Introduction

Earth's Changing Climate

To explain the difference between weather and climate, scientists often say, "Climate is what you expect, weather is what you get." Climate is the weather of a particular region, averaged over a long period of time.[1] Climate is a fundamental factor in ecosystem health—while most species can survive a sudden change in the weather, such as a heat wave, flood, or cold snap—they often cannot survive a long-term change in climate. Global climate is the average of all regional trends, and researchers have concluded that Earth's climate, as a whole, is warming.

Researchers know that human activities including fossil fuel use, agriculture, and land use have been the dominant causes of increased concentrations of greenhouse gases in the atmosphere over the past 250 years. In addition, aerosols and land surface changes are altering Earth's climate, making it extremely likely[2] that human activities have had a net warming effect since 1750.[3] These human-caused changes to the climate system, and their consequences, provide much of the impetus for the National Science Foundation's (NSF) climate change research.

Researchers funded by NSF have discovered signs of a changing climate in nearly every corner of the globe, from the icy expanses of the polar regions of Earth to its equatorial ecosystems. Our planet's climate affects—and is affected by—the sky, land, ice, sea, life, and the people found on Earth. To

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1 More rigorously, climate is defined as the mean and variability of relevant quantities over a period ranging from months to thousands or millions of years. A 30-year period is frequently used for averaging these variables. Appendix I: Glossary. *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007.

2 According to the Treatment of Uncertainties in the Working Group I Assessment of the Intergovernmental Panel on Climate Change, 'extremely likely' corresponds to a likelihood of >95% probability. Solomon, S., et al. Technical Summary, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007 Cambridge University Press. Box TS.1

3 Solomon, S., et al. Technical Summary, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007. Cambridge University Press. pp. 81

piece together the entire puzzle of climate change—what we know, what we still have to learn and what humankind can do to prepare for the future—we must study all of the physical, natural, and human systems that contribute to, and interact with, Earth's climate system.

As researchers work together to solve the climate puzzle, they are revolutionizing the way we understand the Earth system as a whole. Researchers have realized that they must reach across disciplinary boundaries to study questions that extend beyond any one field of science or engineering. In fact, because of the complexity of Earth's climate, this research involves contributions from nearly every field of science, math, and engineering.

In no area is NSF's contribution more important—or more influential—than in interdisciplinary research. NSF responds to the needs of research communities by supporting teams that include experts from multiple disciplines. NSF is unique among other government agencies with a science mission because NSF funds research, infrastructure, and education across *all* disciplines of science and engineering.

With its emphasis on supporting pioneering research, NSF is well positioned to support the broad federal agency response to climate change. The basic research NSF funds is essential to creating a vibrant and strong foundation for the important work of the mission agencies that are responsible for the U.S. government's monitoring of, and response to, climate change and variability. Basic research underpins what we currently know about Earth's changing climate, and will continue to play a vital role in the discovery of new knowledge and the development of tools to help humankind respond to the effects of global climate change. NSF must maintain its steadfast support of the American academic system's groundbreaking research and world-class educational programs in order to continue providing the next-generation of people and ideas that will help the United States and the world meet the challenges imposed by global climate change.

Don Juan Pond, located in the Wright Valley of the Transantarctic Mountains of Antarctica. The McMurdo Dry Valleys are very sensitive to small variations in solar radiation and temperature. For this reason, the dry valleys area may well be an important natural regional-scale laboratory for studying responses to human alterations of climate. *Credit: Jenny Baeseman, University of Colorado; National Science Foundation*

NSF personnel and awardees regularly work with each other, other government agencies, and international organizations to strengthen the goals of climate change research and to identify the unanswered scientific questions. They participate in the U.S. Climate Change Science Program (CCSP) and have served as authors for its numerous Synthesis Assessment Product reports. NSF—the lead U.S. agency in Antarctic research—coordinates and facilitates the activities of NSF- and mission agency-supported research near both poles, areas where some of the most important observational data on global climate change are gathered.[4]

Scores of NSF-supported researchers, including over 40 researchers from the National Center for Atmospheric Research (NCAR)—an NSF-supported research facility and one of the nation's most important assets in climate research—have participated in the United Nations' Intergovernmental Panel on Climate Change (IPCC). Numerous NSF-funded researchers served in leadership roles in the latest IPCC assessment report, and they continue to make significant progress on the research goals identified in the report.

Basic research on the frontiers of mitigation and adaptation strategies, including geoengineering, is an NSF investment area that will become increasingly important in the coming years. NSF's emphasis on exploratory, potentially transformative, basic research makes the agency a natural leader in identifying the most promising strategies for mission agencies, corporations or other organizations to adopt and pursue. NSF's support of economic research, including emissions trading scenarios and the incorporation of economic theory into climate modeling, will help to inform government climate policy decisions.

4 NSF FY 2009 Budget Request to Congress

NSF investments have played a crucial role in our understanding of Earth's climate past, present, and potential future. From its inception, NSF has funded the research of climatologists including Charles David Keeling, whose data on increasing carbon dioxide concentrations in the atmosphere are considered pivotal early evidence in support of the hypothesis of anthropogenic climate change.[5] NSF funding through the decades has led to many of the most fundamental discoveries and advances in human knowledge about the causes and consequences of global climate change and variability. Paleoclimate records, computational climate models, and economic models of climate change are just some examples of the major contributions of NSF's investments in this area. In the future, as the world's human population turns its attention to managing and coping with the effects of climate change, NSF-funded basic research will continue to provide the necessary platform for technological advances, in areas including energy and geoengineering.

Putting the Pieces Together

The evidence we have for a changing planet goes well beyond any one field of science or engineering.

NSF-funded researchers are studying the impacts of climate change on the well-known annual cycle of the monarch butterfly. (e.g. NSF awards 0710343 and 0415340) *Credit: David Cappaert, Bugwood.org*

Ecologists have noted marked changes in the habitats of the species they study—changes in the places where they find a particular species, changes in the dates plants first sprout and bloom, changes in plant growth rates, and even signs of evolutionary adaptation brought on by a warming climate.[6]

Ocean scientists have recorded higher temperatures and rising ocean acidity, which alter the characteristics of the most fundamental organisms of the ocean food chain.[7] Coral reefs—some of which have thrived for centuries—have died off suddenly as a result of ocean temperatures that exceed the corals' ability to survive.[8]

Polar scientists have watched vast tracts of Arctic sea ice melt away, leaving behind more open water than anyone can remember seeing during any previous Northern Hemisphere summer.[9] Glaciologists have witnessed ice shelves—once thought too large to be influenced by anything short of cataclysmic environmental change—break up into a churning sea of icebergs in a matter of days.[10]

Social scientists have recorded the bewilderment of indigenous people. Their cultural knowledge, which stretches back in time through numerous generations, holds no record of the kinds of environmental changes they are encountering today.[11]

This image shows houses in Uummannaq, Greenland. According to Inuit hunter and town resident Pavia Nielsen, "Narwhal come two weeks later than past years because of global warming. The force of nature which always gives us a hard time in the form of a stronger and stronger wind is getting even harder because of the global warming. When the wind is so strong, it means less hunting." *Credit: Joseph Meehan and Narwhal Tusk Research*

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5 Weart, Spencer. *The Discovery of Climate Change*. www.aip.org/history/climate/Kfunds.htm

6 E.g. www.nsf.gov/news/news_summ.jsp?cntn_id=112093; www.nsf.gov/news/news_summ.jsp?cntn_id=105707; NSF Highlight 13082: Genetic Consequences of Climate Change; NSF Highlight 16828: Is There a Relationship between Global Climate Change and Flowering?

7 NSF Highlight 13239: Rising Ocean CO_2 Levels May Stimulate Nitrogen Fixation and Alter Ocean Biogeochemistry

8 www.nsf.gov/news/news_summ.jsp?cntn_id=108801

9 www.nsf.gov/pubs/2008/nsf0842/nsf0842_4.pdf

10 www.nsf.gov/od/lpa/news/02/pr0222.htm

11 ACIA, *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge University Press, 2004

Paleoclimatologists have discovered—through tree ring data, ice cores, and other corroborating records—that the concentration of carbon dioxide, and Earth's average temperature, are nearing levels that haven't been reached for hundreds of thousands of years.[12]

Innovative scientists and engineers have responded to the call for alternative energy sources that reduce the amount of carbon dioxide we put into the atmosphere. Computer scientists are creating new tools for geoscientists, decisionmakers, and the public to understand Earth's changing climate. Social scientists are studying human decisions and behaviors that influence the environment. By studying such issues as land use, urban planning, building design, and economic factors that are linked to anthropogenic climate change, researchers are beginning to tackle some of the more nuanced, but essential, questions regarding the human impact on, and response to, Earth's changing climate.

This report addresses some of the major questions facing climate change researchers, and how those puzzles are being addressed by NSF-funded activities. Complex computer models are being developed and refined to predict Earth's future climate. Observations of climate conditions from observatory networks distributed in Earth's oceans, polar regions, land masses, and near-Earth orbit improve the accuracy of the climate models. Records of Earth's past climate provide important insights into the mechanisms involved in climate cycles of the past, and can help to refine computational models by allowing researchers to simulate past climate. But understanding climate is only part of the story—as we improve our knowledge of how Earth's climate is changing, we also improve our ability to cope with the impacts of global climate change and variability. Through social, economic, and behavioral science, researchers are learning how human behavior factors into climate change—and how human behavior can be modified to ameliorate our impact on Earth's climate. Physical scientists and engineers are developing alternative ways of creating, storing, and using energy to reduce the amount of carbon that human activities contribute to the atmosphere. Researchers are also building the scientific foundation for the tools that humanity may need in the future to counteract the effects of global climate change.

Computational Tools

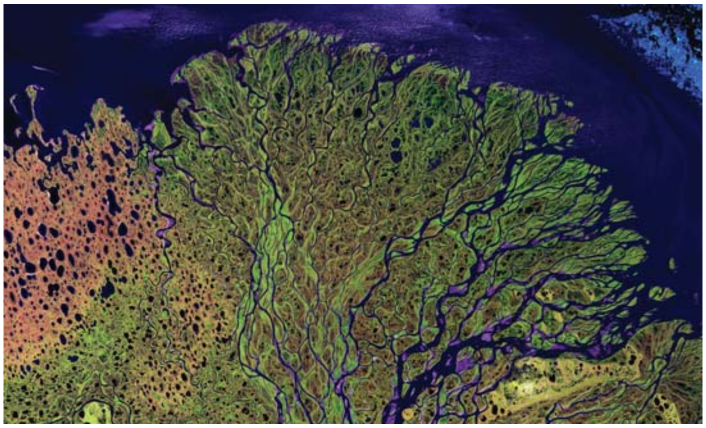
Predicting Earth's future climate depends on advanced computational hardware, software, and networking capabilities. Increasing demands on computational resources result from the increasing sophistication of the models, which are advancing to include an ever-expanding number of physical parameters of Earth's climate system. To keep up with the demand, computational hardware must involve not only bigger and faster supercomputers, but entirely new computer architectures—e.g. data centers that can process massive amounts of data in parallel—and new devices, including smart sensors, smart phones and robots to acquire data. To make the most effective use of the progress in hardware, reliable, advanced, and intelligent software will be essential. Increasingly sophisticated algorithms, new representations of data, and new programming models and languages are a handful of the types of software advances that will be required. New networking tools will not only connect computers and scientists, they will also be essential to acquiring data from remote sensors and instruments, such as satellites, buoys, and environmental sensor stations. As discussed in the following section, networked observational tools are vital to increasing our understanding of climate. They present computer scientists and engineers with the challenges of integrating vast quantities of data gathered across different platforms and network types.

Observational Networks

New observing, networking, and computational capabilities have expanded the horizons of what we can study and understand about our environment and world. Observational networks allow researchers to gather the data needed to create the climate models of the future and to learn more about how climate change is influencing Earth's plants and animals.

12 e.g. NSF Highlight 14727: Ancient Glaciers in Antarctica Key to Understanding Climate Change; NSF Highlight 16360: A Warming Climate Can Support Glacial Ice; NSF Highlight 14040: A Global Trigger for the Termination of the Last Glacial Maximum

In response to the growing demand for data from the research community, NSF is expanding its observational network infrastructure. Some of these networks, including the National Ecological Observatory Network (NEON) and the Ocean Observatories Initiative (OOI), are new, state-of-the-art efforts in collaboration with international partners. These networks take advantage of the latest in cyberinfrastructure and computational linking technologies, one of NSF's core strengths. Other observatories, such as the Critical Zone Observatories, are in their infancy, but provide crucial testing grounds for the observational methods of the future.



NSF-funded researchers are studying the impact that warming temperatures have on Arctic watersheds such as the Lena River. The Lena River Delta is a breeding ground for many species of Siberian wildlife. *Credit: USGS EROS Data Center Satellite Systems Branch*

NSF works in partnership with other government agencies and international organizations on observational infrastructure, including systems that monitor the planet as a whole. The Global Earth Observation System of Systems (GEOSS) is one example of an interagency and international effort to enable coordinated observations, better data management, and increased data sharing.[13] By providing ground-based observations that complement satellite data, NSF participates in National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and U.S. Geological Survey (USGS) satellite-based observation programs.

Climate change knows no national boundaries, and its earliest devastating impacts may occur in developing regions of the world. The science of climate change is inherently an international endeavor; the size and scope of the scientific challenge it presents requires a global effort. NSF actively encourages international cooperation between U.S. researchers and their colleagues abroad.

Solving the Puzzle

We are currently experiencing perhaps the most rapid acceleration in humanity's understanding of our planet. The knowledge gained from the frontiers of basic research—particularly crosscutting, interdisciplinary research—will be essential to creating the decision support systems needed to manage society in the future.

This report will discuss Earth's systems piecewise, beginning with the physical systems of Earth's atmosphere, sea, land, and ice, then focusing on life on Earth, and ending with, perhaps, the most challenging and dynamic piece of all—people. It's important to realize that all of the pieces of the climate puzzle are interconnected, and all of the pieces are necessary to gain a full understanding of climate variability and change. Several key programs and research areas are featured in the main body of the text and a selection of research highlights are included in each section. These highlights are meant to give an idea of the breadth and depth of NSF's portfolio of climate change research investments, but are *far* from being an exhaustive list. Each year, NSF funds thousands of research projects, from short-term, single investigator, exploratory grants to large centers and facilities dedicated to long-

Rice paddy, Bali, Indonesia. Agricultural practices have a significant impact on the global carbon balance. *Credit: © 2009 JupiterImages Corporation*

13 National Science Board, *International Science and Engineering Partnerships* NSB 08-4, pp. 23

term research and environmental observation. Many of these projects touch on some aspect of Earth's climate system, and still others are building the foundation for entirely new ideas that will transform the climate change research of the future.

Just as Vannevar Bush and the other visionaries who turned the idea of a National Science Foundation into reality in 1950 could not have predicted the specific impact of computers and networking on science and engineering, we cannot know exactly what future technologies will bring to climate change research and mitigation and adaptation strategies. But we know we're following a proven model for success.