.

Planning is an evolutionary process, which means that a detailed document is often obsolete as soon as it is printed. However, the broad strokes of a plan should not change frequently, and this overview of the Laboratory's intent for climate signatures research is intended to be general enough that it will remain serviceable for several years.

The Science of Signatures is overseen by the Chemistry, Life, and Earth Science (ADCLES) Directorate Office.

The full Science of Signatures strategic plan, of which this plan is a subset, is available from this office.

Chemistry, Life, and Earth Sciences Directorate Office
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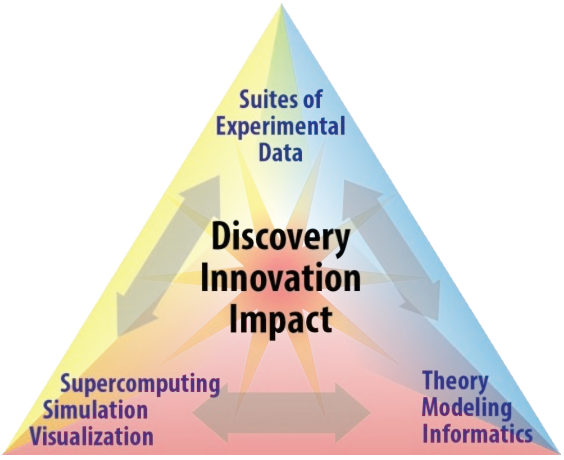

This document was generated by a subset of the Climate Signatures planning team. Primary authors are Brent Newman and Nathan Urban.

Document preparation by ADCLES communications team (Josh Smith).

An HVAC unit controls the atmosphere inside a large chamber to simulate drought stress at the SUMO site. SUMO stands for SUrvival/MOrtality study and it is the largest study of its kind in the world.

2016.

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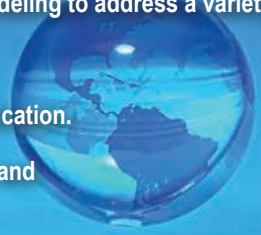
Climate Research at Los Alamos

Because of the ramifications for future generations, climate research must have a solid scientific foundation. At Los Alamos, we are building that foundation by developing signal detection systems that span from software to hardware. Our approaches strongly rely on integrating observational data with analytic and computational models. They help identify the most important aspects of climate systems for further study and measurement, and they target new signatures that may reveal important dynamics that are currently difficult to assess so that we can increase accuracy and reduce uncertainties in the predictions that come from our models. Our end goal is to provide practical, science-based decision support to managers and policy makers at local- to national-levels so that they have the right information to make the best decisions concerning climate policy and action.

At the heart of our approach is understanding and predicting critical controls on climate processes and mechanisms at multiple spatial and temporal scales. We use experiments and integrated observations and modeling to address a variety of climate-related issues, including



- Climate uncertainty quantification.
- Infrastructure vulnerability and planning.
- Atmospheric measurements of greenhouse gases and pollutants.
- Improved models of climate through massively parallel simulation capabilities and other advances in computational and measurement technologies.
- Modeling and quantifying changes in sea ice and permafrost landscapes and their feedback to climate.
- Development and deployment of mobile/portable multi-sensor platforms for measurements of chemical, isotopic, and energy balance signatures.
- Field/modeling studies of climate impacts in water-limited ecosystems.
- Impacts on surface water and groundwater systems, and the linkages between water and energy production.
- Development of better sensors and measurement technologies/approaches for climate studies including in situ and remote sensing systems.
- Development and application of tools for interpreting remotely sensed data including land surface classification and atmospheric chemistry.
- Microbial and metagenomics studies to understand effects of climate on nutrient cycling and soil ecosystems.

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