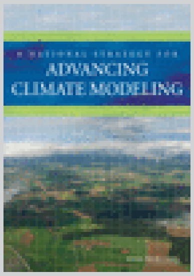

A National Strategy for Advancing Climate Modeling

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Preface

Global warming is a pivotal environmental and social issue of the 21st century. Its long time scales, diverse consequences, and direct ties to our global energy-production infrastructure make it challenging for societies around the world to grapple with and threaten humanity's ability to mount an effective response. This challenge is compounded by the complexity of the Earth-human system. The fundamental science of greenhouse gas-induced climate change is simple and compelling. However, genuine and important uncertainties remain (e.g., the response of clouds, ecosystems, and the polar regions) and need to be considered in developing scientifically based strategies for societal response to climate change.

As in most other areas of science and engineering, over the past 50 years, large numerical models have become an indispensable tool for climate science. They allow increased knowledge of individual physical processes to feed into better system-level simulations, which can be tested with observations of the system as a whole—not unlike simulating a new airplane design and testing it in a wind tunnel. Climate simulations benefit from using a finer mesh of grid points and include more interacting Earth-system processes; this requires the largest computers that scientists can obtain. The efficient use of large computers and the large data sets they develop requires increased support for software design and infrastructure—a major thread running through this report.

Climate modeling began in the United States. The United States continues to support a diversity of regional and global climate modeling efforts, now embedded within a vigorous international climate modeling scene. A rapidly expanding applications community is using climate model outputs for informing policy decisions and as input to other models and demands more detailed and reliable information. Increasingly, the needs of this community, as much as basic scientific questions, are driving the climate modeling enterprise in the United States and abroad.

As models, computing needs, and user needs become more complex, the U.S. climate modeling community will need to collaborate more tightly internally and with its users in order to be effective. Recognizing national traditions of multiagency funding and encouraging diversity and creativity, our long-term strategic vision emphasizes the nurturing of self-governance structures that reach between current climate modeling efforts, coupled with investment in cutting-edge computing infrastructure of which a more unified climate modeling enterprise can take full advantage.

We would like to thank the numerous members of the climate modeling community who generously gave of their time to provide input during this study process. In particular, we would like to thank all of the speakers, workshop participants, interviewees, and reviewers (listed in the Acknowledgments). Finally, we would like to thank the National Research Council staff, without whom this report would not have been possible: Katie Thomas, Rob Greenway, Rita Gaskins, April Melvin, Alexandra Jahn, and Edward Dunlea.

Chris Bretherton, *Chair*
Committee on a National Strategy for
Advancing Climate Modeling

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Eric Barron, Florida State University, Tallahassee
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Andrew Weaver, University of Victoria, British Columbia, Canada
Richard N. Wright, Practice, Education and Research for Sustainable Infrastructure, Washington, D.C.

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the views of the committee, nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. Robert Frosch, Harvard University, appointed by the NRC Report Review Committee, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

Contents

APPENDIXES

Summary

Information about climate[1] is used to make decisions every day. From farmers deciding which crops to plant next season to mayors in large cities deciding how to prepare for future heat waves, and from an insurance company assessing future flood risks to a national security planner assessing future conflict risks from the impacts of drought, users of climate information span a vast array of sectors in both the public and private spheres. Each of these communities has different needs for climate data, with different time horizons (see Box S.1) and different tolerances for uncertainty.

Over the next several decades, climate change and its myriad consequences will be further unfolding and possibly accelerating, increasing the demand for climate information. Society will need to respond and adapt to impacts, such as sea-level rise, a seasonally ice-free Arctic, and large-scale ecosystem changes. Historical records are no longer likely to be reliable predictors of future events; climate change will affect the likelihood and severity of extreme weather and climate events, which are a leading cause of economic and human losses with total losses in the hundreds of billions of dollars over the past few decades.[2]

Computer models that simulate the climate are an integral part of providing climate information, in particular for future changes in the climate. Overall, climate modeling has made enormous progress in the past several decades, but meeting the information needs of users will require further advances in the coming decades.

In an effort to improve the United States' capabilities to simulate present and future climate on local to global scales and at decadal to centennial time scales, the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration, the Department of Energy, the National Science Foundation, and the intelligence community requested that the National Research Council (NRC) produce a strategic framework to guide progress in the nation's climate modeling enterprise over the next 10-20 years. In response, the NRC appointed the Committee on a National Strategy for Advancing Climate Modeling with the task to engage key stakeholders in

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[1] Climate is conventionally defined as the long-term statistics of the weather (e.g., temperature, precipitation, and other meteorological conditions) that characteristically prevail in a particular region.

[2] Total losses from weather- and climate-related disasters are estimated to exceed $700 billion for the time period of 1980-2009 and to exceed $50 billion in 2011 alone from the more than 14 weather- and climate-related disasters in that year. See http://www.noaa.gov/extreme2011 (accessed October 11, 2012).

BOX S.1 INFORMATION FROM CLIMATE MODELS

Climate models skillfully reproduce important, global- to continental-scale features of the present climate, including the simulated seasonal-mean surface air temperature (within 3°C of observed [IPCC, 2007c], compared to an annual cycle that can exceed 50°C in places), the simulated seasonal-mean precipitation (typical errors are 50 percent or less on regional scales of 1,000 km or larger that are well resolved by these models [Pincus et al., 2008]), and representations of major climate features such as major ocean current systems like the Gulf Stream (IPCC, 2007c) or the swings in Pacific sea-surface temperature, winds, and rainfall associated with El Niño (AchutaRao and Sperber, 2006; Neale et al., 2008). Climate modeling also delivers useful forecasts for some phenomena from a month to several seasons ahead, such as seasonal flood risks (Figure 1).

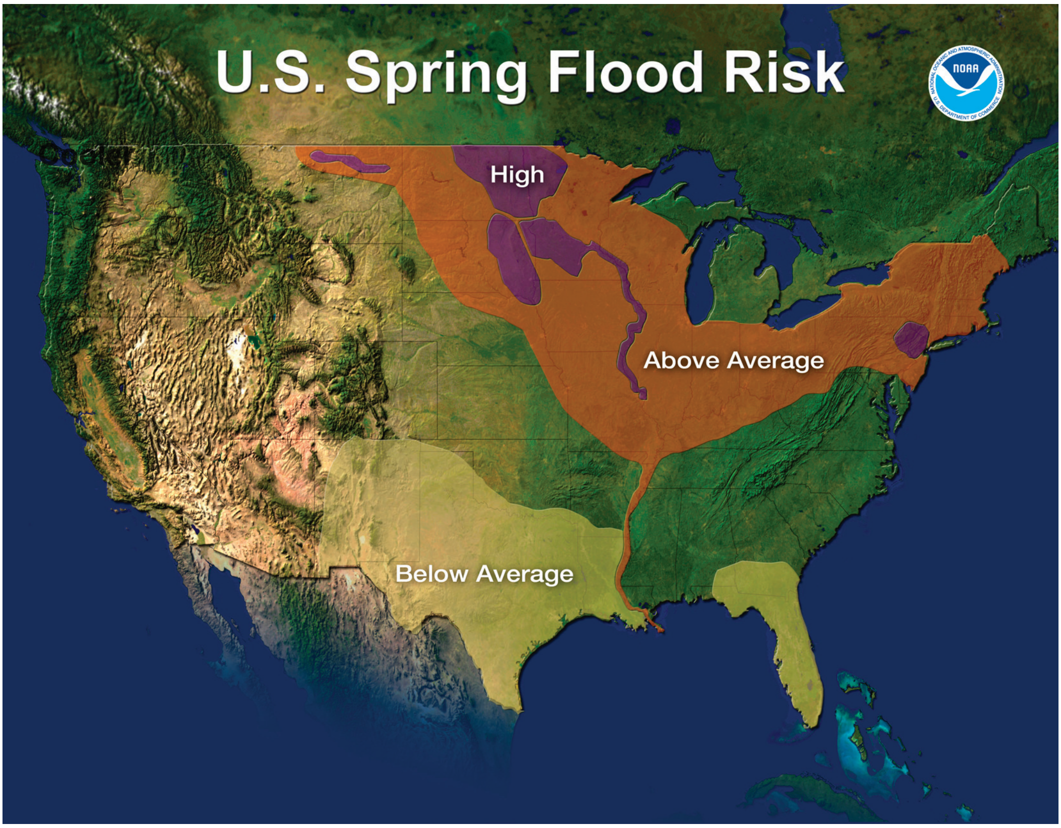


FIGURE 1 Climate models can deliver useful forecasts for some phenomena a month to several seasons ahead, such as this spring flood risk outlook from NOAA's National Weather Service for 2011. See Chapter 1 for more details. SOURCE: http://www.noaa.gov/extreme2011/mississippi_flood.html (accessed October 11, 2012).

BOX S-1 CONTINUED

Beyond these advances, however, the climate modeling community aspires to make substantial further progress in the quality of climate projections, especially on regional space scales and decadal time scales, to deliver the types of climate projections with sufficient resolution and accuracy needed by users. For example, Figure 2 shows projected changes to water runoff for later this century.

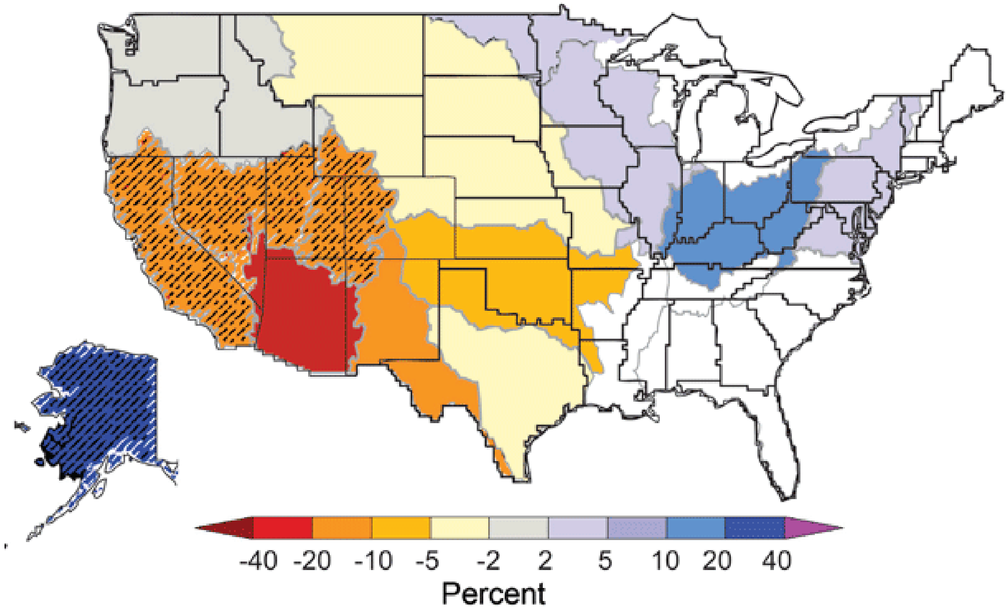


FIGURE 2 Longer-time-scale climate projections can assist in long-term planning. The figure shows projected changes in annual average runoff by the middle of the 21st century. See Chapter 1 for more details. SOURCE: USGCRP, 2009.

a discussion of the status and future of climate modeling in the United States over the next decade and beyond; to describe the existing landscape of domestic and international climate modeling efforts; to discuss, in broad terms, the observational, basic, and applied research, infrastructure, and other requirements of current and possible future climate modeling efforts; and to provide conclusions and/or recommendations for developing a comprehensive and integrated national strategy for climate modeling over the next decade and beyond (see Appendix A for the statement of task and Box S.2 for a description of the committee's activities).

A NATIONAL STRATEGY FOR ADVANCING CLIMATE MODELING

The U.S. climate modeling community is diverse and contains several large global climate modeling efforts and many smaller groups running regional climate models. As a critical step toward making more rapid, efficient, and coordinated progress, the committee envisions an evolutionary change in U.S. climate modeling institutions away from developing multiple completely independent models toward a collaborative approach. A collaborative approach does not mean only one center of modeling; rather it means that different groups pursue different niches or methodologies where scientifically justified, but within a single common modeling framework in which software, data standards and tools, and even model components are shared by all major modeling groups nationwide. An overarching thread of the committee's vision is to promote unification of the decentralized U.S. climate modeling enterprise—across modeling efforts, across a hierarchy of model types, across modeling communities focused on different space and time scales, and across model developers and model output users.

BOX S.2 THE COMMITTEE'S REPORT PROCESS

The committee held five information-gathering meetings over the course of a year, including a large community workshop, to interact with a range of stakeholders from government labs, federal agencies, academic institutions, international organizations, and the broad user community. The committee examined previous reports on how to improve climate modeling in the United States and interviewed key officials and scientists (see Appendix B for a complete list) to help draw lessons from these reports. The charge to the committee emphasized decadal to centennial time scales, but because of the overlap of issues between decadal and intraseasonal to interannual (ISI) time scales, as well as the potential benefits of testing climate models at shorter time scales, the committee believed it was important to extend the focus of the report to shorter time scales, including ISI time scales.

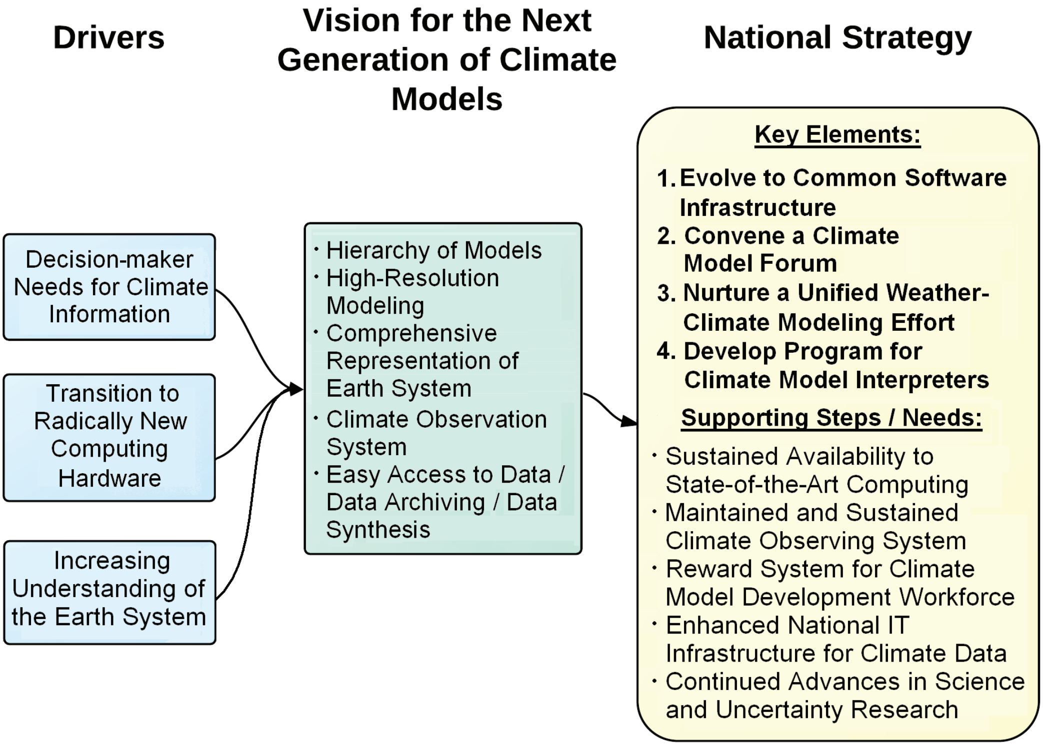


FIGURE S.1 Driven by the growing need for climate information and the coming transition to radically new computing hardware, a new generation of climate models will be needed to address a wide spectrum of climate information needs. A national strategy consisting of four key unifying elements and several other recommendations can help to achieve this vision.

The committee recommends a national strategy for advancing the climate modeling enterprise in the next two decades, consisting of four main new components and five supporting elements that, while less novel, are equally important (Figure S.1). The nation should

1. Evolve to a common national software infrastructure that supports a diverse hierarchy of different models for different purposes, and which supports a vigorous research program aimed at improving the performance of climate models on extreme-scale computing architectures;
2. Convene an annual climate modeling forum that promotes tighter coordination and more consistent evaluation of U.S. regional and global models, and helps knit together model development and user communities;

3. Nurture a unified weather-climate modeling effort that better exploits the synergies between weather forecasting, data assimilation, and climate modeling; and
4. Develop training, accreditation, and continuing education for "climate interpreters" who will act as a two-way interface between modeling advances and diverse user needs.

At the same time, the nation should nurture and enhance ongoing efforts to

5. Sustain the availability of state-of-the-art computing systems for climate modeling;
6. Continue to contribute to a strong international climate observing system capable of comprehensively characterizing long-term climate trends and climate variability;
7. Develop a training and reward system that entices the most talented computer and climate scientists into climate model development;
8. Enhance the national and international information technology (IT) infrastructure that supports climate modeling data sharing and distribution; and
9. Pursue advances in climate science and uncertainty research.

The elements of this strategy are described in more detail below. If adopted, this strategy provides a path for the United States to move forward into the next generation of climate models to provide the best possible climate information for the nation.

ELEMENTS OF A NATIONAL STRATEGY FOR ADVANCING CLIMATE MODELING

Evolve to Shared Software Infrastructure

The entire climate modeling enterprise is computationally intensive. Over the past 15 years, major climate modeling groups have been forced to devote increasing attention to software engineering. One catalyst was a disruptive hardware transition in the late 1990s from vector to parallel supercomputing. It was viewed with trepidation but the climate modeling community adapted well, in part by moving toward common software infrastructure for basic operations like data regridding and coupling between model components.

All indications are that increases in computing performance through the next decade will arrive not in the form of faster chips, but by connecting far more of them, requiring new approaches optimized for massively parallel computing and customized to particular computer designs. A renewed and aggressive commitment to innovatively designed common infrastructure across the U.S. climate and weather modeling communities is needed to successfully navigate this transition without massive duplication of effort that greatly slows overall progress.

This idea of a common software infrastructure is not new or controversial. More than a decade ago, approaches such as the Earth System Modeling Framework were pioneered for this purpose and have become influential and fairly widely used, but no one approach has become a nationally adopted standard. Individual U.S. modeling centers have developed different forms of such infrastructure, upon which they now depend, and have learned from those experiences.

Now is the time to aggressively develop a new common software infrastructure to be adopted across all major U.S. climate modeling efforts. Such an infrastructure could be an important tool in facilitating a more integrated plan for U.S. climate modeling. The committee's vision is that, in a decade, all major U.S. climate models—global and regional—will share a single common software infrastructure that allows interoperability of model components (e.g., atmosphere, land, ocean, or sea ice), even when developed by different centers, and that supports a common data interface. The proposed infrastructure would

- facilitate the migration of models to new, possibly radically different computing platforms (Figure S.2);
- support a research effort to develop high-end global models that execute efficiently on such platforms, enabling cloud-resolving atmospheric resolutions (~2-4 km) and eddy-resolving ocean resolutions (~5 km) within as little as a decade;
- allow centers to easily share model components and design hierarchical model frameworks with individual components simplified or specialized as needed for applications such as paleoclimate or weather forecasting and data assimilation (Figure S.2 and Box S.3);
- allow the academic community, other external modeling groups, and core modeling centers to work together more easily, because different model configurations could be run using very similar scripts; and
- harmonize outputs and file structures from all models, benefiting the model analysis and applications communities.

Decades of experience have shown that a full palette of modeling tools—a "model hierarchy"—is required across various scales and with different degrees of complexity with respect to their representation of the Earth system. The common software infrastructure is envisioned as a tool for linking together a model hierarchy, making it portable to a variety of computer architectures and user friendly for education, aca-

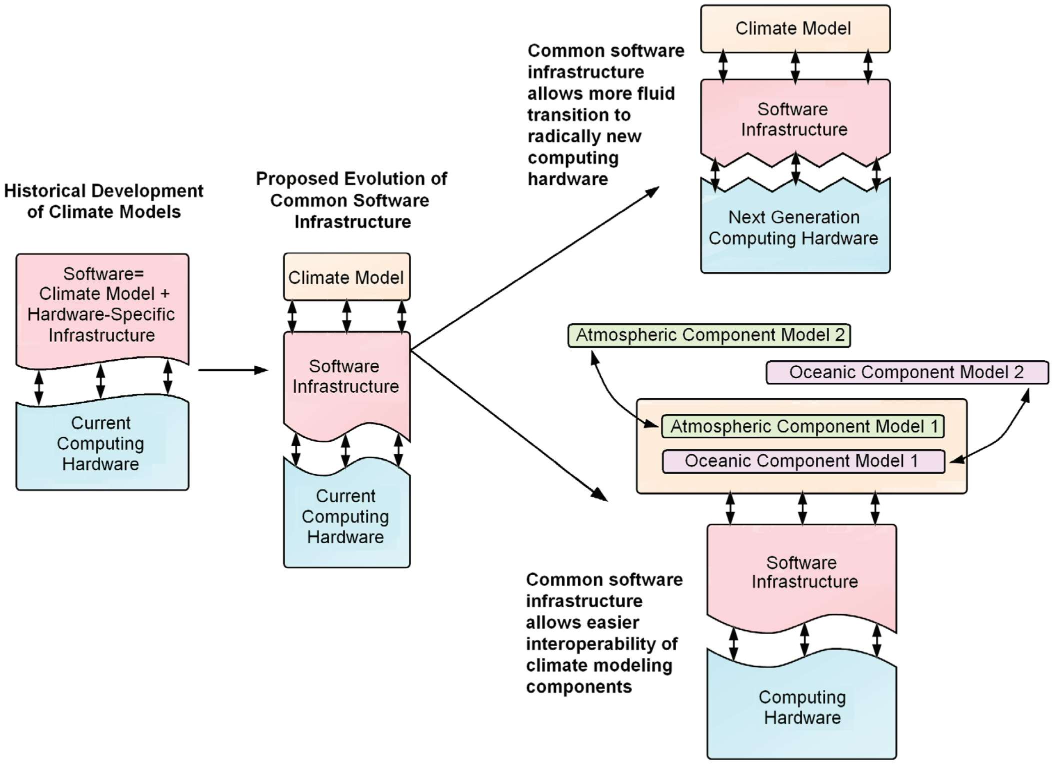


FIGURE S.2 The development of a common software infrastructure that interfaces between the climate modeling computer code and the computing hardware has two important advantages: (1) it will facilitate the migration of models to the next generation of computing platforms by isolating the climate modeling computer code from the changes in hardware and (2) it will allow the interoperability of climate model components, for example to enable the testing of two different atmospheric component models, without having to adapt the component models to different hardware platforms.

demic research, and exploratory science. Within this hierarchy, potential new modeling and evaluation approaches can be tested and compared, and improvements from one type of model can be easily transitioned to other models. It is a manageable investment (at least on a national scale) to carefully design, document, and refine one software infrastructure, and once users have learned it, their experience is transferable to using other model configurations and their output data structures. The committee recommends a community-based design and implementation process for achieving a national common software infrastructure. Although this goal has risks, costs, and institutional hurdles, the committee believes they are far outweighed by its benefits.

BOX S.3 SOFTWARE INFRASTRUCTURE ANALOGY TO OPERATING SYSTEM ON A SMARTPHONE

The software infrastructure described in this report can be thought of as similar to the operating system on a smartphone. The software infrastructure is designed to run on a specific hardware platform (analogous to a specific phone), and climate modelers develop model components (analogous to apps) to run in the software infrastructure to simulate parts of the climate system such as the atmosphere or ocean.

Currently, different modeling centers in the United States have different software infrastructures (operating systems) that run on different pieces of hardware; this is similar to comparing the iPhone to the Android. This means that climate model components (apps) written for one software infrastructure will not work with another (similar to how iPhone apps will not work directly on an Android).

Ultimately, the vision is that the U.S. modeling community could evolve to use the same common software infrastructure (operating system), so that model components (apps) could be interchanged and tested versus one another directly. This would also mean that when the hardware (phone) advances, the software infrastructure (operating system) can be updated to continue to work with the new hardware without having to completely rewrite the climate model components (apps).

The common software infrastructure alone will not allow climate models to take full advantage of the advances in computation of the next 10-20 years. A vigorous research program is needed to improve the performance of climate models on the highly concurrent computer architectures that will be the way forward in the coming decade. The common infrastructure will facilitate the sharing of such an advance across models and modeling centers and thus support this national effort to push the computational frontiers of climate science.

Convene a National Climate Modeling Forum

To help bring together the nation's diverse and decentralized modeling communities and implement the new common software infrastructure, the committee recommends the establishment of an annual U.S. climate modeling forum in which scientists engaged in both global and regional climate model development and analysis from across the United States, as well as interested users, would gather to focus on timely and important cross-cutting issues related to U.S. climate modeling. While modelers can learn about each other's progress at conferences and through scholarly journals, this can be slow, haphazard, and inefficient. The goal of the proposed forum is to promote better coordination among scientists involved in major global and regional modeling efforts across the United States and the user, applications, and analysis communities. These forums could

- serve as a mechanism for informing the community of the current and planned activities at the core modeling centers;
- provide a venue for fostering important interactions among scientists in the core modeling efforts and those at other institutions, including universities;
- facilitate a more coordinated approach to global and regional model development and use in the United States, including the design of common experiments using multiple models and the formation of joint development teams;
- provide an important vehicle to enhance and accelerate communication among climate modeling groups at research and operational modeling centers;
- offer an opportunity to facilitate the development and implementation of a shared national software infrastructure through sustained, regular interactions between the infrastructure software developers and model developers and users;
- offer a vital opportunity for end users of climate model information to both learn about the strengths and limitations of models, and provide input to modelers on the critical needs of end users that could feed back into the model development and application process; and
- provide an opportunity for regular broad-based discussion of strategic priorities for the national climate modeling enterprise.

The development of this approach would benefit greatly from additional resources specifically targeted to such integrative activities, and from support from a strong coordinating institution to integrate activities across multiple agencies. Organizations such as the American Meteorological Society (AMS), the American Geophysical Union (AGU), or the World Climate Research Program could in theory serve this role, but the U.S. Global Change Research Program might be a natural choice for organizing the forum given its mission to coordinate climate research activities in the United States.

Nurture a Unified Weather-Climate Modeling Effort

Unified weather-climate prediction models are increasingly an important part of the spectrum of climate models. Testing a climate model in a "weather forecast" mode, with initial conditions taken from a global analysis from a particular time, allows evaluation of rapidly evolving processes such as cloud properties that are routinely observed. Such simulations are short enough to test model performance over a range of grid resolutions relevant not only to current but also to prospective climate simulation capabilities. Transitioning to a unified weather-climate prediction approach is a major effort that requires substantial infrastructure. This approach is being successfully used by the UK Met Office, a leading international modeling center. In the United States, no weather or climate modeling center has yet fully embraced this philosophy, though several centers have some capability for weather forecasting, climate simulation, and data assimilation.

The committee recommends an accelerated national modeling effort that spans weather to climate time scales. One method to achieve this would be nurturing at least one U.S. unified weather-climate prediction system capable of state-of-the-art forecasts from days to decades, climate-quality data assimilation, and reanalysis. This prediction system would be but one effort within the U.S. climate modeling endeavor. It would be most effective if it involved a collaboration among operational weather forecast centers, data assimilation centers, climate modeling centers, and the external research community, which would need to work together to define a unified modeling strategy and initial implementation steps. To facilitate cross-fertilization with other climate modeling efforts, this effort should take advantage of the common software infrastructure and community-wide code and data accessibility described in the rest of this committee's strategy. Its success would be judged by simultaneous improvement of forecast skill metrics on all time scales.

Develop a Program for Climate Model Interpreters

By improving climate models, the scientific community has made considerable progress in the past decades in its capability to project future climate and its impacts. Nonetheless, important details about future climate remain uncertain. Simultaneously, addressing the wide spectrum of user climate information needs is outpacing the limited capacity of people within the climate modeling community. Effective communication about climate change and its uncertainty to science managers and decision makers is a crucial part of advancing our national climate modeling capability. There is no simple formulaic way to communicate uncertainty; as climate models and their available outputs become more sophisticated, those looking to use this information struggle to keep up.

Climate information is already being provided by a number of public and private entities in various capacities, and there have been numerous other calls for the provision of more extensive government-run climate information services. The committee chose to not weigh in on the debate about the appropriate role for the federal government in providing climate services. Rather, the committee notes the need for qualified individuals who can provide credible information to end users based on current climate models, wherever they work.

To address this need, the committee recommends developing a national education and accreditation program for "climate model interpreters" who can take technical findings and output from climate models, including quantified uncertainties, and use them in a diverse range of private- and public-sector applications. The education component could be a degree or certificate program offered by universities with adequate expertise in climate science and modeling, and the accreditation could be through a national organization that has a broad reach and is independent of any agency or modeling center, such as the AMS or the AGU. The training of climate interpreters is not envisioned as the solution to address all user needs for climate information, but rather as a crucial step that benefits any system for any of the various mechanisms that bridge the climate modeling and user communities.

Supporting Recommendations

Sustain State-of-the-Art Computing Systems for Climate Modeling

Climate simulation is difficult because it involves many physical processes interacting over a large range of space and time scales. Past experience shows that increasing the range of scales resolved by the model grid ultimately leads to more accurate models and informs the development of lower-resolution models. Therefore, to advance climate modeling, U.S. climate science will need the best possible computing platform and models.

The committee recommends a two-pronged approach that involves the continued use and upgrading of dedicated computing resources at the existing modeling centers, complemented by research into more efficient exploitation of the highly concurrent computer architectures that are expected in the next 10-20 years.

The community has been able to exploit other extreme-scale computing facilities that are not solely dedicated to climate as resources of opportunity. Continuing to do so will likely prove useful, but access to these external systems can be unreliable, and they often have operating protocols that are not suited to the very long simulations often needed for climate models. The committee debated whether the current combination of institution-specific computing and use of external computer resources of opportunity was the best national strategy for climate computing. The pros and cons of a national climate computing facility were weighed, and it was concluded that such a facility would be beneficial only if it were created in addition to the current computing capabilities at the modeling centers. An expensive new national climate computing facility would be most attractive and least risky in an environment of sustained budget growth for climate science and modeling, which would allow it to be pursued in parallel with other critical investments in climate modeling.

Continue to Contribute to a Strong International Climate Observing System

Observations are critical for monitoring and advancing understanding of the processes driving the variability and trajectory of the climate system. The evaluation and improvement of climate and Earth system models is thus fundamentally tied to the quality of the observing system for climate. A national strategy for climate modeling would be incomplete without a well-maintained climate observing system capable of comprehensively characterizing long-term climate trends and climate variability. Maintaining a climate observing system is an international enterprise but requires strong U.S. support that has come under serious threat. Over the next several decades, it is imperative to maintain existing long-term data sets of essential climate variables, in tandem with innovative new measurements that illuminate Earth system processes that are still poorly characterized.

Develop a Training and Reward System for Climate Model Developers

Model development is among the most challenging tasks in climate science, because it demands synthetic knowledge of climate physics, biogeochemistry, numerical analysis, and computing environments as well as the ability to work effectively in a large group. The committee recommends enticing high-caliber computer and climate scientists to become climate model developers using graduate fellowships in modeling centers, extended postdoctoral traineeships of 3-5 years, and rewards for model advancement through clear well-paid career tracks, institutional recognition, quick advancement, and adequate funding opportunities.

Enhance the National IT Infrastructure That Supports Climate Modeling Data Sharing and Distribution

The growth rate of climate model data archives is exponential, and maintaining access to these data is a growing challenge. Observational data about the Earth system are also becoming much more voluminous and diverse. The climate research community, decision makers, and other user communities desire to analyze and use both types of data in increasingly sophisticated ways. These trends imply growth in resource demands that cannot be managed in an ad hoc way. Instead, the data-sharing infrastructure for supporting international and national model intercomparisons and other simulations of broad interest—including archiving and distributing model outputs to the research and user communities—should be systematically supported as an operational backbone for climate research and serving the user community. Beyond stabilizing support for current efforts, the United States should develop a national IT infrastructure for Earth system climate observations and model data that builds from existing efforts, so as to facilitate and accelerate data display, visualization, and analysis both for experts and for the broader user community. Without substantial research effort into new methods of storage, data dissemination, data semantics, and visualization, all aimed at bringing analysis and computation to the data, rather than trying to download the data and perform analysis locally, it is likely that the data might become frustratingly inaccessible to users.

Pursue Advances in Climate Science and Uncertainty Research

To meet the national need for improved information and guidance over the coming decades, U.S. climate models will have to address an expanding breadth of scientific problems while improving the fidelity of predictions and projections from intraseasonal to centennial time scales. The committee finds that climate modeling in the United States can make significant progress through a combination of increasing model resolution, advances in observations and process understanding, improved representations in models of unresolved but climate-relevant processes, and more complete representations of the Earth system in climate models. As a general guideline for most effectively meeting future climate information needs, climate modeling activities should focus on problems whose solution will help climate models better inform societal needs, and for which progress is likely given adequate resources. With such focus, advances in Earth system modeling may yield significant progress in the next decade or two for a number of scientific questions, including sea-ice loss, ice-sheet stability, land-ocean ecosystem and carbon-cycle change, regional precipitation changes and extremes, cloud-climate interaction, and climate sensitivity.

As these challenges are faced and models grow in complexity, they are likely to exhibit an increasingly rich range of behavior, full of surprises and unexpected results. Therefore, the committee emphasizes that it is unwise to promise that successive generations of models will invariably result in firmer predictive capability. Progress on these challenges is important, however, to develop a fuller understanding of the climate system, reducing the likelihood of unanticipated changes and improving climate models in the long term.

Uncertainty is a significant aspect of climate modeling and needs to be properly addressed by the climate modeling community. To facilitate this, the United States should more vigorously support research on uncertainty, including understanding and quantifying climate projection uncertainty, automating approaches to optimization of uncertain parameters within models, communicating uncertainty to both users of climate model output and decision makers, and developing deeper understanding on the relationship between uncertainty and decision making.

FINAL COMMENTS

Climate models are among the most sophisticated simulation tools developed by mankind and the "what-if" questions we are asking of them involve a mind-boggling number of connected systems. As the scope of climate models has expanded, so has the need to validate and improve them. Enormous progress has been made in the past several decades in improving the utility and robustness of climate models, but more is needed to meet the desires of decision makers who are increasingly relying on the information from climate models.

The committee believes that the best path forward is a strategy centered around the integration of the decentralized U.S. climate modeling enterprise—across modeling efforts, across a hierarchy of model types, across modeling communities focused on different space and time scales, and between model developers and model output users. A diversity of approaches is necessary for progress in many areas of climate modeling and is vital for addressing the breadth of users' needs. If adopted, this strategy of increased unification amidst diversity will allow the United States to more effectively meet the climate information needs of the nation in the coming decades and beyond.

PART 1

Background

This section of the report provides a general introduction and a historical look at lessons from previous reports on climate modeling.

CHAPTER ONE

Introduction

Climate information is being used by a vast array of organizations within the public and private sectors, with decisions based on climate information being made every day. Users of climate information include national security planners, infrastructure decision makers, public policy makers, insurance companies, water managers, agricultural managers, and more. Each of these communities has different needs for climate data from numerical simulations, with different time horizons and different tolerances for uncertainty. Many user groups want very highly spatially resolved information about the likely range of climate variability and extreme events such as droughts, floods, or heat waves, while others are looking for data on long-term trends. Some concrete examples of current users of climate information are farmers, city planners, water managers, and insurance companies, and details about their use of climate information are described in Box 1.1.

BOX 1.1 EXAMPLES OF CLIMATE DATA USERS

Climate data are needed by many individuals and companies. Below are several representative examples of individuals and organizations who use climate data, why they need them, how they are used, and what the payoff is.

Farmers

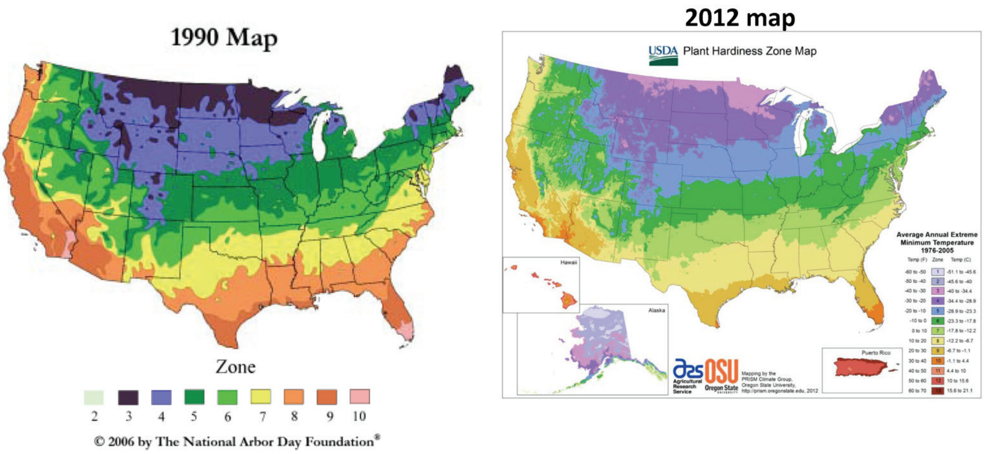
Farmers have always been close to weather and climate, as their economic success depends on the right timing of planting, irrigation, and harvesting and the right choice of crops for the local climate. In their day-to-day decision making about irrigation, farmers depend heavily on short-term weather forecasts, which give them information not only about temperature and precipitation but also about soil moisture levels that are crucial for many crops. One concrete example is corn farming—a $15.1 billion business in the United States[a]—which is very sensitive to drought and low soil moisture. Decisions made on the time scales of weeks to seasons rely on short-term and seasonal forecasts of the soil moisture, which have become invaluable tools to help farmers decide on irrigation needs during drought conditions; it is estimated that by 2015 improved weather forecasts will allow the agriculture sector to save $61 million on irrigation water costs (Centrec Consulting Group, 2007). On time scales of seasons to years, forecasts of El Niño/La Niña conditions help farmers to decide when to plant and harvest their crop, with an estimated economic benefit on the order of $500 million to $950 million per year from the seasonal El Niño/La Niña forecast for the U.S. agricultural sector (Chen et al., 2002). On even longer time scales, the changing climate is shifting growing seasons and regions. Farmers are directly

BOX 1-1 CONTINUED

impacted because many of them have specialized in growing specific crops, which in turn are often highly specialized for the climatic conditions they tolerate (see Figure 1). Longer-term regional climate projections of precipitation, temperature, and soil moisture will allow farmers to decide which crops to focus on in the future and to prepare for investments in new technologies needed to successfully grow new crops.

Mayors of Large Cities

One of the main concerns about climate change is associated with the projected increase in the frequency, duration, and intensity of heat waves. According to the National Weather Service (NWS), "heat is the number one weather-related killer in the U.S.,"[b] claiming more lives each year than floods, lightning, tornadoes, and hurricanes combined. Heat waves also increase the peak demand for electricity, with the potential for blackouts and the high economic cost associated with them. (Estimates for the August 2003 blackout that affected numerous cities in the United States and Canada ranged from $4 billion to $10 billion [U.S.-Canada Power System Outage Task Force, 2004]). Using a heat index that considers absolute temperature and humidity to assess how hot it really feels, the NWS forecasts extreme heat events several days in advance. This allows city officials to prepare for heat waves by warning the public, instituting energy-saving programs, and designating community cooling centers, reducing some of the negative impacts of heat waves



1990 Map

2012 map

Based on data from 1974-1986 (13 years)

Based on data from 1976-2005 (30 years)

FIGURE 1 U.S. Department of Agriculture plant hardiness zone maps are used extensively by gardeners and growers to determine which plants are most likely to thrive at a location. Maps are based on the average annual minimum winter temperature, divided into 10°F zones. The map on the left is based on data from 1974-1986, and the map on the right is based on data from 1976-2005. The more recent map (right) is generally one half-zone warmer than the previous map (left). SOURCES: http://arborday.org/media/map_change.cfm; http://planthardiness.ars.usda.gov/PHZMWeb/AboutWhatsNew.aspx (both accessed October 11, 2012).

BOX 1-1 CONTINUED

and saving lives. In the longer term, climate projection data allow mayors and other planners to develop adaptation strategies (NPCC, 2010) to help plan for some of the negative impacts of these changes. These adaptation strategies include programs to increase the energy efficiency of buildings, investments in power grid infrastructure, and zoning changes to mandate the planting of street trees in heat-stressed neighborhoods. Improved climate data (Figure 2) can help cities make more informed decisions on long-term infrastructure investments that will help to protect the health and economic interests of their constituents.

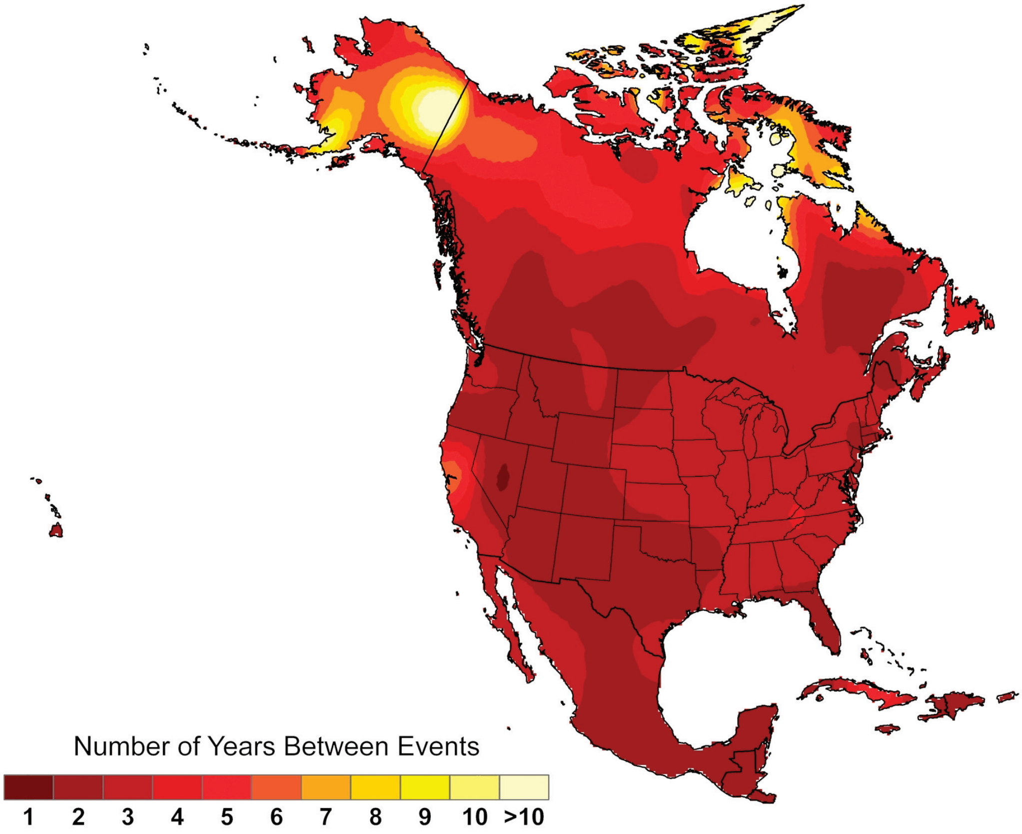


FIGURE 2 Heat waves are projected to occur more frequently in the future. Map shows the projected frequency of extreme heat for later in the century (2080-2099 average). Extreme heat refers to a day so hot that it occurred only once every 20 years in the past, and the projections show that extreme heat will occur every 1-3 years in much of the United States by the end of the century.

BOX 1-1 CONTINUED

Hydropower System Managers

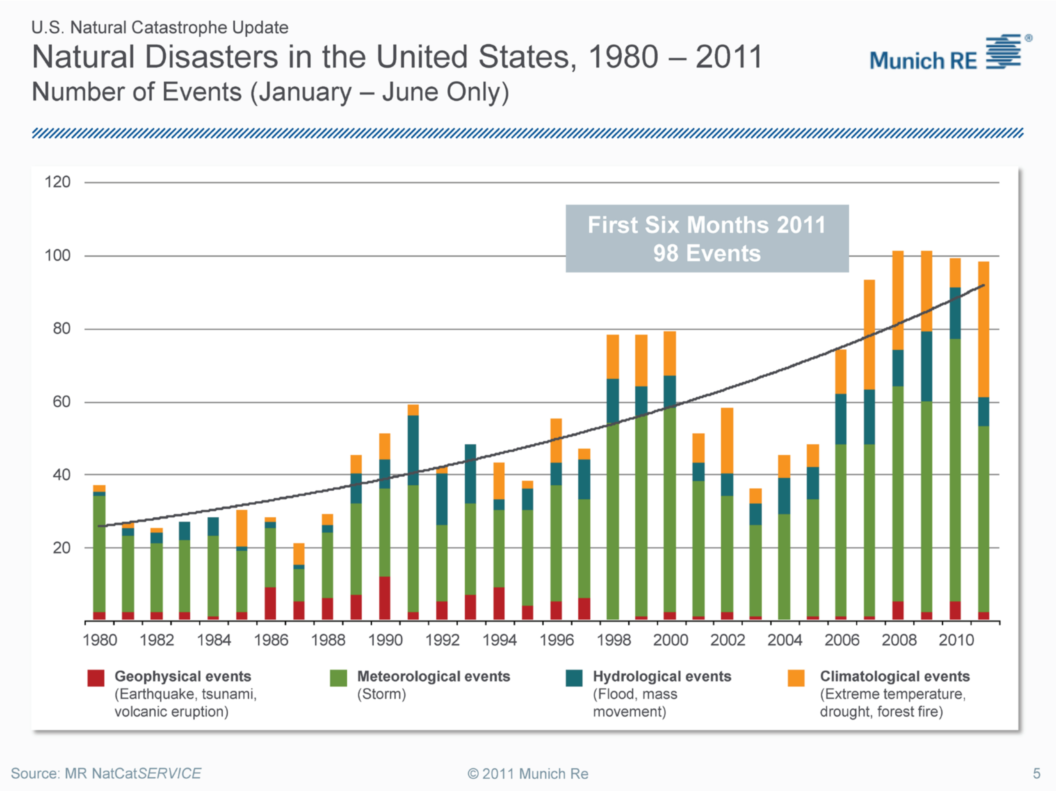
The Federal Columbia River Power System generates more than 76,000 gigawatt-hours (GWh) of electricity per year, accounting for about 30 percent of the electricity used by the more than 15 million people in the Pacific Northwest and having an estimated worth of approximately $4 billion per year (BPA, 2010). To continue generating power at this level, river managers like those for the Columbia River power system need to make both short- and long-term decisions regarding how much water to store (compared to natural flow), which requires climate data to predict and adapt to future changes in river flow. The climate data most needed by river power management are temperature, precipitation, and wind, with information preferably at high spatial resolutions of 1-10 km and with daily or higher frequency. Current climate data are only available at much lower resolutions, but even these data have been useful in projecting seasonal changes, such as increased winter runoff but less spring/summer runoff. Managers also use longer-term projections of climate change to make decisions on modifying existing infrastructure and/or acquiring additional infrastructure (for example, Figure 1.2). Managers such as those who monitor the Columbia River desire more reliable and higher-resolution climate data to help with planning and ultimately their ability to continue to supply power to millions of Americans (Figure 3).

FIGURE 3 Managers of hydropower systems such as those of the Federal Columbia River Power System require climate information for both short-term operational decisions and long-term infrastructure planning. SOURCE: Steven Pavlov, http://commons.wikimedia.org/wiki/File:Grand_Coulee_Dam_in_the_evening.jpg (accesed June 8, 2012).

BOX 1-1 CONTINUED

Insurance Companies

Insurance companies provide insurance to people and businesses against the impacts of natural disasters. Insurance rates for weather- and climate-related disasters such as floods, high winds, droughts, etc., are based on the expected occurrence of those events. To realistically assess the probabilities of weather- and climate-related natural disasters, insurance companies have been using climate data on past weather events for many years to develop specific risk models for different regions and operations (e.g., transportation, farming, and construction). Weather- and climate-related losses have increased rapidly in recent years (Figure 4), with record-breaking


U.S. Natural Catastrophe Update

Natural Disasters in the United States, 1980 – 2011

Number of Events (January – June Only)

First Six Months 2011
98 Events

Source: MR NatCat*SERVICE*

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FIGURE 4 Annual occurrence of natural disasters in the United States, broken down by origin as of 2010, shows that the past may no longer be a reliable guide to the future. Record-breaking insured losses from weather- and climate-related disasters of over $50 billion were recorded in 2011. SOURCE: Munich RE; http://www.munichre.com/app_pages/www/@res/pdf/media_relations/ press_dossiers/hurricane/2011-half-year-natural-catastrophe-review-usa_en.pdf (accessed September 14, 2012).

BOX 1-1 CONTINUED

insured losses of more than $50 billion in 2011.[c] More and more large insurance and reinsurance companies are recognizing that climate change poses an enormous challenge to their business. Accurately reflecting changed risks and actively and profitably managing climate change impacts, rather than withdrawing from high-risk markets, is a major challenge for the insurance industry. To address it, new kinds of climate data are required, focusing on projections rather than historical observations. High-quality regional climate projections of variables such as sea level, temperature, precipitation, wind, and extreme events will be crucial for the insurance industry to rise to this challenge, so insurers can continue to provide disaster coverage for people and businesses in the United States and use their past experience with risk mitigation (e.g., fire and earthquake building codes) to help prevent losses of lives and property (Mills and Lecomte, 2006).

National Security Sector

National security planners and decision makers use climate information and forecasts over a broad range of time scales. The February 2010 *Quadrennial Defense Review* notes that climate change will play a significant role in the future security environment for the United States (Gates, 2010). Concurrently, the U.S. Department of Defense and its military services are developing policies and plans to understand and manage the effects of climate change on military operating environments, missions, and facilities (NRC, 2011c). It has been estimated that $100 billion of naval facilities are at risk from sea-level rise of 3 feet or more (NRC, 2011c) (Figure 5). The national security risks associated with a changing climate have also recently been assessed in a report by the Center for American Progress (Werz and Conley, 2012). The Navy would like to use climate model outputs for information related to increasing Arctic maritime activity, water and resource scarcity, and the impact of sea-level rise on installations (NRC, 2011c). In order to use climate model projections to inform its decisions, the Navy would need high-spatial-resolution regional climate models on decadal time scales, uncertainty quantification of the models, and probability distribution functions in the model output. The Navy is a "good example of a stakeholder that has very specific needs in applications related to its infrastructure and operations, disease, civil instability, migration, water resources, and energy" (NRC, 2011c).

The Building Community

The built environment (buildings, communications, energy, industrial facilities, transportation, waste, water, and associated natural features) shelters and supports most human activities and constitutes a large portion of the nation's wealth (Figure 6). It has important roles in reduction of greenhouse gas emissions and in measures to help society adapt economically, environmentally, and socially to climate change. The building community includes professionals—including architects, engineers, geologists, landscape architects, and planners—as well as owners, investors, facilities managers, contractors, manufacturers of building materials, health and safety regulators, and stakeholders served or affected by the built environment (nearly everyone).

The building community uses climate information, particularly on extremes, to ensure that buildings are safe, functional, and resilient. Historically, the extreme environments used in assess-

BOX 1-1 CONTINUED

FIGURE 5 The amphibious assault ship USS Kearsarge (LHD 3) pulls away from its berth at Naval Station Norfolk. An estimated $100 billion worth of naval facilities are at risk from sea-level rise of 3 feet or more. SOURCE: http://www.navy.mil/view_single.asp?id=125450 (accessed June 6, 2012).

ment and design of the built environment have not been based on climate or weather models. Rather, extreme environments have been defined by statistics of historical records, albeit to within observation and sampling errors. With climate and weather changing, historical records no longer are adequate predictors of future extremes. However, advanced modeling capabilities potentially can provide useful predictions of extreme environments.

Often decisions about buildings and other infrastructure are made for very long time scales—decades and beyond. When looking at building decisions related to material choices, siting, and building design, there are any number of questions related to climate, including: How heavy are future rains and/or snowfalls likely to be? What range of temperatures is likely? What will average precipitation rates mean for the water table? Will it flood? Adaptation of the built environment to climate change is particularly important because it has significant resource implications. The U.S. Department of Commerce estimates total construction spending in the United States to be more than $820,000 million annually.[d]

BOX 1-1 CONTINUED

FIGURE 6 Construction of the Sovereign, Atlanta, Georgia. The building community uses climate information to make decisions about building materials, siting, and building design. These types of infrastructure decisions can have implications for decades. As the climate changes, information from climate models is being used as a guide to future climate conditions. SOURCE: Conor Carey, http://commons.wikimedia.org/wiki/File:Sovereign-Atlanta.jpg (accessed June 6, 2012).

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[a] www.epa.gov/oecaagct/ag101/cropmajor.html (accessed October 11, 2012).

[b] http://www.nws.noaa.gov/os/heat/index.shtml (accessed November 30, 2012).

[c] www.noaa.gov/extreme2011/ (accessed October 11, 2012).

[d] www.census.gov/construction/c30/c30index.html (accessed October 11, 2012).

Over the next several decades climate change and its myriad consequences will be further unfolding and likely accelerating (NRC, 2011a). Probable impacts from climate change, including sea-level rise, a seasonally ice-free Arctic, large-scale ecosystem changes, regional droughts, and intense flooding events, will increase demand for climate information. The value of this climate information is large. One of the more prominent places to see this is through the impacts of extreme climate and weather events; extreme climate and weather events are one of the leading causes of economic and human losses, with total losses between 1980 and 2009 exceeding $700 billion (NCDC, 2010) and damages from more than 14 weather- and climate-related disasters totaling more than $50 billion in 2011 alone.[1] Climate change is affecting the occurrence of and impacts from extreme events, such that the past is not necessarily a reliable guide for the future, which further underscores the value of climate information in the future.

An example of the value of climate information on shorter time scales comes from the flooding throughout the Upper Midwest in the spring and summer of 2011. Extensive rainfall in the spring and summer of 2011 led to flooding of the Mississippi and Missouri rivers. Prior to that spring, climate predictions showed increased risk of flooding throughout much of the Upper Midwest as a result of above-average snowpack melting and precipitation levels (Figure 1.1), allowing government authorities to plan ahead. According to the National Oceanic and Atmospheric Administration (NOAA), these climate predictions allowed the government to coordinate "with local, state and federal agencies before and during the flooding, so that emergency officials could make important decisions to best protect life and limit property damage."[2] Such decisions included evacuations and destruction of levees in some locations to allow excess waters to flow into floodways.

In looking at longer time scales, climate models can provide information on projected rainfall runoff for the coming decades (Figure 1.2). Some areas of the United States, such as the Southwest, are projected to see decreases in average rainfall, while some areas, like the Northeast, will see increases. Such changes will have major implications for future water supplies, crop yields, and wildfire risks, among other effects. This type of projected information allows counties and states to plan ahead for these conditions, including decisions regarding infrastructure. However, the relationship between regional drought and predictable patterns of climate variability is complicated, so users of climate information must understand and deal with considerable predictive uncertainty.

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[1] http://www.noaa.gov/extreme2011/ (accessed October 11, 2012).

[2] http://www.noaa.gov/extreme2011/mississippi_flood.html (accessed October 11, 2012).

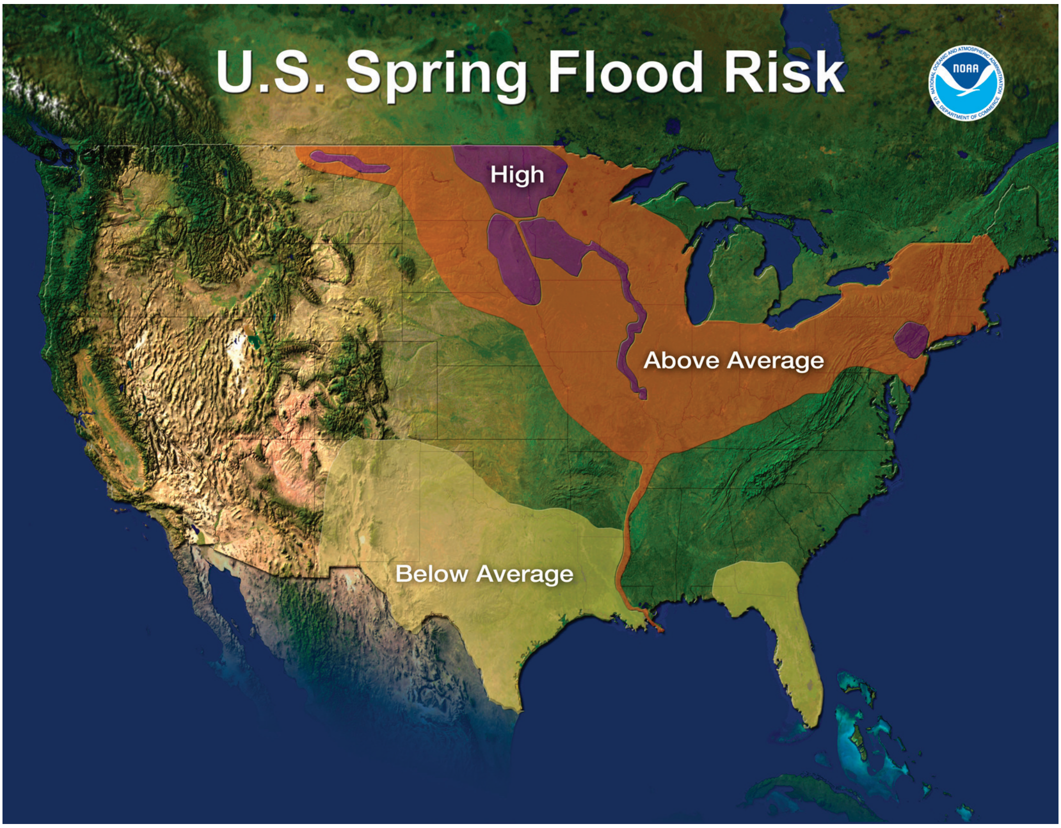

FIGURE 1.1 The spring flood risk outlook from NOAA's National Weather Service for 2011. Extensive flooding of Mississippi and Missouri rivers occurred in 2011. SOURCE: http://www.noaa.gov/extreme2011/mississippi_flood.html (accessed October 11, 2012).

WHAT IS A CLIMATE MODEL?

Information about the future of the climate system comes from computer models that simulate the climate system. Climate models are mathematical representations of physical, chemical, and biological processes in Earth's climate system (Figure 1.3). Computer models are a part of everyday life—there are models that forecast weather, simulate how to fly an airplane, predict tides, and aid in drug discovery. Models are used to study processes that are inherently complex, require large amounts of information, or are impractical to study directly. They are essential tools for understanding the world and allow climate scientists to make projections about the future.

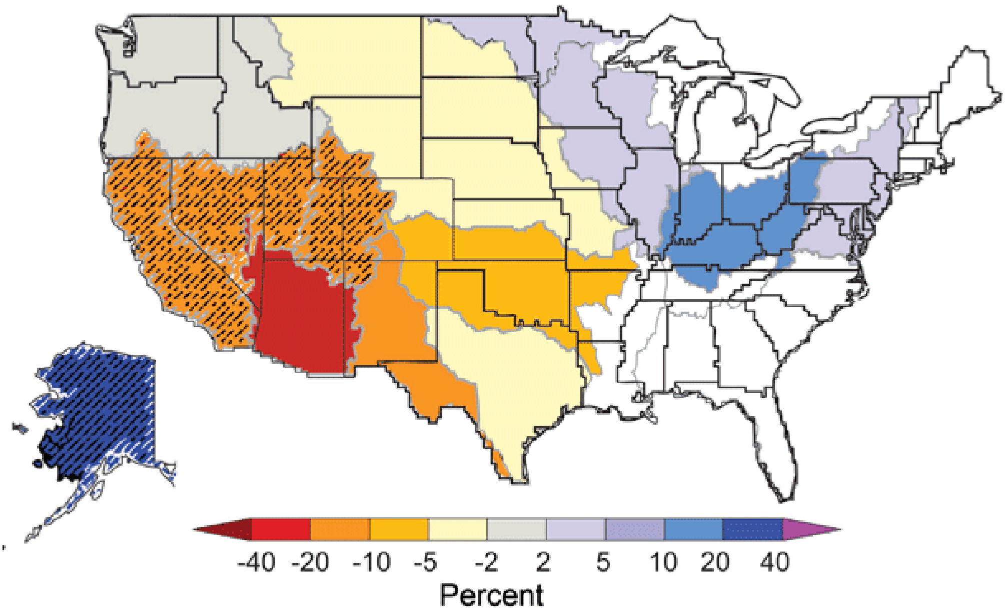

FIGURE 1.2 Longer-time-scale climate projections can assist in long-term planning. The figure shows projected changes in annual average runoff for 2041-2060 relative to a 1901-1970 baseline by water resource region, based on analyses using emissions that fall between the lower and higher emissions scenarios. Lower average runoff is expected in the Southwest and greater runoff is projected for the Northeast. Colors indicate percentage changes in runoff, with hatched areas indicating greater confidence due to strong agreement among model projections. SOURCE: USGCRP, 2009.

The many different kinds of climate models are all derived from fundamental physical laws such as Newton's laws of motion and the chemistry and thermodynamics of gases, liquids, solids, and electromagnetic radiation. These are supplemented by empirical relationships determined from observations of complex processes such as ice crystal formation in clouds; turbulent mixing, and waves in both air and water; biological processes; sea-ice growth; and glacier movement.

The main components within a climate model include

- atmosphere (simulates winds, temperatures, clouds and precipitation, turbulent mixing, transport of heat, water, trace chemicals and aerosols around the globe),
- land surface (simulates surface characteristics such as vegetation, snow cover, soil water, rivers, ice sheets, and carbon storage),

- ocean (simulates temperature, current movements and mixing, and biogeochemistry), and
- sea ice (simulates thickness, fractional cover, ice drift, effects on radiation and air-sea heat and water exchanges).

In climate models, the globe is divided into a three-dimensional grid of cells representing specific geographic locations and elevations. Current global models that run simulations over thousands of years typically use resolutions with 100- to 200-km grid cells. The equations for each component of the climate system are calculated on a global grid for a set of climate variables (e.g., temperature, precipitation). Weather forecasts are now routinely issued out to a week or more in advance, but weather forecasts are intrinsically limited by chaos for periods beyond 1-2 weeks. The atmospheric part of a climate model is functionally identical to a weather forecast model, but the climate model is run far longer to simulate interactions between atmosphere, land, ocean, and cryosphere on time scales of months to millennia. In these projections, individual simulated weather systems are not expected to match reality; only statistics of the

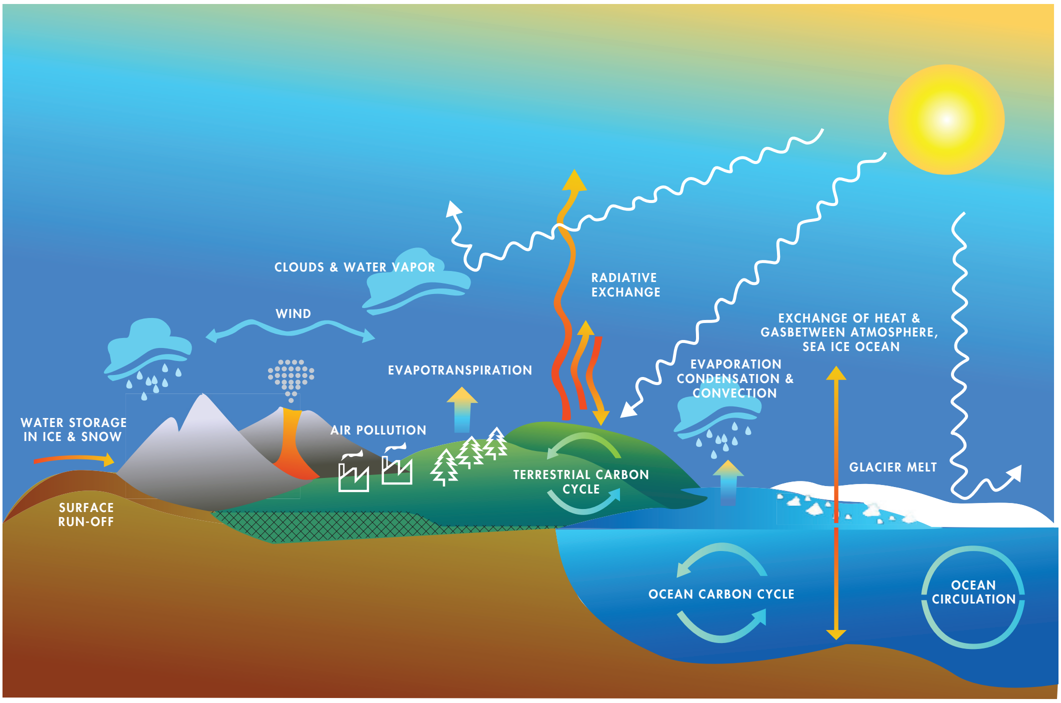

FIGURE 1.3 Climate models are mathematical representations of the physical, chemical, and biological processes in the Earth system. SOURCE: Marian Koshland Science Museum.

simulated weather such as the mean and year-to-year range of annual rainfall can be predicted or compared with observations.

Climate models are computationally intensive; in fact, increases in computational power over the past 50 years have been a major driver in the advancement of climate models. The development of modern-day climate models can be traced back to the first hand-calculated numerical prediction of weather in the 1920s. However, it was not until the prevalence of electronic computers in the 1960s that the extensive numerical demands of even a minimal description of weather systems were met. The possible grid size of a climate model is dependent upon the available power of the computer used to run the model. A finer spatial resolution requires a larger number of grid cells and a shorter integration time step and therefore more computation time to perform the simulation. Likewise, a coarser resolution has fewer grid points and provides less detailed results and a less faithful representation of the effects of small-scale features such as mountains or coastlines (GFDL, 2011). Figure 1.4 shows how a climate model with 50-km horizontal grid spacing can simulate annual mean precipitation over the complicated mountainous terrain of the western United States much more accurately than can the same model run at 300-km or 75-km resolution (to note, practical considerations mean that the greater computational expense of running at higher resolution reduces the number of realizations that can be generated).

WHAT IS THE CURRENT STATE OF CLIMATE MODELING?

Climate modeling activity is extensive both in the United States and internationally. Climate models have advanced over the decades to become capable of providing much useful information that can be used for decision making today. But there are and will continue to be large uncertainties associated with climate information, which users will have to understand and incorporate into their decision making.

Climate Modeling in the United States

Climate modeling activities that examine the entire planet are referred to as "global models," and those that focus on specific parts of the globe are called "regional models." Global modeling activities are generally larger and more resource-intensive efforts. The current U.S. organizational structure for global climate modeling has multiple centers that develop and use climate models in largely independent efforts. These institutions coincide primarily with U.S. funding agencies: the National Science Foundation (NSF) and Department of Energy (DOE) support the National Center

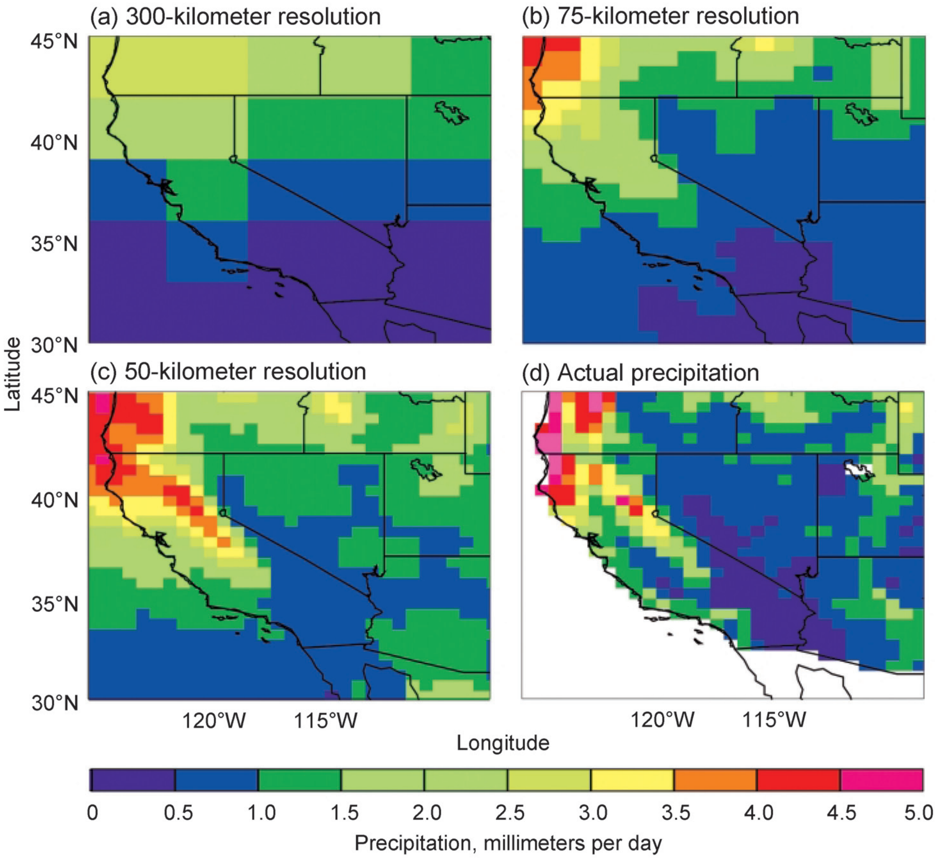

FIGURE 1.4 Annual-mean precipitation in the western United States simulated by a climate model with three different resolutions (300, 75, and 50 km) compared with observational data (VEMAP) at 50-km resolution. The higher-resolution model (c) shows better agreement with observations (d). SOURCES: Walter, 2002, based on Figure 13 in Duffy et al., 2003.

for Atmospheric Research (NCAR), NOAA supports the Geophysical Fluid Dynamics Laboratory (GFDL) and the National Centers for Environmental Prediction (NCEP), and the National Aeronautics and Space Administration (NASA) supports efforts at both the Goddard Institute for Space Studies and the Goddard Space Flight Center. Global climate models are run on supercomputers and use data storage facilities housed both inside and outside the labs (Figure 1.5). Many of these climate models, especially those centered at NCAR, rely on computer code derived through major collaborations with outside developers from other national and international labs and academia.

The largest climate modeling efforts at NCAR and GFDL involve the full-time efforts of more than 100 Ph.D.-level scientists, software engineers, and other support staff and budgets on the order of $10 million or more, as does NCEP's operational weather and climate forecasting effort.

Regional climate modeling activities in the United States are even less centralized. There are many regional modeling activities, both within and outside the United States, with more focus on developing regional climate change scenarios for specific regions, but efforts on model development, evaluation, and analysis are limited compared to the global modeling efforts. This is natural given that there are many regions and local issues of concern. In the United States, most regional modeling is focused around a few basic modeling codes such as the Weather Research and Forecasting model, but each group typically customizes important details of such a model to its own region and applications. Regional climate models are often run on small, cheap, widely available computer clusters rather than supercomputers.

Although the federal government is a key player in climate model operation and development, academia and the private sector also have important roles. A few

FIGURE 1.5 Global climate models are run on supercomputers, like the NOAA climate research supercomputer Gaea at Oak Ridge National Laboratory in Tennessee (pictured). It has a peak speed of 1.1 petaflops (more than 1,000 trillion calculations per second). SOURCE: ORNL photos/Jay Nave (http://blogs.knoxnews.com/munger/2011/12/noaas-petascale-computer-for-c.html).

universities run their own climate modeling centers, albeit on smaller scales than the large modeling centers listed above. University-based research plays a crucial role in efforts to better understand processes in the climate system that can lead to improved parameterizations in models. It also advances theoretical understanding of the climate system, often with the aid of models and model output from the large centers. The universities also train graduate students that may eventually work with global and regional climate models. The private sector is an emerging player in climate modeling. Many consulting firms analyze climate model output to assess likelihood of key climate change variables at the regional scale. Overall, such ill-defined boundaries make it difficult to estimate (or even define) the size of the U.S. climate modeling enterprise, in either dollars or personnel.

Climate Modeling Internationally

Many other countries are also engaged in large climate modeling efforts. There are major global climate modeling centers in Canada, England, France, Germany, China, Japan, Australia, Norway, and Russia. The Earth Simulator supercomputer in Japan has been over the past few years a noteworthy cutting-edge platform for ultra-high-resolution climate simulations. Regional climate modeling efforts are more widespread internationally, including in several Latin American and European countries. Several global weather forecasting centers (e.g., NCEP in the United States, the UK Met Office and the European Centre for Medium-Range Weather Forecasts in England) are also involved in seasonal and longer-term climate forecasting, provide gridded "reanalyses" of the global state of the atmosphere every 6-12 hours over the past 25-50 years that are widely used (with caveats) by climate researchers, and have improved their weather models in ways that also benefit climate simulation.

Important international activities related to climate modeling are the Intergovernmental Panel on Climate Change (IPCC) and the Coupled Model Intercomparison Project (CMIP) (see Figure 1.6). The IPCC was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme to conduct assessments of the scientific basis for understanding the risk of human-induced climate change, its potential impacts, and options for adaptation and mitigation (IPCC, 1998; WMO, 1988). The IPCC Fourth Assessment Report (AR4) reports utilized publications based on the outputs from the CMIP3 project (discussed below) contributed by 23 different climate models from 16 research groups around the world to come to their conclusions (Meehl et al., 2007). Because of the extensive nature of an intergovernmental climate assessment, producing the IPCC reports is an inherently difficult task and involves thousands of people with different expertise, cultures, interests, and expectations.

Another important international activity is CMIP. It was established in 1995 under the auspices of the Working Group on Coupled Modeling. CMIP sponsors international comparisons of climate models, of which the last two, CMIP3 and CMIP5, have been coordinated with the IPCC Fourth and Fifth Assessment Reports (AR4 and AR5), respectively. The comparisons use standardized specifications of model inputs and standardized output formats agreed on by an international committee, and an extensive suite of model outputs is archived and made publically available for the science and applications communities. The DOE-funded Program for Climate Model Diagnosis

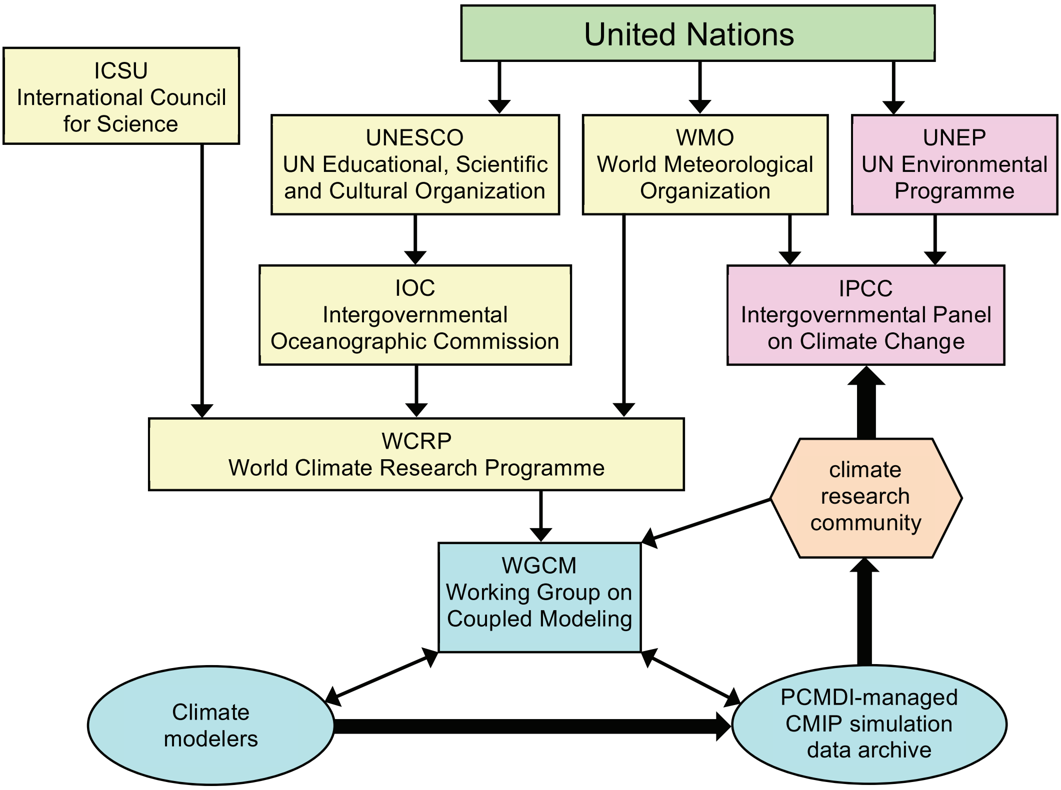

FIGURE 1.6 This figure shows the relationship among IPCC, CMIP, and PCMDI with respect to the larger climate research community. CMIP and IPCC are managed by separate organizations within the United Nations but are coordinated in the timing of their activities. SOURCE: Taylor et al., 2012.

and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory has been instrumental in developing CMIP, including archiving, analysis, and quality control of model output, although CMIP now has broad international institutional support. CMIP has developed into a vital community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation, and data access.

What Can Climate Models Do Well?

Climate models have evolved into remarkably sophisticated tools for addressing a diverse range of scientific and societally relevant issues. Their fidelity can be assessed by comparing them statistically with such observations (Box 1.2) as the mean seasonal cycle, seasonal extremes of temperature, rain and snowfall, and other routinely measured quantities around the globe, as well as statistics of the El Niño-Southern Oscillation and other important forms of climate variability and the observed changes of climate over the past century and across previous eras. The evolution of climate models over the past 50 years and the diversity of models used for different purposes and across different space and time scales are discussed in more detail in Chapter 3.

Climate models skillfully reproduce important, global- to continental-scale features of the present climate, as assessed in more detail by IPCC (2007c, Chapter 11). For instance, over most parts of the globe, the simulated seasonal-mean surface air temperature is within 3°C of observations (IPCC, 2007c), compared to an annual cycle that can exceed 50°C in places, and simulated seasonal-mean precipitation has typical errors of 50 percent or less on regional scales of 1,000 km or larger that are well resolved by these models (Pincus et al., 2008). In the oceans, projected seasonal-mean sea-surface temperatures are within 1-2°C of those observed over most of the globe, and major ocean current systems like the Gulf Stream are correctly positioned (IPCC, 2007c). The simulated seasonal patterns of sea-ice extent, snow cover, and cloudiness are also in broad agreement with observations (IPCC, 2007c; Pincus et al., 2008). Swings in Pacific sea-surface temperature, winds, and rainfall associated with El Niño are simulated by a number of climate models with fairly realistic amplitude, location, and period (AchutaRao and Sperber, 2006; Neale et al., 2008). Other forms of natural climate variability, such as the year-to-year range of seasonally averaged temperature or rainfall over regions of 1,000 km or larger in size and their spatial patterns of year-to-year variability, are also simulated reasonably well (Gleckler et al., 2008). Simulation of the statistics of extreme hot and cold spells has also improved (IPCC, 2007c), especially in models using grid spacings of less than 100 km. In many ways climate models have become remarkably accurate tools for simulating observable statistical aspects of the Earth system (see Chapter 3 for more details of historical model improvements).

Climate models do have well-known limitations for simulating the current climate, stemming from both the coarseness of their grid spacing and the challenge of encapsulating the complex physical interactions between all parts of the climate system. For instance, the grid of current climate models cannot represent fine-scale details of mountain ranges important for simulating snowpack, rainfall, and glaciation in such regions, details of coastal processes such as oceanic upwelling or tidal currents, or hurricanes and severe thunderstorms. Tropical rainfall and many cloud processes rely on interactions between very small scale air motions and other processes such as condensation or freezing that are also not straightforward to represent in current climate models. Other limitations include a lack of fully coupled land-ice or ocean biogeochemistry models in many simulations, which are areas of active research but which are just starting to be included in climate simulations. Furthermore, credible simulations of some processes, such as the formation of continental ice sheets, would require model runs of tens of thousands of years that are not yet feasible on current computers.

The main concern among scientists, decision makers, and the interested public is the extent to which climate projections can be trusted based on model simulations for the next decades, the next century, and beyond. Here the crucial problem is that human greenhouse gas and aerosol emissions are quickly moving the climate outside its natural range over at least the past few million years, so it is doubtful that the past can act as a guide to the future. Furthermore, theory, observations, and climate models all point to strong positive internal feedbacks within the climate system that increase its response to changes in its composition. How can we be sure our best climate models can reliably simulate not only the current climate, but also how human influences (presupposing we know what they will be) will change climate?

The best indicators are (i) the ability of models to simulate observed climate change of the past 150 years and especially the more rapid and more comprehensively measured changes of the past 30 years, and (ii) the spread in projections made using different climate models or model versions, both taken in the context of paleoclimate observations and simulations that suggest circumstances that may favor abrupt or rapid changes in climate regime. Comparisons of multiple state-of-the-art models against one another (and observations) advance understanding of the climate system and help build trust in model projections. Intermodel differences provide a lower bound on the uncertainty of climate projections. They may miss sources of error common to all current models; one might hope that, as climate models become more comprehensive, the likelihood of such errors diminishes as long as the model components and their interactions are carefully tested against observations. Chapter 10 of

BOX 1.2 HOW DO CLIMATE MODELS GET EVALUATED?

As the IPCC report *Climate Change 2007: The Physical Science Basis* notes, "there is considerable confidence that climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above" (IPCC, 2007c). There are three primary reasons for this confidence: (1) As noted above, the fundamentals of a climate model are based on established physical laws, such as laws of conservations of energy, mass, and momentum. (2) Climate model simulations are routinely and extensively assessed by being compared with observations of the atmosphere, ocean, cryosphere, and land surface (Figure 1). (3) Climate models are able to reproduce features of past climates and climate changes (e.g., the warming of the past century, and the mid-Holocene warming of the Northern Hemisphere 6,000 years ago).

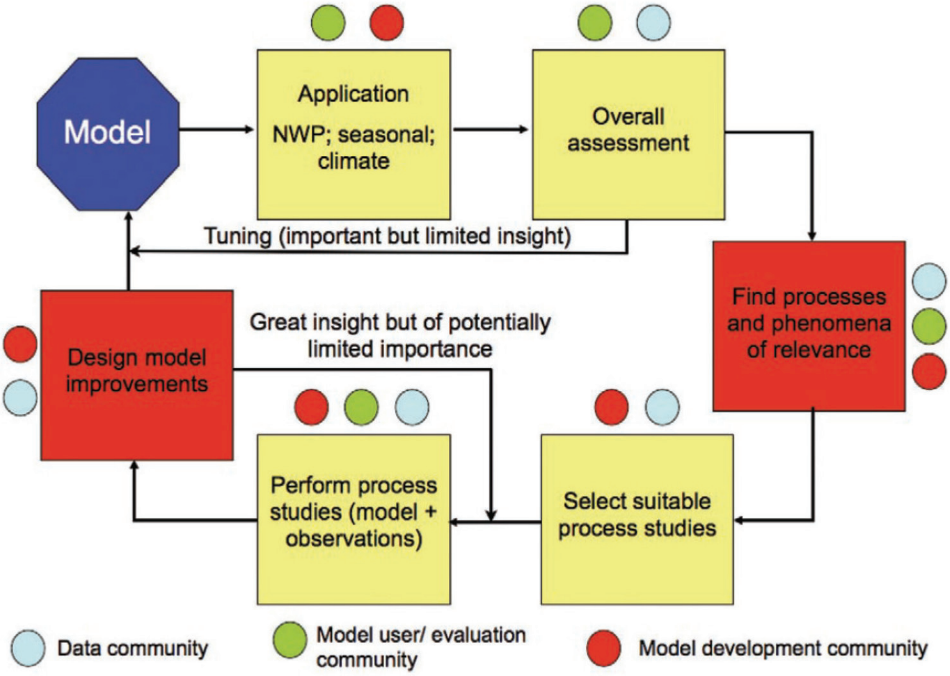

FIGURE 1 Climate model development and testing involves multiple stages and the contributions of the model development community, the model user/evaluation community, and the data community. SOURCE: Jakob, 2010.

BOX 1-2 CONTINUED

Current climate models are calibrated during their development process to match observations within reasonable uncertainty ranges. However, the warming to date due to greenhouse gas increases has been partially compensated by an uncertain amount of cooling caused by human-induced enhancement of light scattering by aerosols and by their effect on clouds; this compensation has been estimated to be from 20 to 70 percent (with 90 percent confidence) based on a range of observational and model-based studies (IPCC, 2007d). Over the 21st century, global aerosol emissions are expected to not increase further, but greenhouse gas emissions are likely to accelerate for at least the next few decades, so this compensation will become less significant. Because of the uncertain cooling by aerosols the current warming cannot be used to constrain the "climate sensitivity." Thus, the simulated 21st-century global-average warming varies across the international suite of climate models with a range of approximately 30 percent[a] as is further discussed in Chapter 4.

Models provide quantitative estimates of future climate change, but with significant sources of uncertainty—lack of knowledge, or imperfect knowledge about specific quantities or the behavior of a system. These include the uncertainty in the "forcing" on the climate system from future greenhouse gas and aerosol emissions, as well as natural processes such as volcanic eruptions and solar variability, used as inputs to climate models; the uncertainty in the climate system response to this forcing; the uncertainty from natural internal variability of the climate system; the uncertainty from incomplete representations of known but complicated and small-scale processes (such as cumulus clouds) and of poorly understood processes (such as ice nucleation in clouds); and the uncertainty from "unknown unknowns" (see Chapter 6 for more information on uncertainty).

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[a] More specifically, the interquartile range is 30 percent of the mean, where the interquartile range is a measure of statistical dispersion, and measures the difference between the 75th percentile and the 25th percentile of the data.

IPCC (2007c) discusses some other strategies that are also used to estimate or bound model uncertainties.

Figure 1.7 shows which aspects of climate can be most robustly predicted, separated by phenomenon and time scale, based on such assessments. In general, climate models more robustly predict trends at larger space and time scales, and they predict temperature trends more reliably than precipitation trends. They all project a reduction in summer sea-ice extent, but not as large as that observed in recent years. They robustly predict the contribution to global sea-level rise from heat uptake in the oceans, but most do not include a representation of ice-sheet melt and the disintegration of the tongues of large glaciers that may considerably accelerate sea-level rise over the next century. They agree that the polar regions will become wetter and that the subtropics will become drier, but they do not agree on which regions of the subtropics will experience strong drying. As climate models become more comprehensive and their grid scale becomes finer, they can provide meaningful projections of more parts of the climate response and their possible feedbacks on the overall climate system, but this does not necessar-

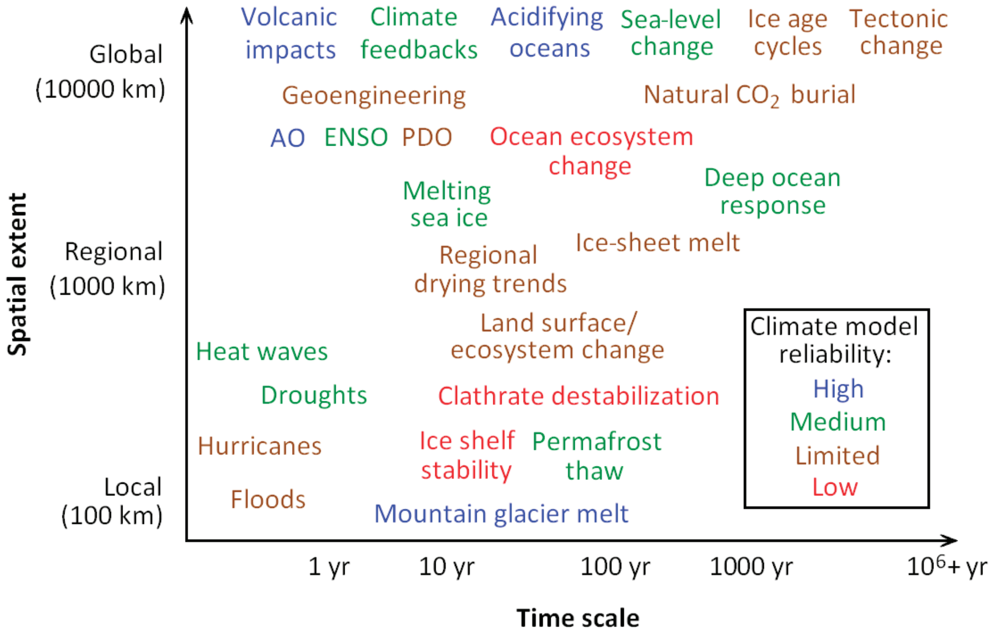

FIGURE 1.7 Time and space scales of key climate phenomena. Color coding shows relative reliability of climate model simulations of these phenomena (or their statistics in the present climate, for climate variability/extremes).

ily reduce projection uncertainty about some aspects of climate change. Indeed, global climate sensitivity, defined as the global warming simulated by a climate model in response to a sustained doubling of atmospheric CO_2 concentrations, still shows a similar 30 percent spread[3] across leading models as it did 20 years ago.

Climate Information Delivery to Users

Although a number of aspects of the climate system can be projected with some degree of confidence, this climate information may not be useful for making decisions. As climate models have become more ambitious, so have their users. Many users of climate model outputs need to make decisions on how or whether to respond to climate change, in some cases within institutions where the reality or importance of climate change is not universally acknowledged. Users consider the information from the climate models a valuable commodity, but they are not always sure what data are available to them or how to best use them to inform their decisions. The research community, both by limited capacity and by culture, is often hard pressed to respond to the desires of the user community for new types of model output at high time and space resolution. Quantifying uncertainty in climate projections is still a multifaceted research problem, making communication of relevant uncertainties with diverse user groups challenging, especially when these uncertainties are perceived to be discouragingly large or the climate model output is only part of a modeling chain.

WHY THIS STUDY?

With many studies and reports showing that there will likely be significant impacts as a result of climate change (IPCC, 2007a,b,c; NRC, 2010a,b,d,e, 2011a), now is an appropriate time to examine the capabilities of the nation's climate modeling enterprise to ensure that it is advancing adequately. The modeling community has already developed plans to make continued progress over the next 3-5 years. However, both the climate science and applications communities would enormously benefit from a major advance in improving the usefulness of climate projections, especially on regional space scales and decadal time scales and including trends in extreme events. Is this possible? Is this likely? How can the United States best position itself to advance and better use climate models? What resources and planning will that take? The need has arisen for a forward-looking, comprehensive, strategic assessment of how best to improve the United States' capabilities to simulate past, present, and future climate on local to global scales and at decadal to centennial time scales.

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[3] This is a 30 percent interquartile spread; see previous footnote for definition of interquartile.

In recognition of this need, the Committee on a National Strategy for Advancing Climate Modeling was tasked by NOAA, NASA, DOE, NSF, and the intelligence community to produce a high-level assessment, providing a strategic framework to guide progress in the nation's climate modeling enterprise over the next 10-20 years (see Appendix A for the full statement of task).

STRUCTURE OF THIS REPORT

In response to the statement of task for this committee (Appendix A), this study has built upon recent efforts to engage and coordinate the national and international climate modeling community, recent NRC and interagency reports that have made recommendations about both U.S. climate modeling and its role in the broader and more diverse climate research and applications communities, and recent actions and progress by federal agencies and other domestic groups. Ultimately, the report attempts to provide a coherent set of recommendations understandable to nonexperts (Box 1.3 includes the definition of a number of key terms), and to set out a comprehensive, unified, and achievable vision for climate modeling for the next decade and beyond that can form the basis of a national strategy that advances climate models, climate observations,[4] and user needs.

To obtain advice from a broad spectrum of climate modelers, researchers using climate model output, and the diverse and growing community of users of climate model outputs and projections, the committee convened a 50-person community workshop to engage with leaders from the modeling and user communities. During day-long open sessions at four other meetings, the committee heard from other stakeholder groups, both nongovernmental and from various levels of government, that are trying to use climate projections for long-term planning (Appendix B has more detail on the information-gathering process). The presentations and discussions encompassed global and regional models, downscaling, computing and data, user needs and education, the role of the private sector, and cultivating a coordinated national modeling and user community that spans many goals and applications.

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[4] One cannot consider advancing climate modeling without attention to the supporting climate observations, both space-based and in situ, needed to initialize, force, and validate climate models, as well as for monitoring climate variability and change. The United States currently does not have a coordinated climate observing system, or a strategy that could lead to a coherent system, across both in situ and remotely sensed observations. As noted in the report *Improving the Effectiveness of U.S. Climate Modeling* (NRC, 2001b): "the lack of a suitable sustained observing system for climate limits progress in climate modeling." This statement still rings true today, and therefore this report only discusses observations at a high level.

The committee was charged with examining "decadal to centennial" time scales (Appendix A) but decided to extend the report to also touch on shorter time scales, including intraseasonal to interannual (ISI) time scales, even though ISI climate prediction has recently been assessed by another NRC report (NRC, 2010c). Four motivations for this were the following: (1) Seasonal to interannual prediction is a valuable test of climate models, because phenomena that evolve on this time scale like El Niño have been well observed for more than 25 years, during which they have gone through enough cycles to allow the seasonal prediction skill of climate models to be tested and compared. (2) Decadal prediction of climate is a natural extension of interannual climate prediction, because it also requires a detailed initial knowledge of the ocean state. (3) For many users, simulation of climate variability about the long-term trends we project is also very important; ISI simulations observationally test aspects of the skill of climate models in predicting this variability. (4) Currently, ISI climate prediction is a nexus between U.S. operational weather and climate forecasting at short time scales (e.g., as performed at NCEP) and research-oriented climate modeling at long time scales. Hence, it may be a fruitful arena to explore closer interactions between the operational and research modeling communities.

This report is structured in three sections. In addition to the introduction in this chapter, this first section reviews the history of previous reports as context for this report (Chapter 2). Building on that background material, the second section of the report examines a number of the issues that are currently facing the U.S. climate modeling community. These issues include climate model hierarchy, resolution, and complexity (Chapter 3); scientific frontiers in climate modeling (Chapter 4); integrated climate observations (Chapter 5); characterization, quantification, and communication of uncertainty (Chapter 6); the climate model development workforce (Chapter 7); the relationship of U.S. climate modeling efforts with international efforts (Chapter 8); and operational climate prediction systems (Chapter 9).

This final section of the report examines several key issues in the U.S. climate modeling enterprise where the committee presents its primary recommendations and an overarching national strategy for advancing climate modeling in the United States over the next two decades. These issues include the challenges and opportunities related to computational infrastructure (Chapter 10), unified climate modeling (Chapter 11), interfacing with the trained climate model user and educational communities (Chapter 12), and optimizing U.S. institutional arrangements (Chapter 13). A number of specific recommendations are presented throughout the text. These recommendations are synthesized into an overarching strategy in the final chapter of the report (Chapter 14).

BOX 1.3 DEFINITION OF KEY TERMS

Boundary conditions: External data input into climate models that define conditions that are fixed relative to the dynamic elements of those models. In the case of Earth system models, the boundary conditions define the orbit of Earth, the land/ocean cover, the height of the mountains, drainage basins and paths of rivers, and the radiation from the sun, among other things. See also *Forcings*.

Climate models and Earth system models: Climate models are computer codes that encapsulate the physical laws governing the motions and cycles of energy and water in the atmosphere, ocean, and land surface, including sea ice and snow. Earth system models are climate models that additionally incorporate representations of the chemical and biological processes that control the cycling of human-produced and natural aerosols, as well as biogeochemical substances including carbon, nitrogen, and sulfur. Some Earth system models also represent ice sheets and climate-induced changes in the distribution of different types of vegetation.

Climate predictions and projections: Climate predictions are model simulations that are started from our best estimate at the state of the climate system at a particular time. Climate projections, on the other hand, are simulations started from a statistically representative initial state. Both predictions and projections are made using estimates of future values of the forcings. The goal of projection is to look at the statistics of the simulated climate and how they change; the goal of prediction is to forecast the evolution of the actual climate state, including variations in El Niño or the Atlantic meridional overturning circulation.

Common modeling framework: A group of programs that provides a high-performance, flexible software infrastructure, which enables climate models to run on very large parallel computers and that supports coupling diverse, modular climate model components.

Data assimilation: The process of making best use of observational data to provide an estimate of the state of the system that is compatible with a given model and that is better than could be obtained using just the data or the model alone.

Forcings: External data input into climate models that drive climate variations and change (e.g., greenhouse gas concentrations, volcanic aerosols, and solar irradiance variations).

Model fidelity: The measure of agreement between the statistical distributions of a climate variable or group of variables as simulated by a model compared with observations (e.g., the seasonal and geographical root-mean-square difference between simulated and observed rainfall over 1980-2010).

Model forecast skill: The typical accuracy of a forecast, e.g., as measured by the agreement between realistically initialized model predictions of some variable (e.g., winter-mean surface air temperature over Kansas based on model predictions from 6 months before) and their corresponding verifications over some period. The relation of fidelity to skill is similar to that between prediction and projection. In particular, model fidelity (correctly predicting the statistical distribution of this quantity) need not imply model skill (skillfully predicting warm winters when they are observed).[a]

BOX 1-3 CONTINUED

Multimodel ensemble: A set of simulations from several different models, forced by the same external forcing. Considerable evidence suggests that an average over simulations from different models produces a better match to observational climatological distributions than similar-sized averages of simulations from any single model.

Perturbed physics experiments: Multiple simulations from the same models using a plausible range of parameters or representations of physical processes. These simulations make it possible to analyze the sensitivity of simulation results to some of the choices made in model development.

Operational climate prediction: Distinct from climate model research and development, operational climate prediction is a regularly scheduled, user-driven, product-oriented process that conforms to a specified schedule of generation and delivery of products and that depends on dedicated computing and information delivery resources with failsafe contingency plans.

Parameterization: The process of representing the effects of processes other than resolved-scale fluid motion (e.g., cumulus cloud dynamics and microphysics; land-surface or sea-ice modeling; or transfer of heat, salt, and nutrients in unresolved oceanic eddies) in a climate model by using the resolved fields whose time evolution is predicted by the model.

Reanalysis: The process of reassimilating historical observations of atmospheric and oceanic quantities such as temperature, pressure, wind, humidity, current, and salinity using fixed state-of-the-art models and data assimilation techniques to produce long time series of global fields.

Regional climate models: Climate models that are restricted to a portion of the globe so as to reduce the computational cost and thereby increase the spatial resolution, and which use the output of a coarser-resolution global climate model at their boundaries. Such models are often used in "downscaling," the process of representing global climate model output at the relatively small spatial scales that are more relevant to decision makers. Regional climate models sometimes include greater scientific complexity that can inform particular applications and decision makers.

Seamless prediction: Viewing weather and climate prediction as problems that share common processes and dynamics and that can be addressed using modeling approaches that span a broad range of time scales and spatial resolutions.

Tuning: The process of adjusting the values of parameters used in climate models to achieve the best fit to observations in a dependent control data set. The values are adjusted only within the range of observational uncertainty of those parameters.

Uncertainty: Lack of knowledge or imperfect knowledge about specific quantities or the behavior of a system.

Unified modeling across time scales: The ultimate realization of seamless prediction whereby a single climate model is used to predict the weather, seasonal climate, and decadal climate change.

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[a] There is some evidence that model fidelity and prediction skill are related (see DelSole and Shukla, 2010).

CHAPTER TWO

Lessons from Previous Reports on Climate Modeling

This report is not the first to look at the issue of how to improve the nation's climate models. In this section, a set of reports and articles that have been produced over the past several decades are examined (Table 2.1). The goal is to use the lessons from these previous reports to inform this one.

In addition to examining these documents themselves, this committee also commissioned 11 interviews to gain insight into the reception of these reports as part of the information-gathering process (Appendix B). The interviewees are individuals who

TABLE 2.1 Previous Reports and Articles on Improving Climate Modeling in the United States Consulted in this Review

Year	Author	Report Title
1979	NRC	Carbon Dioxide and Climate: A Scientific Assessment
1982	NRC	Meeting the Challenge of Climate
1985	NRC	The National Climate Program: Early Achievements and Future Directions
1986	NRC	Atmospheric Climate Data, Problems and Promises
1990	Changnon et al. /NOAA	NOAA Climate Services Plan
1998	NRC	Capacity of U.S. Climate Modeling to Support Climate Change Assessment Activities
2001	NRC	Improving the Effectiveness of U.S. Climate Modeling
2001	USGCRP	High-End Climate Science: Development of Modeling and Related Computing Capabilities
2008	Schaefer et al.	An Earth Systems Science Agency
2008	Bader et al. / CCSP	Climate Models: An Assessment of Strengths and Limitations. Synthesis and Assessment Product 3.1.
2009	Doherty et al.	Lessons Learned from IPCC AR4: Scientific Developments Needed to Understand, Predict, and Respond to Climate Change
2009	NRC	Restructuring Federal Climate Research to Meet the Challenges of Climate Change
2010	NRC	America's Climate Choices

are or were active in the community and in a position to comment on the use and the impact of the previous reports as well as future directions in climate modeling. The results of the interviews generally inform the discussion in this section.

The first section of this chapter reviews a series of previous reports and articles chronologically. The second section then highlights a few key lessons that the committee draws from this set of previous reports and the responses of the interviewees.

PREVIOUS REPORTS

Reports from the 1970s and 1980s

The possibility of climate change caused by carbon dioxide emissions has been a subject of concern to the U.S. government at least since the administration of Lyndon Johnson (Johnson, 1965). The National Academy of Sciences published a significant report on climate change and climate models in 1979, which was "an independent critical assessment of the scientific basis of these (climate change) studies and the degree of the certainty that could be attached to their results" (NRC, 1979). During the 1980s there were three National Research Council (NRC) reports on meeting national needs in climate science (NRC, 1982, 1985, 1986).

As a response to these reports, in the early 1990s within the National Oceanic and Atmospheric Administration (NOAA) there were discussions on the need for the development of climate services. The opening paragraph of Changnon et al. (1990) is repeated here:

> For the past two decades it has been widely recognized that the Nation's climate service activities were not functioning well and were poorly organized. In 1978, a major motivation for the National Climate Program Act (Public Law 95367) was to improve dissemination and use of climate information. Congress found that information regarding climate was not being fully disseminated or used, and Federal efforts have given insufficient attention to assessing and applying this information. The Program mandated "systems for management and active dissemination of climatological data, information, and assessments." Since 1978 there have been several calls for an organized climate service system to improve the situation.

Throughout the 1990s a number of documents were produced, both formal and informal, about the need for more organization and coordination of U.S. efforts in climate modeling and climate observations. There was also an increasing recognition of growing societal needs for information on climate and climate change.

Reports from the Late 1990s and Early 2000s

Three reports that appeared in the late 1990s and early 2000s are of direct relevance to the current report. A first NRC report, *Capacity of U.S. Climate Modeling to Support Climate Change Assessment Activities* (NRC, 1998), was written in anticipation of U.S. climate modeling needs associated with the United Nations Framework Convention on Climate Change.[1] A major finding of the report was that modeling efforts that were of small and intermediate size were leading edge, but that high-end U.S. modeling efforts were "less prominent" in international assessments than models from other countries. This statement was based on a perceived sparseness of citations and of direct use of results from U.S. models in international assessments. Findings from this study included strong statements that a lack of a coordinated strategy for climate modeling led to the inefficient use of inadequate resources. *Capacity of U.S. Climate Modeling* concluded the following:

> Although an entirely top-down management approach for climate modeling is viewed as undesirable, national economic and security interests nevertheless require a more comprehensive national strategy for setting priorities, and improving and applying climate models.

A second NRC report, *Improving the Effectiveness of U.S. Climate Modeling* (NRC, 2001b), sponsored by NOAA and the National Science Foundation, was framed as a "first response" to *Capacity of U.S. Climate Modeling*. *Improving the Effectiveness* concluded that the United States needed a centralized capability to deliver the climate modeling products required by society. At the time of *Improving the Effectiveness*, the prominent societal need was assessment of climate change and its impacts on regional, national, and global scales. The report also placed climate modeling as part of a larger enterprise that includes a climate observing system, high-performance computer systems, software frameworks, human resources, analysis environments, and organizational support for the interface of climate modeling activities to greater societal needs. The report stated that

> [a] new way of focusing resources to meet the specific challenges posed by these various demands implies a less fragmented and therefore more centralized mode of addressing these problems. The nature of the institutional and management requirements were discussed in terms of a Climate Service, which here is the designation for the organizational entity that would create the climate information products and manage the climate modeling activities that would deliver these products.

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[1] http://www.unfccc.int (accessed October 11, 2012).

Improving the Effectiveness called for an operational capability, but with tighter coupling of the research and operational communities than in the national weather-forecasting enterprise.

High-End Climate Science: Development of Modeling and Related Computing Capabilities (USGCRP, 2001) was commissioned by the Environment Division of the White House Office of Science and Technology Policy in January 2000. Like *Improving the Effectiveness*, it was a response to *Capacity of U.S. Climate Modeling*. At the time the report was commissioned, it was a fact that U.S. climate models would *not* contribute results to the U.S. National Assessment (National Assessment Synthesis Team, 2000, 2001); hence, climate modeling capacity was de facto inadequate, and the goal of the report was to get an actionable understanding of this inadequacy.

High-End Climate Science focused on the fragmentation of U.S. modeling efforts and the other parts of the climate enterprise (e.g., observing system, computer systems, and software). This fragmentation was caused not only by the agency funding processes, but also by the underlying reward structure. For individuals and institutions, fragmentation can have perceived benefits, including individual autonomy contributing to creativity, innovation, and individual recognition. Hence, more centralized approaches are naturally resisted by some. The report argued that without addressing fragmentation and its causes, additional funding would not effectively address inadequacies in the provision of products that required synthesis of information, expertise, and software. The report was cautious about building new institutions, because human resources were limited and already fully engaged in existing institutions. Nevertheless, it recommended a product-focused climate service organization with a new "business model" to meet societal needs for climate information.

Reports from the Mid-2000s to the Present

The 2008 article "An Earth Systems Science Agency" (Schaefer et al., 2008) was written largely by former high-level officials of U.S. agencies who had served while the previous reports were published. They called specifically for merging NOAA and the U.S. Geological Survey into an independent Earth Systems Science Agency. The authors cited "inadequate organizational structure, ineffective interagency collaboration, declines in funding, and blurred authority for program planning and implementation," reiterating the theme of dysfunctional institutional fragmentation. In order to address these issues, they stated, "The executive and legislative branches of the federal government and of the states will have to transcend bureaucratic boundaries and become much more innovative in developing and implementing policy responses."

Climate Models: An Assessment of Strengths and Limitations (Bader et al., 2008) was a report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. This report analyzed the current state of climate modeling and future developments, focusing mainly on expected improvements due to increases in resolution as well as due to the inclusion of carbon-cycle processes and other biogeochemical cycles.

Restructuring Federal Climate Research to Meet the Challenges of Climate Change (NRC, 2009) anticipated a new strategy for climate change research following the 2008 presidential election. This study recommended a restructuring of research programs from traditional disciplines to a set of problems that were of societal relevance. With this focus, stakeholders would be more naturally engaged, and the problems of integration, synthesis, communication, and application would be more naturally addressed. This report, again, pointed out the need for coordination: "Coordinate federal efforts to provide climate services (scientific information, tools, and forecasts) routinely to decision makers." They further recommended:

> The restructured climate change research program provides a framework to coordinate federal efforts to provide climate services to meet the climate information needs of policy and decision makers concerned with impacts, mitigation, and adaptation to climate change at federal, state, and local levels. The services should be led by a single agency but have broad participation from other federal agencies.

The recent collection of reports, *America's Climate Choices* (NRC, 2010a,b,d,e, 2011a), calls for a "single federal interagency program or other entity to coordinate and implement an integrated research effort." Another finding is the need for "use-inspired, fundamental research that contributes to both improved understanding and more effective decision making." *America's Climate Choices* also substantiates the enormous range of the information that is needed and the complementary development of models to address these needs. Of special note is the requirement for information on regional and local scales that is relevant to planners and resource managers.

LESSONS FROM THE RESPONSES TO PREVIOUS REPORTS

The reports described here paint a consistent picture over the two decades: individual researchers and small groups in the United States perform leading-edge, discovery climate science research, which generates knowledge, but there is a recognized need to synthesize this knowledge and perform integrated, "high-end," product-oriented research and implementation to address specific problems. Many other formal and informal reports from authors at all professional levels have expressed concerns about the inability in the United States to generate needed climate science products. A challenge, therefore, to the current committee is how to disrupt the inertia of the U.S. climate science enterprise: Going forward, what do we do differently? This section reviews several lessons drawn from the responses to these previous reports.

What Improves Usefulness of Reports

One response to previous reports has been the commissioning of additional reports to study how to implement particular recommendations from previous reports. For instance, the 1990 NOAA planning document of Chagnon et al. (1990) was a response to NRC reports in the 1980s. Both *Improving the Effectiveness* and *High-End Climate Science* were responses to *Capacity of U.S. Climate Modeling*. This succession of reports has led to more articulation of the scope of the U.S. climate science enterprise. Although the system-level response has been limited, the exposure of the scope and key elements that require attention has led to improved capabilities as agencies pick up those elements for which they have expertise, mission, and funding.

As mentioned above, 11 interviews of individuals in a position to comment on the use or impact of the previous reports were carried out by independent interviewers (Appendix B). A question asked of the interviewees was to discuss what elements or features helped to make these types of reports more useful. Their common sentiment was that these reports were used primarily by program and organizational managers within agencies that fund and carry out climate modeling research. Reports often serve as visible manifestations of the community thinking. Of most value are practically oriented recommendations and options, rather than overly academic discussions. Although these are not unexpected conclusions, they are useful reminders for this report.

Finding 2.1: Previous reports can influence strategic thinking within the government at the program level, and reports are generally most useful if they include practical recommendations.

Importance of Software Infrastructure

Both *Improving the Effectiveness* and *High-End Climate Science* made strong recommendations about the development of software infrastructure to support (1) the exchange of modeling code across institutions, (2) the sharing of intellectual capital, and (3) the simplification of the interface between the climate community and the computational environment and computational vendors. Both the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) acted upon these recommendations. DOE initiated projects such as the Common Component Architecture and Model Coupling Toolkit. NASA recast its High Performance Computing and Communications activities into Computational Technologies and funded a multiagency activity to support model interoperability and reuse. This resulted in the Earth System Modeling Framework (see Box 10.2), which remains active as a multiagency activity. Investments in infrastructure to support analysis focused on model evaluation environments such as the Program for Climate Model Diagnosis and Intercomparison (a project initiated in 1989) and capabilities to improve access to data from model simulations, especially the Earth System Grid. Many of these activities remain active today, with significant project-based, bottom-up emergence of organized communities and evolving community governance, for example, the Global Organization of Earth System Science Portals,[2] the Earth Systems Grid Federation,[3] and the Global Interoperability Program.[4]

In addition, NOAA established the Climate Test Bed in 2005 to "accelerate the transfer of research and development into improved NOAA operational climate forecasts, products, and applications." In 2010, NOAA and DOE initiated the National Climate-Computing Research Center at Oak Ridge, Tennessee, representing a significant strategic change in provision of computational resources for climate-focused computing. NASA specifically refocused its primary Earth science computational center as the NASA Center for Climate Simulation. The National Center for Atmospheric Research (NCAR) is presently building the NCAR-Wyoming Supercomputing Center, which is a data-centric facility designed to accommodate the specific attributes of climate research.

Through its discussions, information gathering, and interviews, the committee finds that sustained investments in software infrastructure have advanced U.S. climate modeling and its ability to deliver modeling products. The development and adoption of community software infrastructure can be slow and uneven, even when its purpose is attractive (see Box 10.2). However, within a decade such investments are supporting the execution of new climate simulations with flexibility and robustness that was previously impossible.

The committee believes this view of the importance of software infrastructure is widely recognized and cites as evidence the 2008 review of NOAA's Climate Research and Modeling Program, which noted the important role that NOAA's framework, the

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[2] http://go-essp.gfdl.noaa.gov/ (accessed October 11, 2012).

[3] http://esg-pcmdi.llnl.gov/esgf (accessed October 11, 2012).

[4] http://gip.noaa.gov/ (accessed October 11, 2012).

Flexible Modeling System, plays in management of multiple instantiations of ocean and atmosphere models to support simulations for the Coupled Model Intercomparison Project, Phase 5 (CMIP5).[5] More recently, the computational and scientific advances based on a wide range of software engineering improvements were discussed at the 2010 Annual Community Earth System Model Workshop, including the increasing use of the Earth System Modeling Framework (ESMF), a trend which continues in the current development.[6]

This progress has been hard fought, and there remains discussion in the science and science management communities on the merit of expenditures on software infrastructure. In the early 2000s there was a feeling that software technologies would be comfortably adopted by scientific organizations—"build it and they will come." Since the early 2000s there has been significant research into the development and adoption of infrastructure that points to the naïveté of this original notion. This research into infrastructure adoption, the identification of barriers, and strategies to overcome those barriers stands as significant new knowledge that informs the climate community going forward. Edwards et al. (2007) state,

> The careful nurturance of infrastructural change, and attending to the tensions that emerge from it, is a managerial and political skill of the highest order. It is also true that management often fails, and the quiet politics of infrastructure emerge as politics of a more recognizable and sometimes uncomfortable type. Such instances of tension and resistance may constitute important sites of infrastructural learning and improvement, provided we can produce mechanisms that reliably surface and honestly report on difficulty, limitation, and failure (not a simple prescription, given the incentive structures prevailing among funders, sponsors, and builders of infrastructure). Tensions are best thought of as both barriers and resources to infrastructural development, and should be engaged constructively; in particular, they should be leveraged for their contributions to long-term properties of infrastructural fit, equity, and sustainability. Approaching tension from this perspective represents one way out of what we might term the edifice complex—the tendency to build first and ask questions later, or to treat the technical "code-and-wires" core as the realest or most essential thing about infrastructure, and the rest a social add-on—that has too frequently defined and limited the work of infrastructural development.

In U.S. climate organizations, management directive or management perception of improved organizational efficiencies does not, first and foremost, motivate adoption of infrastructure. Infrastructure adoption occurs when individuals, institutions, and man-

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[5] A. Wittenberg, NOAA/Geophysical Fluid Dynamics Laboratory (GFDL), personal communication.

[6] M. Vertenstein, NCAR, personal communication.

agement all see advantages that may be scientific, computational, and resource driven. That is, the value of integrated and shared capabilities exceeds the value perceived in the current, fragmented mode of function. Based on this, the benefits achieved to date of investments in infrastructure are as much social and organizational as they are technical.

There are many tangible examples of successes in infrastructure investments; we highlight three. The first is the National Unified Operational Prediction Capability (NUOPC), which has brought together NOAA, the Navy, and the Air Force to coordinate planning and model development. As stated in the NUOPC mission:

> The NUOPC partners determined that the Nation's global atmospheric modeling capability can be advanced more effectively and efficiently with their mutual cooperation to provide a common infrastructure to perform and support their individual missions.[7]

NUOPC strives to address long-existing challenges of links between research and operations and addresses issues of workforce stresses by sharing of intellectual resources and experiences.

The second example is one of connecting both communities and scales. An important user of climate information is the hydrology community. The European Commission funded the development of the Open Modeling Interface, OpenMI, a common software framework within the hydrology community. Within the community defined by the Consortium of Universities for the Advancement of Hydrologic Science,[8] OpenMI has been used with ESMF to connect hydrologic and global models. This allows connections not simply to individual researchers, but also from community to community. It also supports the concerted development of both scientific and infrastructure capabilities across spatial and temporal scales.

The final example reaches back to the earlier reports *Improving Effectiveness* and *High-End Climate Science*. At that time, one of the reasons that European models were considered to be more prominently cited in assessment studies was attributed to the investment in software infrastructure. An archetypal example was the European Center for Medium-range Weather Forecasts, where infrastructure was viewed as an essential part of ECMWF's strategy to sustain excellent science, to engage external collaborators, and to stay ahead of changes in computational hardware. In addition, the managed model environment and attention to infrastructure at the UK Met Office (UKMO) eases execution of controlled experiments with global and regional models as

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[7] http://www.nws.noaa.gov/nuopc/ (accessed October 11, 2012).

[8] http://www.cuahsi.org/ (accessed October 11, 2012).

well as applications of the same model to both weather and climate.[9] The investment in common software infrastructures has clearly benefited these European laboratories.

Finding 2.2: Previous investments and efforts in common software infrastructure have paid substantial dividends and have helped to support social integration of the diverse climate modeling community by supporting bottom-up community cooperation.

Need for Climate Information

The reports from the late 1990s and early 2000s called for the development of capabilities that were specifically focused on regular delivery of a set of user-driven climate products and the need for some type of organizational or institutional entity responsible and accountable for their delivery. *High-End Climate Science* made the specific recommendation of "two major core simulation activities": one center formed from existing operational capabilities in the National Weather Service and another center to be federated from existing climate modeling assets; this recommendation did not get adopted, but it did heighten awareness of the need to coordinate research-driven and user-driven modeling. An issue with which both *Improving the Effectiveness* and *High-End Climate Science* wrestled was the need to provide a home and adequate emphasis for seasonal and El Niño-Southern Oscillation-scale prediction. This type of modeling activity fell between larger existing efforts for weather prediction and long-term climate simulations and was fragmented between two parts of NOAA—GFDL and the National Centers for Environmental Prediction (NCEP)—as well as other agencies. In response to these perceived needs, new capabilities have been developed, for example, NCEP's Climate Forecast System (Saha et al., 2006) and a new NOAA-supported National Multi-Model Ensemble[10] seasonal prediction project.

Although many positive changes to address issues of resources, coordination, and structuring of the U.S. climate enterprise were initiated by these reports, large systemic challenges remain. The article "An Earth Systems Science Agency" (Schaefer et al., 2008) pointed to the same types of organizational shortcomings as were outlined in both *Improving the Effectiveness* and *High-End Climate Science*. *Improving the Effectiveness* also noted that the United States needs to improve the capabilities of climate models to address the following societal needs:

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[9] A. Brown, UKMO, personal communication.

[10] http://www.cpc.ncep.noaa.gov/products/NMME/ (accessed October 11, 2012).

- short-term climate prediction on scales of months to years,
- study of climate variability and predictability on decadal to centennial time scales,
- national and international assessments of anthropogenic climate change,
- national and international ozone assessments, and
- assessment of the regional impacts of climatic change.

These needs were identified decades ago, remain today, and motivate the current committee.

Many interviewees felt that, until the climate modeling community committed to support provision of user-driven predictive products, there would be little chance of garnering additional sponsor support. It is fully realized by both interviewees and the committee that there remain formidable challenges in climate prediction with open fundamental questions. However, given that the present state of knowledge about our future climate is sufficient to identify risk and to motivate the need for profound societal response, there is a need for the development of the routine production and evaluation of experimental products, with the development of operational capabilities as experimental products mature.

Finding 2.3: Previous reports highlight the need for routine and reliable climate information, products, and services. In addition, the view outside the modeling community is that more of these products are needed.

Challenges of Institutional Reorganizations

Climate modeling needs to be considered as a part of a broader enterprise, existing in a balance with climate observations, high-performance computing, and discipline-specific information systems that support analysis, access, and interpretation of climate information. Currently, the U.S. climate modeling enterprise that addresses this suite of activities is spread across a number of different modeling groups; in particular weather and climate modeling are largely being done in separate institutions. Our interviewees strongly and broadly valued maintaining a diversity of approaches within the suite of climate modeling activities, offering justifications based on scientific, organizational, and mission-related reasons. Several also noted that diversity poses risks to the effectiveness of the climate modeling enterprise ranging from systematic fragmentation and the potential perception of uncertainty regarding climate information from outside the science community.

Numerous previous reports discussed above called for increased coordination of climate research activities within the U.S. government. These calls were echoed by several of the interviewees, who suggested that strategies for strong unification and perhaps centralization need to be considered. However, there was near consensus among the interviewees who commented on these suggestions that restructuring and reorganizing federal assets and agencies into a single climate agency would be risky and inadvisable. More than one interviewee stated that a weakness of previous reports was that they did focus on restructuring.

There is a clear tension between the near-universal call for increased coordination and synthesis of knowledge, and the lack of progress toward that goal. Part of this lack of progress can be attributed to the differing mandates of the various agencies involved in climate research, and this issue is discussed more thoroughly by several previous reports in their review of U.S. Global Change Research Program (USGCRP) as a coordinating activity (Box 2.1). The interviews documented that the effectiveness of the USGCRP coordination activities has been strongly dependent upon external political factors associated in part with changes of administrations and Congresses. The *America's Climate Choices* report describes the current view of USGCRP and the Climate Change Adaptation Task Force:

> The USGCRP and the Climate Change Adaptation Task Force have largely been confined to convening representatives of relevant agencies and programs for dialogue, without mechanisms for making or enforcing important decisions and priorities.

The NRC Advisory Board for USGCRP, convened in 2011, noted in a review of the recently released 2012 USGCRP Strategic Plan that USGCRP needs a stronger overall governance structure, including an ability to compel reallocation of funds to serve the program's overarching priorities (NRC, 2012b). The current committee shares this view.

As noted above in the description of software infrastructures, the emergence of bottom-up communities with viable governance strategies to support community planning and decision making has met with success in a number of areas. This is an organic development of self-governance at the project level and provides a foundation for the future. Attention to governance brings attention to interfaces, for example between scientific algorithms, software, and computational environments. Success in these nascent communities requires development of decision-making processes that balance the requirements and the expectations of the community members.[11] That is,

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[11] For example, in the second funding cycle of ESMF, focus was extended from technology to the formation of a multiagency organization. This focus on process and governance included development of ways to manage sponsor and user expectations, requirements, and delivery. Following this refocusing ESMF garnered

BOX 2.1 U.S. GLOBAL CHANGE RESEARCH PROGRAM

The U.S. Global Change Research Program (USGCRP) coordinates and integrates federal research on changes in the global environment and their implications for society. The USGCRP began as a presidential initiative in 1989 and was mandated by Congress in the Global Change Research Act of 1990, which called for "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."[a]

Thirteen departments and agencies participate in USGCRP, which was known as the U.S. Climate Change Science Program from 2002 through 2008. The program is steered by the Subcommittee on Global Change Research under the Committee on Environment and Natural Resources, overseen by the Executive Office of the President and facilitated by an Integration and Coordination Office. USGCRP agencies interact with a wide variety of groups around the world including international, national, state, tribal, and local governments, businesses, professional and other nonprofit organizations, the scientific community, and the public. USGCRP agencies coordinate their work through Interagency Working Groups (IWGs) that span a wide range of interconnected issues of climate and global change. The IWGs address major components of Earth's environmental and human systems, as well as cross-disciplinary approaches for addressing issues under USGCRP's purview. One of these working groups is currently focused on advancing climate modeling (the Interagency Group on Integrative Modeling).

During the past two decades, the United States, through USGCRP, has made the world's largest scientific investment in the areas of climate change and global change research. In fiscal year 2010, USGCRP investments in activities such as observations and monitoring, information services, research and modeling, assessment, communications, and outreach totaled about $2 billion. Recently, USGCRP released a 10-year strategic plan and has spent significant effort in implementing a process to conduct systematic and iterated national assessments of the consequences of climate change (USGCRP, 2012).

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[a] http://www.globalchange.gov/about/overview (accessed October 11, 2012).

the community integrates activities at a working level and across institutions. Climate Process Teams are viewed as an activity that is effective in such focused and substantive integration (see more in Chapter 5). Likewise, NUOPC (described above) is linking agencies and laboratories in new ways. If the United States is going to address the advancement of the synthesis of information to address climate change, then it would be most effective for the country to build on these emergent communities. They represent accumulated expenditures in science, infrastructure, and human resources that

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an increased number of funding agencies and focused applications projects on, for example, space weather and sediment transport (see, for example, http://www.earthsystemmodeling.org/components/ [accessed October 11, 2012]).

are substantial and unlikely to be duplicated in the future. Going forward, the technical advances in modeling and analysis infrastructure, the accomplishments in the reductions of barriers in infrastructure adoption, and the emergence of participatory communities are essential elements of a national strategy to advance climate modeling.

The committee's analysis is that USGCRP is a necessary element of the governance of the federal community; however, it is not sufficient. Simply coordinating, more tightly, federal budgets through the current programs does not ensure the necessary synthesis nor does it ensure balanced investment across all of the parts of the climate enterprise. Thus, we propose that mechanisms for governance of cross-agency climate modeling activities would be best served if they are strongly anchored in the working level, i.e., through working groups and community-based planning. The development of a sustained, community-wide integrating activity in parallel with the activities of USGCRP is an essential element of governance; therefore, such a group would need to develop credibility with cross-agency funding activities, i.e., with USGCRP, as having strategic and programmatic goals in balance.

Finding 2.4: Previous reports have consistently called for more coordination and consolidation of climate modeling agencies and institutions, but these have met with limited success. The emergence of bottom-up community governance offers new strategies for working-level decision making to support integrated and balanced planning and implementation.

PART 2

Current Issues in Climate Modeling

Building on the background material in the first section, this section of the report examines a number of the issues that are currently facing the U.S. climate modeling community. A number of specific recommendations are presented throughout the text. These recommendations are synthesized into an overarching strategy in the final section of the report.

CHAPTER THREE

Strategies for Developing Climate Models: Model Hierarchy, Resolution, and Complexity

There is an almost bewildering landscape of climate models used in different communities and for different purposes. At present, as in the past, important advances in climate science are being made with models from across this landscape, including both more comprehensive models that are arguably more realistic and simpler models whose behavior can be more readily understood.

In the 1950s, simple *energy-balance models* of climate with analytical solutions gave important insights into climate sensitivity and processes such as ice-albedo feedback. In the 1960s and 1970s, simple column *radiative-convective equilibrium models* were used to interpret the behavior of early atmospheric general circulation models.

Through the 1970s and 1980s, high-end *general circulation models* became progressively more comprehensive to better capture climate change feedback processes and to provide more credible regional information on climate change. The incorporation of dynamic ocean and sea-ice models in the 1980s and 1990s to create *coupled climate models* allowed some of the first estimates of the transient response of the climate system to changing greenhouse gases.

In the 1990s and 2000s, more complete treatments of sea-ice and land-surface processes were included, along with submodels of terrestrial vegetation, ecosystems, and biogeochemical cycles such as the carbon cycle. The role of aerosols and atmospheric chemistry has become a major focus of recent climate modeling efforts, including representations of processes related to the formation of the Antarctic ozone hole and of aerosol effects on climate (e.g., their interaction with clouds). These new models are often referred to as *Earth system models* (ESMs), because they can track the propagation and feedbacks of perturbations through the different components of the Earth system. Currently, most ESMs use global resolutions of 100-300 km and 20-100 vertical layers and can be run for thousands of simulated years at a few years to a few decades per day of actual time on supercomputing systems. Figure 3.1 highlights aspects of the evolution of climate models over the past few decades.

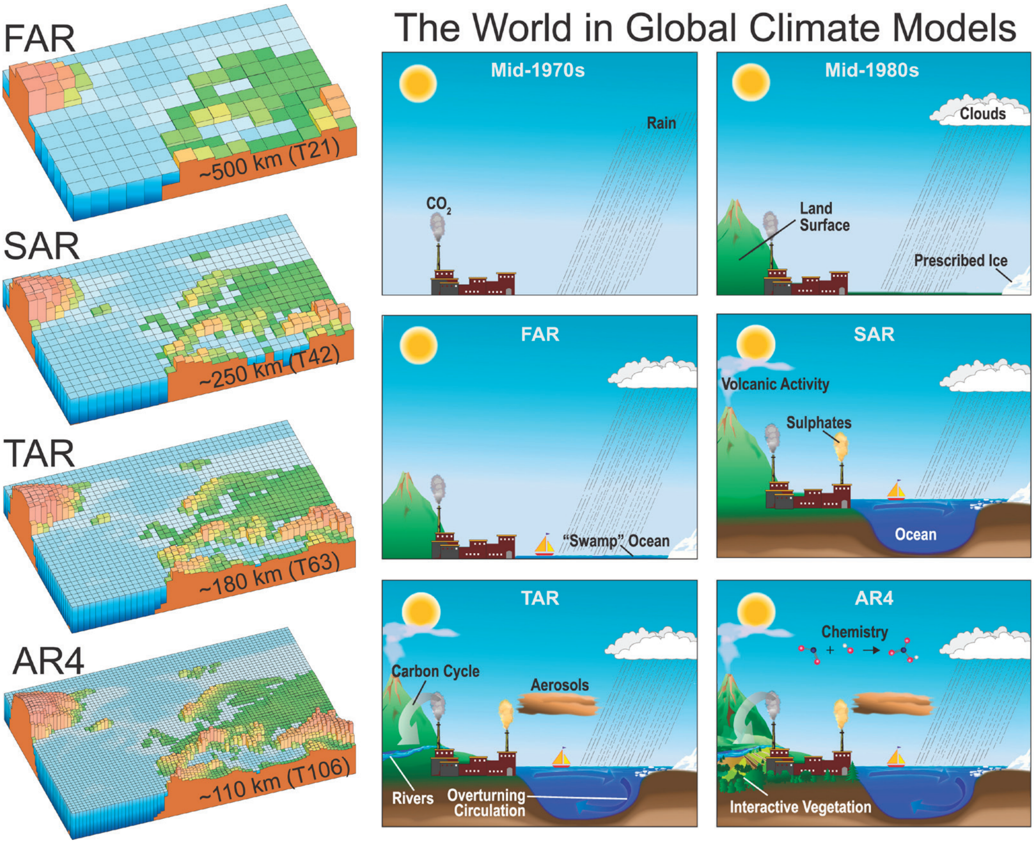

FIGURE 3.1 Illustration of increasing complexity and diversity of elements incorporated into common models used in the Intergovernmental Panel on Climate Change (IPCC) process over the decades. Evolution of the resolution (left side) and physical complexity (right side) of climate models used to inform IPCC reports from the mid-1970s to the most recent IPCC report (IPCC, 2007a,b,c). The illustrations (left) are representative of the most detailed horizontal resolution used for short-term climate simulations. SOURCES: Figure 1.2 and 1.4 from IPCC (2007c). FAR, First Assessment Report, 1990; SAR, Second Assessment Report, 1995; TAR, Third Assessment Report, 2001; AR4, Fourth Assessment Report, 2007.

Although comprehensive climate models are becoming more complex, an increasing range of other models has helped to evaluate and understand their results and to address problems that require different tradeoffs between process complexity and grid resolution. *Uncoupled component models*, often run at higher resolution or with idealized configuration, allow a more controlled focus on individual processes such as clouds, vegetation feedbacks, or ocean mixing and enable the behaviors of the uncoupled components to be studied in more detail.

Unified weather-climate prediction models (Chapter 11), which are typically run with higher resolution than general circulation models (GCMs), are an increasingly important part of the spectrum of climate models. Testing a climate model in a weather forecast mode, with initial conditions taken from a global analysis at a particular time, allows evaluation of rapidly evolving processes such as cloud properties that are routinely observed (Phillips et al., 2004). Such simulations are short enough to test model performance over a range of grid resolutions relevant not only to current but also to prospective climate simulation capabilities.

Process models such as *single-column models* and *cloud-resolving models* were developed as a bridge between observations and parameterized representation of unresolved processes needed in GCMs. This has fed back into GCM development through evaluation and improvement of physics parameterizations. This has also led to the development of a special class of *"superparameterized" climate models* in which the atmospheric physics in each column of the global model is simulated using a high-resolution cloud-resolving model that better represents the small-scale cloud-forming processes associated with turbulence and atmospheric convection (Khairoutdinov et al., 2005). This method, however, is computationally demanding, so its use has been limited mainly to research so far.

Because of computational requirements for running GCMs at high resolution, *nested regional atmospheric and oceanic models* forced at the lateral boundaries have become attractive tools for addressing problems requiring locally high spatial resolutions, such as orographic snowfall and runoff, or oceanic eddies and coastal upwelling. Regional atmospheric models were mainly adapted in the past two decades from regional weather-prediction models and have attracted a somewhat different and more diverse user and model development community than global models (Giorgi and Mearns, 1999). These models have been used to further the understanding of regional climate processes, to provide dynamical downscaling of GCM simulations to produce more spatially resolved (typically between 5- and 60-km resolution) seasonal-to-interannual predictions and century-scale climate projections, as well as to test physical/chemical process parameterizations at finer spatial resolutions that anticipate the next generation of global climate models, including slow time scale physics (such as land-surface processes) that are not amenable to testing by weather forecast simulations. Hybrids between regional and global models are being actively developed, using *stretched* or *variable grids* that simulate the entire globe but telescope to much finer resolution within a region of interest.

There has always been a desire for global models that can simulate climate change and variability on millennial and longer time scales, for example, for understanding glacial cycles. This has led to *Earth system models of intermediate complexity* (EMICs), which use highly simplified process representations but add slowly evolving components such as ice-sheet and dynamic vegetation models that are critical on centennial to millennial scales. Some of the physics developed in such models has been the nucleus of parameterizations now used in ESMs for simulating processes like the carbon cycle. EMICs are also important tools for understanding the role of different Earth system components and their interactions in climate variability at millennial and longer time scales.

Climate models have also started to include some representations of human systems. Examples include efforts to represent air quality in atmospheric models and water quality, irrigation, and water management in land-surface models. More substantial efforts in coupling integrated models of energy economics, energy systems, and land use with ESMs have recently been undertaken to represent a wider range of interactions between human and Earth systems. These models, called *integrated assessment models*, could be useful tools for exploring climate mitigation and adaptation where human systems play an important role.

The landscape of climate models that developed naturally in the past will continue to evolve. Figure 3.2 shows one view of the landscape of the types of current models

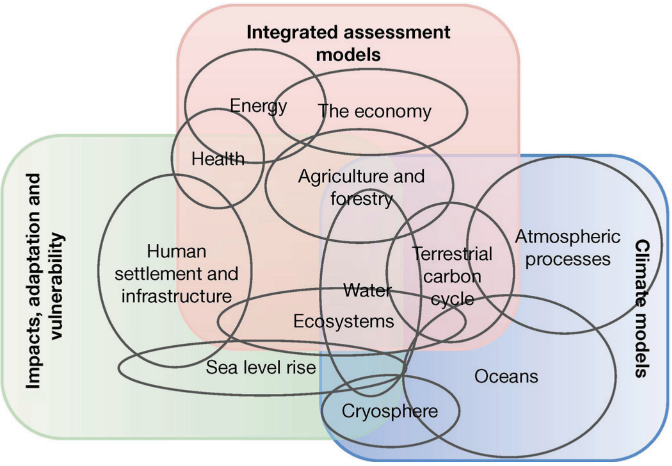

FIGURE 3.2 The landscape of the various types of climate models within a hierarchy of models is complex and overlapping. This is one view of that landscape centered on the three broad types of models and analytic frameworks in climate change research that contribute to the IPCC reports: integrated assessment models, physical climate models, and models and other approaches used to help assess impacts, adaptation, and vulnerability. SOURCE: Moss et al., 2010. Reprinted by permission from Macmillan Publishers Ltd., copyright 2010.

involved in the IPCC assessments. This chapter discusses issues of model resolution and complexity as well as future trends in the hierarchy of models and development pathways.

MODEL RESOLUTION

A major component of climate models is the dynamical core that numerically solves the governing equations of the system components. Computation of the solution is carried out on a three-dimensional spatial grid. Increasing model resolution enables better resolution of processes, but this comes at considerable computational cost. For example, increasing horizontal resolution by a factor of 2 (say from 100 to 50 km^2) generally requires a factor of 2 decrease in time step for numerical stability. Thus, the overall computational cost is a factor of 8. Furthermore, to avoid distortion of the results, the horizontal resolution cannot be increased without concomitant increases in vertical resolution. Increasing complexity independently adds to the computational cost of a model, so a balance must be sought between resolution and complexity. In practice, the ensemble of these considerations has led to an increase in atmospheric grid resolution from ~500 km to ~100 km in state-of-the-science climate models since the 1970s.

To enable higher resolution within computational constraints, alternative approaches such as regional climate models and global models with variable resolution, stretched grids, or adaptive grids have been developed to provide local refinements for geographic regions or processes of interest. Similar to global atmospheric models, regional climate models numerically and simultaneously solve the conservation equations for energy, momentum, and water vapor that govern the atmospheric state. Solving these equations on limited-area domains requires lateral boundary conditions, which can be derived from global climate simulations or global analyses. Because of the dependence on large-scale circulation, biases in global climate simulations used to provide lateral boundary conditions propagate into the nested regional climate simulations. Similar to global models, regional models are sensitive to model resolution and physics parameterizations. However, the nesting approach can introduce additional model errors and uncertainties. This issue has been addressed in a series of studies using an idealized experimental framework, known as "Big Brother Experiments (BBE)" (Denis et al., 2002). As summarized by Laprise et al. (2008), the BBE show that, given large-scale conditions provided by the GCMs, regional climate models can downscale to produce finer-scale features absent from the GCMs. Moreover, the fine scales produced by the regional models are consistent with what the GCMs would generate if they were applied at similar spatial resolution as the regional models, thus confirming the practical validity of the nested regional modeling approach.

More recently, global variable-resolution models using unstructured grids have become feasible (Skamarock et al., 2011). By eliminating the physical boundaries, these models provide local mesh refinement with improved accuracy of the numerical solutions. However, the challenge of developing physics parameterizations that work well across the variable resolution is significant. Systematic evaluation and comparison of different approaches is important for developing a more robust framework to model regional climate. Besides increasing grid resolution, subgrid classification is used in some land-surface models or even atmospheric models (e.g., Leung and Ghan, 1998) to capture the effects of land-surface heterogeneity such as vegetation and elevation to improve simulations of regional climate.

There is considerable evidence that refining the horizontal spatial resolution of climate models improves the fidelity of their simulations. At the most fundamental level, increasing resolution should improve the accuracy of the approximate numerical solutions of the governing equations that are at the heart of climate simulation. However, because the climate system is complex and nonlinear, numerical accuracy in solving the dynamical equations is a prerequisite to climate model fidelity, but is not the only consideration.

One of the more obvious impacts of improving climate model resolution is the representation of geographic features. Resolving continental topography, particularly mountain ranges and islands, can significantly improve the representation of atmospheric circulation. Examples include the South Asian monsoon region and the vicinities of the Rockies, Andes, Alps, and Caucasus, where the mountains alter the large-scale flow and give rise to small-scale eddies and instabilities. Resolving topography can also improve simulations of land-surface processes such as snowpack and runoff that rely strongly on orographically modulated precipitation and temperature (e.g., Leung and Qian, 2003) and may also have upscaled or downstream effects on atmospheric circulation (e.g., Gent et al., 2010) and clouds (e.g., Richter and Mechoso, 2006). Similarly, weather and climate variability associated with landscape heterogeneity, as well as coastal winds influenced by local topography and coastlines, are better represented in models with refined spatial resolution, which can also lead to improved simulation of tropical variability through improved coastal forcing (Navarra et al., 2008).

Many processes in the ocean and sea ice can benefit from increasing spatial resolution. Improved resolution of coastlines, shelf and slope bathymetry, and sills separating basins can significantly improve the simulation of boundary and buoyancy-driven coastal circulation, oceanic fronts, upwelling, dense water plumes, and convection, as well as sea-ice thickness distribution, concentration, deformations (including leads and polynyas), drift, and export. In particular, high spatial resolution is needed in the Arctic Ocean, where the local Rossby radius of deformation (determining the size of the smallest eddies) is on the order of 10 km or less, and exchanges with other oceans occur via narrow and shallow straits. Bryan et al. (2010) showed improvements in simulating the mean state as well as variability with an ocean model at 10 km versus 20-50 km spatial resolution, suggesting a regime change in approaching the 10 km resolution.

Besides improving stationary features such as those associated with terrain, increasing spatial resolution also allows transient eddies such as synoptic-scale frontal systems and local convective systems to be better represented. These transient eddies, as well as small-scale phenomena in the ocean-atmosphere system such as tropical cyclones, play important roles in the energy, moisture, and momentum transports that determine the mean climate and its variability.

Most current climate models divide the atmospheric column into 20-30 vertical layers, but some models include more than 50 layers with the increased vertical levels mostly added near the surface (to better resolve boundary-layer processes) or near the tropopause (to better simulate atmospheric waves and moisture advection).

Typical vertical resolution of ocean models that are part of climate models is 30-60 vertical layers, which could be at fixed depths or vary according to density or topography. Ocean models whose vertical grids extend to the ocean bottom are better able to represent the abyssal circulation. As in the case of atmospheric models, increased vertical resolution is added near the surface in order to better resolve the surface mixed layer and upper ocean stratification, as well as shelf and slope bathymetry. In addition, high vertical resolution is often needed near the bottom, especially to improve representation of bottom boundary-layer, density-driven gravity flows (e.g., over the Arctic shelves) and dense water overflows (e.g., Denmark Strait or Strait of Gibraltar).

Finally, there is evidence of feedbacks that are strongly dependent on model resolution and that therefore influence a model's response to perturbations, for example:

- atmospheric blocking, which is dependent on the feedbacks between the large-scale atmospheric circulation and mesoscale eddies (Jung et al., 2011);
- feedbacks between western boundary currents with sharp temperature gradients in the ocean and the overlying atmospheric circulation (Bryan et al., 2010; Minobe et al., 2008);

- feedbacks between tropical instability waves in the ocean and wind speed in atmospheric eddies (Chelton and Xie, 2010);
- air-sea interactions in presence of a sea-ice cover, which depend on the accuracy of detailed representation of sea-ice states, including ice edge position, thickness distribution, and deformations; and
- ice sheet-ocean interactions, which require representation of local flow under and into the ice, including fjord circulation and exchanges.

However, increasing spatial resolution is not a panacea. Climate models rely on parameterizations of physical, chemical, and biological processes to represent the effects of unresolved or subgrid-scale processes on the governing equations. Increasing spatial resolution does not automatically lead to improved accuracy of simulations (e.g., Duffy et al., 2003; Kiehl and Williamson, 1991; Leung and Qian, 2003; Senior, 1995). Often, the assumptions in the parameterizations are scale dependent, although so-called scale-aware parameterization development has been pursued recently (e.g., Bennartz et al., 2011). As model resolution is increased, the assumptions may break down, leading to a degradation of the simulation fidelity. Even if the assumptions remain valid over a range of model resolutions, there is still a need to recalibrate the parameters in the parameterizations as resolution is refined (sometimes called model tuning), and the tuning may only be valid for the time period for which observations used to constrain the model parameters are available. The lack of understanding and formulation of the interactions between parameterizations and spatial resolution makes it hard to quantify the influence of spatial resolution on model skill. Furthermore, structural differences among parameterizations may have comparable, if not larger, effects on the simulations than spatial resolution.

Climate projections at finer scales (such as resolving climatic features for a small state, single watershed, county, or city) are typically produced using one of two approaches: either dynamical downscaling using higher-resolution (50 km or finer) regional climate models nested in the global models or empirical statistical downscaling of projections developed from global climate model output and observational data sets. Neither downscaling approach can reduce the large uncertainties in climate projections, which derive in large part from global-scale feedbacks and circulation changes, and it is important to base such downscaling on model output from a representative set of global climate models to propagate some of these uncertainties into the downscaled predictions. The modeling assumptions inherent in the downscaling step add further uncertainty to the process. There has been inadequate work done to date to systematically evaluate and compare the value added by various downscaling techniques for different user needs in different types of geographic regions. However, as the grid spacing of the global climate model becomes finer, simple statistical downscaling approaches become more justifiable and attractive because the climate model is already simulating more of the weather and surface features that drive local climate variations.

Finding 3.1: Climate models are continually moving toward higher resolutions via a number of different methods in order to provide improved simulations and more detailed spatial information; as these higher resolutions are implemented, parameterizations will need to be updated.

Finding 3.2: Although different approaches to achieving high resolution in climate models have been explored for more than two decades, there remains a need for more systematic evaluation and comparison of the various downscaling methods, including how different grid refinement approaches interact with model resolution and physics parameterizations to influence the simulation of critical regional climate phenomena.

MODEL COMPLEXITY

The climate system includes a wide range of complex processes, involving spatial and temporal scales that span many orders of magnitude. As our understanding of these processes expands, climate models need to become more complex to reflect this understanding. The balance between increased complexity and increased resolution, subject to computational limitations, represents a fundamental tension in the development of climate models.

Model complexity can broadly be described in terms of the sophistication of the model parameterizations of the physical, chemical, and biological processes, and the scope of Earth system interactions that are represented. Increasing sophistication of model parameterizations is evident in models of all Earth system components. Atmospheric models, for example, have grown from specified clouds to simulated clouds using simple convective adjustment and relative humidity-based cloud schemes to a host of shallow and cumulus convective parameterizations with different convective triggers, mass flux formulations and closure assumptions, and cloud microphysical parameterizations that represent hydrometeors (mass and number concentrations) in multiple phases. Today most climate models include some representation of atmospheric chemistry and aerosols, including aerosol-cloud interactions (e.g., Liu et al., 2011). Although model parameterizations have become more detailed, uncertainty in process representations remains high as different formulations of parameterizations can lead to large differences in model response to greenhouse gas forcing (e.g., Bony and Dufresne, 2005; Kiehl, 2007; Soden and Vecchi, 2011).

Land-surface models have grown from simple bucket models of soil moisture and temperature in the 1970s (Manabe, 1969) to sophisticated terrestrial models that represent biophysical, soil hydrology, biogeochemical, and dynamic vegetation processes (e.g., Thornton et al., 2007). Most land-surface models now represent the canopy, soil, snowpack, and roots with multiple layers and simulate detailed energy and water exchanges across the layers (Pitman, 2003). Some models have begun to include a dynamic groundwater table (e.g., Leung et al., 2011; Niu et al., 2007) and its interactions with the unsaturated zone. With the representation of canopy, soil moisture, snowpack, runoff, groundwater, vegetation phenology and dynamics, and carbon, nitrogen, and phosphorous pools and fluxes, land-surface models can now simulate variations of terrestrial processes important to predictions from weather to century or longer time scales.

Ocean models are energy conserving and typically use hydrostatic (assumption of balance between the pressure and density fields) and Boussinesq approximations (assumption of constant density) to solve the three-dimensional primitive equations for fluid motions on the sphere. However, non-Boussinesq models are also used, especially to study sea-level rise. In many models, a free surface formulation is used to allow unsmoothed realistic bathymetry, especially in z-level vertical high-resolution models. Other models use a hybrid coordinate system in the vertical, which combines an isopycnal discretization in the open, stratified ocean, terrain-following coordinates in shallow coastal regions, and z-level (vertical) coordinates in the mixed layer and/or unstratified seas.

Sea-ice models commonly consist now of both dynamic and thermodynamic processes. They can often include an improved calculation of ice growth and decay, multicategory sea-ice thickness distribution to allow nonlinear profiles of temperature and salinity, snow layer, computationally efficient rheology approximation, advanced schemes for remapping sea-ice transport and thickness, and ice age for comparison with satellite measurements (e.g., Maslowski et al., 2012).

Besides increasing the complexity of individual model components, the scope of Earth system interactions that are represented has continued to increase to capture the feedbacks among Earth system components and to provide more complete depictions of the energy, water, and biogeochemical cycles. Some land-atmosphere feedbacks are snow-albedo feedback, feedback between soil moisture, vegetation, and cloud/precipitation. Some key ocean-atmosphere feedbacks are the Bjerknes feedback between easterly surface wind stress, equatorial upwelling, and zonal sea-surface temperature (SST) gradients, feedback between clouds, radiative energy fluxes, and

SST, and between sea ice, albedo, and ocean circulation. Carbon dioxide has "carbon-cycle" feedbacks with land and ocean ecosystems and with ocean circulations. Many more feedbacks are also important to the response of the Earth system to climate perturbations.

More complete depiction of the energy, water, and biogeochemical cycles enabled by coupled ESMs has important implications for climate predictions at multiple time scales. Errors in characterizing sources, sinks, and transfer of energy, water, and trace gases and aerosols due to missing, oversimplified, or uncoupled system components can have significant impacts on climate simulations because of feedback processes such as those described above.

The ability to predict climate in the long term will be limited by the ability to predict human activities. Prognostic climate calculations are dependent on the scenarios of future emission and land use, which traditionally have been exogenously prescribed. This prescription is tenuous because land cover and water availability will change as climate changes, and humans will respond and adapt to those changes. In fact, the largest force altering the Earth's landscape in the past 50 years is human decision making (Millennium Ecosystem Assessment, 2005a,b,c).

Integrated assessment models (IAMs) couple models of human activities with simple ESMs. IAMs typically take population and the scale of economic activity as prescribed from outside as well as the set of technology options available to society and national and international policies to develop time-evolving descriptions of the details of the energy, economic, agriculture, and land-use systems on annual to century time scales. IAMs open the door to internally consistent descriptions of simultaneous emissions mitigation and adaptation to climate change. For example, integrating human ESMs with natural ESMs provides a mechanism to reconcile the most obvious internal inconsistencies, such as the competition for land to mitigate anthropogenic emissions (e.g., through afforestation or bioenergy production), while adapting to climate change (e.g., expansion of croplands to compensate for reduced crop yields). IAMs introduce a new set of modeling assumptions and uncertainties; a continuing challenge will be designing IAMs with an appropriate balance of sophistication between the model components for the specific problems to be addressed.

Finding 3.3: Climate models have evolved to include more components in order to more completely depict the complexity of the Earth system; future challenges include more complete depictions of Earth's energy, water, and biogeochemical cycles, as well as integrating models of human activities with natural Earth system models.

FUTURE TRENDS AND CHALLENGES

Over the past four decades there has been steady, quantifiable progress in climate modeling (Figure 3.3). Much additional insight has been gained with new components and processes and higher resolution. These trends suggest considerable further increase in model fidelity can be achieved over the next two decades if anticipated advances in computational performance can be fully exploited.

These advancements will require significant changes in the numerical codes and software engineering, as discussed in more detail in Chapter 10, because future computers will have many more processors, but each will still have a clock speed similar to today's 1-2 GHz. In 2012, systems with ~500,000 processors that deliver a peak computational performance rate of 10 petaflops are becoming available. In theory such computers would already allow a global climate model with a grid spacing as fine as 6-10 km to simulate 5-10 years per day of computer time, a throughput rate suitable for decadal climate prediction or centennial-scale climate change projection. In practice, current climate model codes are not parallelized nearly well enough to efficiently use so many processors, and the highest-resolution centennial simulations use 25- to 50-km grid spacing. A decade hence, supercomputers will have 10^7-10^9 processors. If models could be designed to efficiently exploit this degree of concurrency (a major challenge), then this would enable an additional 2-2.5× refinement of global climate model grids to "cloud-resolving" resolution of ~2-4 km.

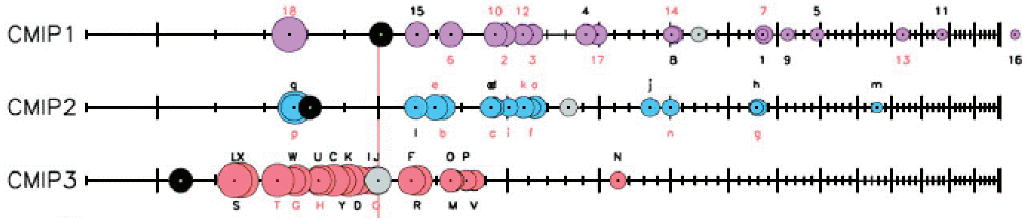

FIGURE 3.3 Performance of subsequent generations of climate models compared to observations showing improvement from the earliest (CMIP1) to latest (CMIP3). The x axis shows the performance index (I^2) for individual models (circles) and model generations (rows). The performance index is based on how accurately a model simulates the seasonally varying climatology of an aggregate of fields such as surface temperature, precipitation, sea-level pressure, etc. Best performing models have low I^2 values and are located toward the left. Circle sizes indicate the length of the 95 percent confidence intervals. Letters and numbers identify individual models (see supplemental online material at doi:10.1175/BAMS-89-3-Reichler); flux-corrected models are labeled in red. Grey circles show the average I^2 of all models within one model group. Black circles indicate the I^2 of the multimodel mean taken over one model group. SOURCE: Modified from Reichler and Kim, 2008.

While model resolution continues to increase, model complexity is anticipated to expand to fill critical gaps in current ESMs to address the scientific challenges discussed in Chapter 4. For example, one of the most daunting scientific challenges in climate modeling is the creation of internally consistent calculations of future climate that represent interactions between terrestrial Earth systems, climate systems, and human Earth systems. Modeling of biogeochemistry in the ocean and terrestrial biosphere will need to be more complete to represent the coupled hydrologic, biological, and geochemical processes. Proper inclusion of atmospheric chemistry is computationally daunting because of the large number of chemical variables and their large range of reaction time scales. Other research areas include modeling of ocean and land contributions to reactive and trace gases (e.g., how soil microbial populations regulate the release and consumption of trace gases) and interactive marine and terrestrial ecosystem models. More sophisticated models of ice sheets and of aerosol interactions with clouds and radiation are being developed to reduce key uncertainties in interpreting the historical record of climate change and in climate projection.

New model parameterizations need to be designed to work well across the range of model grid spacings and time steps over which they may be used, which is often not straightforward. The design of a parameterization is subjective and involves expert judgment about what level of complexity to represent and how physical processes interact, creating *structural uncertainty* (see Chapter 6). Hence, different climate models often incorporate different parameterizations of a given physical process. Careful observational testing is required to validate, compare, and improve parameterizations. First steps to advance the model development and testing processes are presently under way to address these challenges. One example is the Department of Energy-funded Climate Science for a Sustainable Energy Future project, which involves nine U.S. institutions working on regional predictive capabilities in global models for 2015-2020 in a strategic, multidisciplinary effort, including development of observational data sets into specialized data sets for model testing and improvement, development of model development testbeds, enhancement of numerical methods and computational science to take advantage of future computing architectures, and research on uncertainty quantification of climate model simulations.

"Complexity" is still a diffuse term in these discussions. To the committee's knowledge, there has not been a systematic comparative study of complexity across high-end climate models. Randall (2011) comes closest. If the behavior of a complex model under known modifications to inputs is conceptually understood, it may become possible to reproduce that behavior in a simpler model. A model hierarchy allows key mechanisms of climate response in complex models to be related to underlying physical principles through simpler models, hence giving complex models credibility. Model hierarchies also allow one to proceed in this manner by slotting out (either conceptually or in software) a model component, which could be a physics parameterization, a hierarchy of fluid dynamical solvers, a dynamical framework (e.g., regional versus global), or a complete model component (e.g., land-surface models) for a simpler or more computationally efficient one. One could even return to a box model with a handful of degrees of freedom (see Held [2005] for a good discussion of simulation versus understanding in a model hierarchy).

It is the nature of complex systems to exhibit emergent and surprising behavior: as researchers in other fields involving systems with many processes and feedbacks (such as biological systems) find, there are many dynamical pathways linking cause to effect, and hypotheses encouraged by simpler models often fail in a more complex model, and in nature. Even simple models often require substantial cross-disciplinary expertise to develop and effectively use and are beyond the capability of a single investigator to sustain. Maintaining a hierarchy of models with some shared components enables systematic evaluation of model components and allows models of different complexities to be maintained and used for specific scientific investigations of different time and space scales.

Finding 3.4: A hierarchy of models will be a requirement for scientific progress in order to maintain the ability to (1) systematically evaluate model components one at a time and (2) use simpler models to understand complex model behaviors and underlying mechanisms.

Finding 3.5: Investments to increase resolution as well as increase complexity are both needed. The community does not yet have the experience to extrapolate which investment may result in faster or larger benefits in the future.

MODEL EVALUATION

To guide future investments in model development, careful assessment of the additional benefits of increasing model resolution and complexity will be important. Model evaluation, in the context of predictability and uncertainty, will be increasingly critical to improve understanding of model strengths and weaknesses. Quantitative evaluation has the added benefit of helping to provide more robust estimates of uncertainty (see Chapter 6) and to discriminate the quality of climate simulations and predictions made using different models (e.g., Knutti, 2010).

However, evaluation of the increasingly more complex and higher-resolution models will be a significant challenge. Different model evaluation strategies have been explored by the climate modeling community to take advantage of the hierarchy of models, including single-column models, regional models, and uncoupled and coupled global models discussed above. Strategies that have been explored range from running idealized simulations (e.g., aqua-planet simulations) to isolate specific aspects (e.g., tropical variability) of the models, to running short case studies or weather forecasts with focus on fast processes such as clouds, to performing sensitivity experiments with new parameterizations included one at a time to reveal weaknesses of other parameterizations, to running long-term integrations of coupled and uncoupled models to evaluate the variability generated by the models and to model intercomparisons that elucidate the sources and consequences of model discrepancies.

Central to the discussion of model evaluation is the definition of performance metrics. There has been considerable progress in recent years from single metrics that quantify evaluation of a fairly narrow range of model behaviors to multivariate methods that can evaluate more aspects of models, including the spatial patterns of bias and variability and the correlations among different variables (e.g., Cadule et al., 2010; Gleckler et al., 2008; Pincus et al., 2008) as well as more modern methods of statistical analysis that are only beginning to be applied to climate simulations.

Such evaluation is hampered by the limited availability and quality of the climate observational record. For truly rigorous quantification of model fidelity, long-term observational records of climate-relevant processes and phenomena are needed that include estimates of uncertainty. Much of the instrumental record is associated with weather analysis and prediction, which means that many processes of importance to climate have not been robustly monitored.

Model development testbeds (e.g., Fast et al., 2011; Phillips et al., 2004) are important advances to streamline and modernize model evaluation through development of model-observation comparison techniques, use of a wide range of observations, and use of computational software to facilitate the model evaluation processes. Objective measures of model skill are actively being developed to guide model development and implementation. More advanced methods of evaluating climate models are coming into use that take advantage of more recent statistical analysis methods and the growing use of ensembles of climate simulations to estimate uncertainty and reliability and ensembles of climate models confronted with the same experimental protocols to evaluate the relative performance of different models. Much work is needed to refine our understanding of the relationship between observations and ensembles of climate simulations, especially because Earth's climate represents a single realization. Furthermore, highly detailed evaluation of the representation of climate processes in models is critical as the models become more complex. The growing body of paleoclimate simulations can also be compared to observations of past climate to determine the robustness of assumptions and parameters in current climate models.

Computational infrastructures that help streamline the simulation and analysis processes, as well as improved observing systems and analyses to provide data with sufficient spatial resolution and long time periods to evaluate models, are further discussed in Chapter 10 and Chapter 5, respectively.

Finding 3.6: As models grow in complexity and ensembles of climate simulations become commonplace, they are likely to exhibit an increasingly rich range of behaviors and unexpected results that will require careful evaluation; important tools for these evaluations are robust statistical comparisons among models with both historical and paleoclimate observations.

THE WAY FORWARD

To inform research, planning, and policy development, a full palette of modeling tools is required. The choice of model for a given problem would ideally be optimized to various length and time scales and with different degrees of complexity in their representation of the Earth system. This hierarchy of models is necessary to advance climate science and improve climate predictions from intraseasonal to millennial time scales.

An important challenge, therefore, for the U.S. climate modeling community over the next two decades is how to efficiently manage the interactions between models in hierarchies or linked groups of models. A shared model development process identifies key gaps in our understanding and defines experiments aimed at resolving those using protocols that different models can run (the "MIP" process). There is a need for methodological advances in comparisons across levels of the model hierarchy in a modern, distributed architecture. Common infrastructure allows differing process representations to be encoded within a common framework to allow clear comparisons. Components that enjoy community-wide consensus will be widely used; components for which there is still disagreement can go head-to-head in systematic experiments. In addition, a desirable characteristic of a model hierarchy is that results obtained at a given level in the hierarchy can inform development at other levels. Software has a role to play here; systematic approaches to maintaining model diversity under a common infrastructure are discussed in Chapter 10.

In summary, creating a structure within the model hierarchy that uses common software frameworks and common physics where appropriate is highly beneficial. Doing this well can develop the interdisciplinary modeling communities, reduce overlapping efforts, allow more efficient development of new modeling tools, promote higher standards or best practices, facilitate interpretation of results from different modeling approaches, speed scientific advance, and improve understanding of the various sources of modeling uncertainty.

Decision makers at many levels often desire projections of climate and its future range of variability and extremes localized to individual locations or very fine, subkilometer, scales. While the resolution of global climate models may eventually be this fine, the committee judges that this is not likely to occur within the next 20 years. In the meantime, other statistical or dynamical downscaling techniques will continue to be used to provide finer-scale projections. Although an evaluation of various methods would be useful, this would likely require a study unto itself. Furthermore, as global climate resolutions become finer themselves, statistical downscaling techniques become simpler and more straightforward and the need for more computationally expensive dynamical downscaling may diminish. Thus, the committee focused its attention in this report on improving the fidelity of models at all scales. However, like downscaling itself, using climate models with finer grids does not guarantee a much more certain or reliable climate model projection at local scales. As noted above, the uncertainties in climate models even at local scales derive in large part from global-scale processes such as cloud and carbon-cycle feedbacks, as well as uncertainties in how future human greenhouse gas and aerosol emissions unfold.

Recommendation 3.1: To address the increasing breadth of issues in climate science, the climate modeling community should vigorously pursue a full spectrum of models and evaluation approaches, including further systematic comparisons of the value added by various downscaling approaches as the resolution of climate models increases.

Recommendation 3.2: To support a national linked hierarchy of models, the United States should nurture a common modeling infrastructure and a shared model development process, allowing modeling groups to efficiently share advances while preserving scientific freedom and creativity by fostering model diversity where needed.

CHAPTER FOUR

Scientific Frontiers

Global climate models need to represent the intricate workings of the climate system and they need to provide information on the ways climate change and climate variability will impact society, including sea-level rise, regional climate trends and extremes, food security and ecosystem health, and abrupt climate change.

Ideally, global climate models would simulate climate dynamics at a spatial resolution high enough to resolve features like cities, river drainages, and mountain ridges, as well as convective storms and ocean eddies, minimizing the need for further downscaling of the model output—a grid spacing of 1-5 km would suffice for many purposes and is achievable within 10-20 years. This resolution is expected to improve representation of critical climate processes such as clouds and cumulus convection, mesoscale ocean eddies, and land-surface processes. Such models would provide information that meets the needs of society and would include fully interactive Earth system components (i.e., atmosphere, ocean, cryosphere, biosphere, land-surface, and human systems). Models should have seasonal and decadal predictive skill, should be able to replicate historical trends and modes of variability (e.g., El Niño/Southern Oscillation [ENSO]; decadal-scale Atlantic and Pacific variability), and should be able to capture the processes and feedbacks involved in major paleoclimate events, such as the last glacial cycle and decadal-scale climate transitions that occurred during the glacial period (i.e., Dansgaard-Oeschger events).

While this idealistic vision is clear, some of this may not be realistic because of intrinsic limits in predictability and practical limits to resolution, physical understanding, and observational constraints. Substantial improvements in model resolution are expected and important (Chapter 3), but the challenges of simulating climate physics are not magically resolved as models go to high resolution and increased complexity. It takes time to add and properly validate new processes and components to a model. Extensive testing and sensitivity experiments are required, involving hierarchical regional climate models and global climate models with a variety of scale-sensitive parameterizations.

However, these challenges and limits should not constrain ambition and exploration. It is difficult to foresee the advances in technology, observational capacity, and process understanding that will extend modeling capability in the coming decades. There needs to be a strategic research agenda for climate science, observations, and modeling as the climate modeling community keeps pace with the information needs of a changing climate system, while at the same time improving climate model capabilities and skill.

In this chapter specific scientific targets for advancing climate science and climate modeling in the coming decades are identified. They require modeling efforts at both global and regional scales, or a fusion of these efforts. This chapter emphasizes problems where (i) progress is likely, given appropriate strategic/scientific investment, and (ii) progress would directly benefit societal needs with respect to weather and/or climate impacts and investments in climate change mitigation and adaptation.

STRENGTHS OF CLIMATE MODELS

Bader et al. (2008) provide a detailed discussion of strengths and weaknesses of the current generation of global climate models. Current models have demonstrable skill in many aspects of climate dynamics, including their ability to simulate large-scale features of ocean and atmospheric circulation, planetary Rossby waves, extratropical cyclone dynamics and storm tracks, radiative transfer, and global temperatures (Chapter 1). Climate models conserve energy, mass, and momentum; can be integrated for multiple centuries; and have demonstrated the ability to simulate the broad features of 20th-century climate, both the mean state and historical climate change. The rich array of models and expertise, nationally as well as internationally, allows for extensive testing and model intercomparison activities. This cooperation within the global community provides further insight and confidence into the capabilities of climate models. No other global scientific endeavor enjoys this level of international cooperation, or is subject to the same degree of scientific and public scrutiny; although this presents some challenges, this has helped to drive climate modeling forward.

Several considerations underlie the reliability of climate models for many aspects of climate change. It is important to recognize that climate projections are not *forecasts* of the specific state of the climate system at a particular place and time; rather, they should be interpreted as a realization of the mean statistics of weather for a period of time in the future (commonly taken as the average over multiple decades). Constructing the statistics of future climate conditions is a different problem from predicting what the weather will be like on a given day or month in the future; it is less sensitive to nonlinear dynamics and initial conditions, as the statistics of short-lived weather systems average out over many years. The average climate of a location depends on the relative frequency of different weather systems, which is governed by large-scale features of atmospheric circulation that are reasonably robust in climate models.

Although the magnitude of climate change that will occur this century is uncertain, all climate models indicate that the planet will warm. The suite of global climate models deployed in IPCC (2007c) report a mean climate sensitivity[1] of 3.2°C, with a standard deviation of 0.7°C (IPCC, 2007c, Table 11.2); this indicates broad agreement, with some scatter, about the effects of carbon dioxide on global mean temperature. Other large-scale aspects of climate change are also robust, such as water vapor feedbacks (increasing atmospheric moisture), thermosteric sea-level rise, ocean acidification, Arctic amplification of climate warming, warming feedbacks due to reductions in seasonal snow cover, and a poleward shift of circulation systems.

Despite these confirmations of the value of climate models, a number of longstanding and emerging problems require improvements and developments in model capability. Bader et al. (2008) provide a detailed summary of weaknesses of the current generation of climate models. The next section examines some of these weaknesses and outlines several high-priority scientific frontiers that can be better addressed through advances in climate models.

GRAND CHALLENGES FOR CLIMATE MODELS

Climate change is expected to affect society in many ways, including impacts on health, infrastructure, food and water security, ecological integrity, and geopolitical stability. Climate models are essential tools to inform planning and policy development surrounding these issues, but advances are required on a number of research fronts to improve the information that climate models can provide. High-priority questions include the following:

- Climate sensitivity: How much will the planet warm this century?
- How will climate change on regional scales? How will this affect the water cycle, water availability, and food security?
- How will climate extremes change?
- How quickly will sea level rise?
- How will Arctic climate change?
- What is the potential for abrupt change in the climate system?
- How will marine and terrestrial ecosystems change?
- How will society respond to and feed back on climate change?
- Can the evolution of the climate system over the next decade be predicted?

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[1] Climate sensitivity: the equilibrium, global mean temperature change associated with a doubling of CO_2.

It is not straightforward to prioritize these scientific questions, because they operate on different time scales (and, hence, are of varying urgency); some are more "basic" in nature, and the importance and societal cost of climate change impacts such as drought, sea-level rise, increased tropical storm frequency, and Arctic sea-ice loss depend on the specific regional or national context (i.e., vulnerability of lives and infrastructure in different parts of the world). This list of grand challenges is therefore not ranked, but the first four questions are flagged as "high-priority issues" for climate modeling that have the most impact, require the most attention, are globally important, and/or limit progress on other important issues. The sections below discuss the state of the modeling for these issues and provide ideas for potential ways forward.

Climate Sensitivity: How Much Will the Planet Warm This Century?

The severity of future warming affects most aspects of climate change, and mitigation and adaptation strategies hinge on this question, so better constraints on this question are one of the highest priorities in the climate modeling enterprise. If climate models cannot capture the mean state and main features of atmosphere and ocean circulation, they cannot provide meaningful insight regarding regional details. Although all climate models project global warming in response to increasing greenhouse gas concentrations in the atmosphere, there is uncertainty as to the magnitude and rate of expected warming for a given radiative forcing. This uncertainty in climate sensitivity is due to a range of internal feedbacks in different climate models, particularly with respect to how clouds are expected to change, as well as from a lack of observational constraints.

Although there is some irreducible uncertainty in projections of future climate change, improved confidence in climate sensitivity is important if climate models are to provide more useful guidance to planning and policy decisions. For a given emissions scenario, much of the uncertainty arises from the treatment of cloud processes, the carbon cycle, and aerosols within climate models. The brief discussion of these processes below includes an analysis of likely improvements in these aspects of climate models over the next 10-20 years.

Cloud Processes

Simulation of clouds and how they will respond to future greenhouse gas and aerosol changes is a central challenge in climate modeling. Small changes in cloud cover, thickness, altitude, and cloud particle size and type (liquid versus ice) affect the radiative energy balance significantly. The differences from these small changes are enough to explain the majority of model-to-model differences in global warming over the next century.

The problem is challenging for several reasons. First, clouds are quite variable on all time and space scales. Second, many clouds (e.g., cumulus cloud systems) are not well resolved by the grid of a typical climate model. Third, clouds often result from the small-scale interaction of multiple physical processes, which are separately represented in the climate model. Cumulus clouds, for instance, involve turbulent updrafts usually initiated by surface-driven turbulence in which small droplets condense into rain or freeze into small ice particles, some of which fall as snow and some of which are ejected or detrained into the surroundings as cirrus clouds of various thicknesses. There is still considerable controversy about how to best represent some of these processes (e.g., cumulus convection and ice cloud microphysics) and how to best handle complex interactions between parameterizations.

"Low cloud feedbacks" from marine boundary-layer clouds in the lowest 1-2 km of the atmosphere are the largest source of spread between predicted global temperature change in leading climate models (Soden and Held, 2006; Soden and Vecchi, 2011). These clouds are hard for climate models to vertically resolve, and they involve tight interactions of turbulence, cloud and precipitation formation, radiation, and aerosol at subgrid scales. Low clouds are particularly sensitive to human-induced aerosol increases, which change their typical droplet size and albedo, so they are also the principal contributor to intermodel differences in simulating the effect of human-induced aerosols on climate change.

Inaccuracies in the representation of organized tropical cumulonimbus cloud systems contribute to systematic errors made by many climate models in the mean geographical and seasonal distribution of tropical precipitation (e.g., monsoons and "double-ITCZ [Intertropical Convergence Zone]" biases) and its variability on diurnal, intraseasonal (e.g., the Madden Julian Oscillation), and interannual scales (e.g., El Niño). Through their effects on latent heat and rainfall, these errors lead to circulation biases and generate planetary-scale waves in the upper troposphere that disperse to the midlatitude storm tracks, affecting simulations of the entire Earth system.

Full cumulonimbus-permitting ("cloud-resolving") global simulations with no deep cumulus parameterization require a horizontal resolution of 4 km or less, with vertical resolutions of 200-500 m. While this may not be commonplace for multicentury global climate simulations, it is already feasible for global simulations of a few weeks or for longer simulations with regional models and will likely become attractive within the next decade for some types of global climate modeling. Such simulations give much more realistic descriptions of the diurnal cycle of deep convection over land and of the Madden-Julian Oscillation but still may include biases in seasonal-mean tropical precipitation or cloud statistics, due to residual parameterization uncertainties in processes that are still unresolved such as ice processes, boundary-layer turbulence, and small-scale land-surface inhomogeneity. In particular, the boundary-layer cloud and cloud-aerosol uncertainties in climate models will not automatically go away in atmospheric models of cloud-resolving resolution, although they may become easier to reduce. Although these are short-term processes, they have a potentially large spatial and cumulative effect on modeled tropical circulation; systematic biases can influence overall climate sensitivity in decadal to centennial predictions in climate models.

Carbon-Cycle Feedbacks

The cumulative extent of greenhouse gas emissions, primarily the amount of carbon dioxide (CO_2) and methane (CH_4) released into the atmosphere, are of first-order importance to future climate. About half the CO_2 from fossil fuel combustion remains in the atmosphere and is the principal forcing of climate change; the remainder is absorbed by the land and oceans. There are numerous feedbacks in the carbon cycle however, both positive and negative, that influence the amounts of CO_2 and CH_4 that remain in the atmosphere versus those which are taken up in the ocean and the land surface. These carbon sinks need to be included in climate models to provide the best possible estimate of future greenhouse gas forcing in the atmosphere.

Feedbacks are two-way processes, however; climate change affects land cover and the ocean by modifying ecosystem structure and function, as well as the physical controls on gas exchange (e.g., solubility of CO_2 in the ocean, and soil respiration rates). These changes can in turn have important impacts on climate. Ecosystem models predict the distribution of natural land cover on the basis of local temperature, precipitation, and other factors. These ecosystem models are now being coupled with general circulation models (GCMs). Efforts so far have focused on feedback loops involving the biogeochemical cycle of carbon. For example, increasing soil respiration and tropical forest dieback resulting from expected 21st-century changes in temperature and precipitation patterns could produce a major positive feedback on CO_2. There is also the potential of large positive feedbacks involving increased emission of methane from warming wetlands and thawing permafrost.

CO_2 exchange between the land and the atmosphere is via the processes of photosynthesis and decomposition, whose rates vary with sunlight, atmospheric CO_2, temperature, precipitation, and ecosystem distribution. Where not water or nutrient limited, photosynthetic uptake in vegetation can increase in a high-CO_2 environment, providing a negative feedback to CO_2 accumulation in the atmosphere. Currently the imbalance between these processes results in net carbon storage on land, but the first generation of the Earth system model results suggest that this could switch to a net carbon loss to the atmosphere with shifts in ecosystems (e.g., Cox et al., 2000) and as soil respiration rates increase with warming.

Earth system models for the next decade will include multiple processes that interact with carbon cycling, and feedbacks that occur between these processes and climate change. These include the major biogeochemical cycles providing nutrients important for life (e.g., nitrogen and phosphorus). The establishment and mortality of ecosystems will change in response to the changing climate and in turn influence carbon fluxes, atmospheric CO_2, and climate. The transient dynamics of this interaction depend on the time scales of growth, senescence, and mortality intrinsic to ecosystems (including ephemeral and invasive species) as well as on the rate of climate change. Furthermore, variations of structure and functioning within ecosystems, as a result not only of local climate variations but also of age, health, and other differences, must be central components of the next-generation carbon-cycle models. These models need to include models of disturbances beyond fires and land use and include pests, infestation, and other processes that could influence the survival of and competition among ecosystems.

A major advance in the next decade must be in the representation of carbon-climate feedbacks via subsurface processes, for which there are only sparse observations. Most important is soil water, the critical determinant of photosynthesis and decomposition rates, as well as the health and survival of ecosystems. For example, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) generation of climate models do not agree on whether soil moisture near the end of the 21st century will increase or decrease with global warming (see IPCC, 2007c, Chapter 10). Carbon-rich permafrost soils are particularly vulnerable to climate change. Models of the next decade should include the dynamics of permafrost, as well as functional classification of microbe communities and mechanistic representation of soil biogeochemistry. As an example, a shift between populations of methanogens and methanotrophs as a consequence of warmer, drier soils would have first-order importance for methane flux to the atmosphere.

CO_2 exchange between the oceans and the atmosphere is driven by the difference in CO_2 partial pressures in the surface waters and the atmosphere, with the oceanic value dependent on the ocean circulation, marine biology, and carbonate chemistry. Ocean biogeochemistry is a central determinant of the uptake of CO_2 from the atmosphere and will change as the climate and ocean change. Ocean biogeochemistry models currently include climate-sensitive carbonate chemistry, rudimentary representation of different classes of phytoplankton and zooplankton, and multiple nutrient cycles (nitrogen, phosphorus, silica, and iron). They will continue to be improved with observations and understanding of their responses to macro- and micronutrient variations. New modeling directions need to include the cascading impacts on the entire marine biota from ocean acidification and purposeful and inadvertent additions of macronutrients (e.g., from rivers) and micronutrients such as iron, and their impact on surface CO_2 concentrations. Better resolution of coastal circulation and biogeochemistry will be helpful, as well as improved coupling with continental hydrology models.

Aerosol and Atmospheric Chemistry Feedbacks

The role of aerosols in modulating radiative fluxes through the atmosphere, both directly and indirectly through their influence on cloud formation, is a major source of uncertainty in current climate models. Most climate models now include an interactive simulation of aerosols to describe aerosol-climate interactions, but the underlying chemistry and microphysics are only crudely parameterized. This limitation introduces uncertainty in model quantification of aerosol radiative forcing and its dependence on the hydrologic cycle, both through hygroscopic growth and precipitation scavenging. In addition, atmospheric oxidant and nitrogen chemistry are generally not described in climate models, and this limitation stymies a proper description of simple chemical feedbacks, such as methane-hydroxyl radical (OH) coupling, and more complicated feedbacks involving the effects of changing land cover on atmospheric composition. In general, maintaining an appropriate tradeoff between the complexity of aerosol descriptions and chemical mechanisms represented in climate models and their computational cost continues to be an important research topic.

Atmospheric aerosols are greatly sensitive to land cover and vegetation. Increased desertification associated with drying of the subtropics could represent an important source of dust. Changes in ecosystem structure and function would affect the supply of organic aerosol produced by oxidation of biogenic volatile organic compounds (VOCs). The resulting climate feedback loops are potentially important, and they could be either positive or negative depending on the poorly understood radiative properties of dust and the climate dependence of biogenic VOC emissions. The latter emissions depend in a complicated way on vegetation type, temperature, water availability, leaf phenology, and CO_2. Current land-cover models disagree on the sign of the change in biogenic VOC emissions in response to 21st-century climate change. Aerosol yields from biogenic VOCs may also depend on the preexisting supply of anthropogenic aerosols, further complicating the feedback loops.

Atmospheric chemistry plays a critical role in aerosol formation and contributes to other climate-chemistry feedbacks driven by changes in land cover. Deposition of reactive nitrogen (nitrate, ammonium) may significantly affect carbon uptake by ecosystems, and climate change in turn will affect the terrestrial emission and atmospheric chemistry of nitrogen oxides and ammonia. Biogenic changes in nitrogen oxide and VOC emissions will affect the concentration of the hydroxyl radical (OH), the main sink for methane, and will also affect ozone. Like the land-cover impacts and feedbacks that are involved in the carbon cycle, understanding of these effects requires coupling of sophisticated, dynamic ecosystem and land-surface models.

The advance of coupled land-surface, vegetation, boundary-layer, and aerosol chemistry models promises to be an exciting frontier that may transform aspects of climate modeling, and climate model utility in, for example, air quality and land-use simulations. It may pave the way for unification of current efforts in air pollution modeling and in human-climate interactions, discussed further below. In the context of decadal to centennial climate change, these short-term processes influence climate system sensitivity through cumulative effects on radiative transfer and cloud properties. Aerosol chemistry, through direct and indirect effects on atmospheric absorption and scattering, are one of the greatest sources of intermodel climate variability.

How Will Climate Change on Regional Scales? How Will This Affect the Water Cycle, Water Availability, and Food Security?

Climate change impacts and adaptation activities are most strongly manifest on regional scales, where ecological and human systems are adapted to a specific set of historical climate "normals." Agriculture, water resource management, transportation, energy systems, recreational activities, wildfire hazards, and biological systems are all vulnerable to shifts from these historical normals, creating a demand for climate models that can provide accurate and detailed regional information. This demand is a challenge for the current generation of models, particularly with respect to simulation of regional precipitation; climate models need improved skill on regional scales to address this need. Issues concerning rainfall and the hydrologic cycle are of foremost concern. Simulation of ecosystems, ice-ocean interactions, and severe weather, among other climate processes of interest, also require model skill at regional scales.

Accurate simulation of regional precipitation patterns and trends is difficult. Current models are generally limited in their ability to simulate regional precipitation patterns (Kerr, 2011), and this is a significant weakness given the importance of drought to agriculture, water resources, food security, and geopolitical stability (Romm, 2011). Regional precipitation is controlled by atmospheric moisture convergence associated with large-scale and mesoscale circulation, but local forcing from the surface related to orography, land-surface heterogeneity, and precipitation recycling in general alter its amount and intensity, thereby modulating its spatial and temporal characteristics.

Projections of 21st-century regional precipitation trends are of particular societal interest. Climate models consistently agree that globally averaged annual mean precipitation will increase poleward of 45° latitude, as well as over the warmest parts of the tropical oceans (IPCC, 2007c). Held and Soden (2006) gave a simple theoretical argument for this behavior as a consequence of the increased water-holding capacity of a warmer atmosphere as well as increased rates of evaporation in a warmer world. In the subtropics and in some midlatitude regions, many models project drying trends, but the location and magnitude of projected drying vary between models. Model differences in regional precipitation trends have multifaceted causes, including grid resolution but also treatments of cumulus convection, air-sea interaction, land-surface processes, upper ocean dynamics, aerosols, cloud microphysics, and the simulated global climate sensitivity.

These factors interact. As discussed above, model representations of cloud physics, convective processes, orographic and frontal forcing, and land-surface exchanges (i.e., evapotranspiration) are still limited by model resolution as well as process understanding. Because hydrologic cycle processes are inherently multiscale, increasing model resolution to more explicitly represent finer-scale processes is important. Partly because of insufficient spatial resolution, models tend to "drizzle" a lot, overestimating the number of precipitation days but underestimating high-intensity precipitation events (e.g., days with rainfall totals in excess of 10 mm) (e.g., Dai, 2006). Spatial precipitation patterns are similarly blurred in climate models because of the limited ability to resolve strong orographic and frontal gradients.

Orography is an important forcing mechanism for precipitation worldwide. There are significant challenges in predicting both cold and warm season orographic precipitation fundamentally because of the myriads of scale interactions involved. For example, mountains can modulate large-scale circulation, causing changes in local moisture convergence, but local condensation and microphysical processes also influence flow stability upstream. In summer convective regimes, orography can induce convective storms that can organize onto larger spatial scales as they are blown downwind, challenging models' ability to simulate the multiscale precipitation patterns (Houze, 2012). Resolution of snow versus rainfall in mountain regions is also critical for water resources management and climate change adaptation studies (Leung et al., 2004). Addressing limitations in measurements and data assimilation over mountain regions can provide stronger observational constraints for modeling.

Besides orography, frontal forcing is another precipitation mechanism where increasing model resolution is beneficial. Storm tracks are prominent features of the extra-tropical regions. A cold front can produce narrow bands of precipitation, sometimes with embedded severe rainstorms or snowstorms, and in the warm sector, squall lines and severe thunderstorms are common. High-spatial-resolution and nonhydrostatic models can better capture the temperature gradients and simulate frontogenesis that produces the upward motion responsible for frontal clouds and precipitation.

The land surface, particularly where there is substantial vegetation, plays a significant role in the global hydrologic cycle, but current estimates of evapotranspiration and precipitation are not sufficiently accurate to close the hydrologic cycle, even on an annual basis over relatively large river basins (Lawford et al., 2007; Roads et al., 2003). There are a variety of challenges associated with simulation of the hydrologic cycle in GCMs, some associated with representation of convection and cloud processes (see above), but some connected with issues of resolution and appropriate representation of land-surface processes (e.g., land-surface cover, soil moisture, vegetation, agriculture, and the associated evapotranspiration), as well as feedbacks between the land surface and the atmosphere (Dirmeyer et al., 2012).

Sophisticated regional- and continental-scale models exist for land-surface hydrology, but these models are only coupled with GCMs, through the grid scale, with subgrid variability of essential land-surface processes being forced by grid mean atmospheric forcing. For realistic routing of surface water and representation of land cover, hydrology models require fine resolution (1 km on continental scales, and considerably less in many regional studies). This resolution is essential to predictions of soil moisture and evapotranspiration fluxes to the atmosphere and is also the scale of information needed by water resource managers. Work to couple land-surface hydrology models with atmospheric models is advancing, through direct coupling approaches and through "tiling"' or "representative land-surface units" (subgrid representation of the landscape), and more sophisticated, energy- and moisture-conserving schemes are needed.

In addition to precipitation, many other processes involving land surface-atmosphere moisture, energy, and chemical exchange at regional scales are expected to be better represented as coupling schemes and resolution improve, for example, influences of land-use changes on the climate, aerosol sources, crop- and biome-specific evapotranspiration rates, and the influence of built structures (e.g., cities, wind farms) on atmospheric turbulence and forced convection. In return, improved regional-scale climate change forecasts, including, for example, wind, snow, and growing-degree-day forecasts at scales of around 5 km, can feed into climate change impact and adaptation studies for cities, agriculture, tourism development (e.g., ski areas), and renewable energy developments. However, regional projections are more reliable for temperature than for precipitation fields because of the intrinsic scale and complexity of physical processes at play. Improved model fidelity at regional scales is essential to assessment of water resource and agricultural stress and to drought and flood hazards, which are also an element of climate extremes.

Another challenge for global and regional climate models is their representation of patterns or modes of variability, such as ENSO, the Southern Annual Mode, the Arctic and North Atlantic Oscillations, and Pacific decadal variability. Because of their persistence, these ocean-atmosphere patterns strongly influence regional climate variability on time scales of years to decades. If not represented well in models, or if these modes are triggered and sustained at different times in different models, regional climate projections can diverge. Such errors place limits on decadal predictability, particularly on regional scales, and caution is required when interpreting the results from a small number of realizations and/or a small number of models. Work is needed to better understand modes of decadal variability, the underlying ocean-atmosphere feedbacks, and their representation in models.

How Will Climate Extremes Change?

Severe weather events such as tropical cyclones, droughts, floods, and heat waves have tremendous impacts on society, economically, and through loss of life. Extreme events are not predictable years in advance, because most of these reflect an instantaneous state of the weather, with its well-known limitations to prediction. On the other hand, insofar as these events are a function of the mean climate state, statistical probabilities for extreme weather events may be possible to project, which would have great value for decision support and infrastructure design. There are good examples of the ability to extract statistical information on climate extremes from climate models (e.g., Katz, 2010; Kharin and Zwiers, 2005), and experience is growing in the application of advanced statistical methods to assessment of climate hazards and climate change adaptation strategies (Klein-Tank et al., 2009).

For reliable insight from climate models, however, models need to be adept at representing the essential phenomena (e.g., tropical cyclone frequency and strength; tornado development; heavy rain events). Physical arguments and climate models suggest that precipitation extremes are controlled by different physics than time-mean precipitation. Climate models project more frequent floods and droughts in the 21st century, but, as with regional rainfall trends discussed above, intermodel differences in the magnitudes and regional patterns of model trends are substantial, due to many of the same factors. Drought persistence is another example, involving feedbacks between soil moisture, evapotranspiration, atmospheric and surface temperatures, dust aerosols, cloud condensation nuclei, and interactions between regional and synoptic circulation patterns (i.e., blocking). Simulation of these feedbacks requires multiscale modeling with an interactive and sophisticated treatment of land-surface and boundary-layer processes.

Tropical cyclones are only roughly represented in many climate models, primarily because of low spatial resolution of the tight circulation and sharp gradients found in tropical cyclones. Simulations done with very high (25 km or less) resolution models greatly improve the representation of tropical cyclones, even without including the nonhydrostatic effects that are needed to include the vertical component of velocity in the model's prognostic variables. Some coupled models are now able to simulate interannual variations in the frequency and intensity of tropical cyclones (e.g., National Centers for Environmental Prediction Climate Forecast System [CFS]), and seasonal forecast skill for upcoming hurricane seasons is improving. Seasonal landfall forecasts may be the next frontier.

In most cases, prognoses of severe weather will have to be statistical in nature (i.e., estimation of the likelihood of extreme events in future decades in a specific region). Statistical likelihoods are of great value for many applications, however, such as water resource management, infrastructure and emergency relief planning, and the insurance industry (Box 1.1). It is arguable whether climate models need to generate the full range of behavior and variability that is seen in the real world in order to extract information on extremes. In some cases, probability distribution functions may be constructed and offer appropriate inferences on extremes (e.g., Hegerl et al., 2004). In a nonstationary climate, however, statistical properties of probability distribution functions for some climate phenomena (e.g., the dispersion or shape of distributions) may evolve relative to the historical climate record.

How Quickly Will Sea Level Rise?

Global eustatic (mean) sea-level rise over the past century has been driven by a combination of thermal expansion of the oceans, melting of mountain glaciers and the Greenland ice sheet, and increased dynamical discharge to the oceans in Greenland

and Antarctica (Church and White, 2011). On a regional scale, sea-level change is more complex, involving local land movement (e.g., isostatic, tectonic, or subsidence due to groundwater depletion), atmospheric winds and pressures, regional ocean circulation changes (which influence thermosteric changes), and changes in the gravitational field in response to changing land-surface mass (e.g., Wake et al., 2006). Hazards posed by sea-level rise are most acute when compounded with storm surge events that are superimposed on high tides and the various other factors that drive more gradual, sustained sea-level rise in a region (e.g., Dasgupta et al., 2009). Storm surges arise from tropical cyclones and marine storm events. The challenge of forecasting local and regional sea-level rise and associated hazards is therefore multifaceted. This is a true Earth system problem involving many aspects of climate dynamics and geophysics, including Earth and ice-sheet models that have not traditionally been included in climate modeling efforts.

For global mean sea level, one of the greatest challenges involves simulation of ice-sheet mass balance and ice-ocean interactions. Recent, dramatic changes in the Greenland and Antarctic ice sheets are driven by both increased surface melting and ocean warming at intermediate depths, where marine outlet glaciers and ice shelves are in contact with the sea (e.g., Holland et al., 2008). The current generation of ice-sheet models and ice-climate models cannot simulate these processes and other aspects of ice-sheet dynamics that give rise to interannual ice-sheet variability. Hence, models are limited in their ability to assess ice-sheet sensitivity to climate change. Most ice-sheet models use only minimal climate data (e.g., temperature and precipitation fields), without interactive or physically based (process-resolving, energy-conserving) coupling with climate models. Coupled ice sheet-climate model simulations to date typically simulate ice-sheet melt as a function of positive degree days, based on interpolated GCM temperature fields (e.g., Huybrechts et al., 2011; Ridley et al., 2005, 2010; Vizcaino et al., 2010); without a proper energy balance at the ice-atmosphere interface, these simulations do not conserve energy. Physical processes at the ice-ocean interface (calving, marine melting) are also neglected or oversimplified in models.

These simplifications limit the range of behavior in modeled ice-sheet interactions with the climate system. For instance, ice-sheet models have no sensitivity to ocean warming, and the climate processes that may give rise to ice-shelf breakup, grounding line retreat, and marine ice-sheet instabilities are not well represented. Improved models of ice dynamics are also needed. Fast-flowing outlet glaciers and ice streams need to be spatially resolved in ice-sheet models, and the controls on fast flow (e.g., basal lubrication, calving and basal melting at the ice-ocean interface, and grounding line dynamics) need to be better understood and included in the models (Nick et al., 2009).

The intrinsic resolution of these processes will continue to be a challenge. Ice-sheet models require horizontal resolutions of about 5 km to resolve the snow accumulation and melt (energy balance) processes near the ice-sheet margin, where orographic gradients are high. Even greater resolution may be needed where ice is in contact with the ocean to simulate floating ice dynamics, grounding line migration, and fluxes of energy and mass at the ice-ocean interface. The latter requires coupling with regional and/or coastal models of ocean circulation at and below the ice front (i.e., beneath ice-shelf cavities).

Interactive two-way coupling is required for simulation of decadal- to century-scale sea-level rise, including energy- and mass-conserving schemes to simulate melt rates at the ice-ocean interface and in the ice-sheet ablation zone. Much of this is technically feasible, and regional-scale modeling studies show promise for both ice-ocean and ice-atmosphere interactions (e.g., Box et al., 2008; Grosfeld and Sandhäger, 2004; Holland and Jenkins, 1999). To extend this to a global scale, considerable numerical and scientific resources need to be channeled at this problem. However, considerable progress can be expected in the next 10-20 years to improve the realism in ice-sheet and sea-level projections.

Steric changes in ocean height also need to be better constrained. The evolution to eddy-resolving ocean models will improve this aspect of sea-level projections through more detailed representation of mixing processes. Increased observational constraints on evolution of intermediate and deep waters will also inform and improve the models. In combination with increasing attention to geophysical processes and local landscape models (e.g., for coastal geomorphology and relative sea-level considerations), improved projections of regional sea-level rise should be possible in the coming decades.

OTHER SCIENTIFIC PRIORITIES

Several other important scientific questions identified above are discussed here. These are arguably of lower priority because they are of more regional interest or represent basic Earth system science processes, which lay the groundwork for longer-term advances in climate modeling. They are nonetheless pressing questions that require advances in climate modeling.

How Will Arctic Climate Change?

The Arctic is an important player in long-term global climate evolution, and it may also contribute to abrupt climate change. The Arctic sea-ice cover is particularly critical in effecting such change, because it insulates Earth's relatively warm ocean water from the cold atmosphere, and it strongly influences Earth's absorption of solar radiation through high albedo (or reflectivity) compared with "dark" absorptive ocean. The multiyear icepack acts as a key indicator of the state of global climate through "polar amplification." Polar amplification is a self-reinforcing system, which amplifies polar climate warming through positive feedback loops derived from decreasing snow and sea-ice coverage.

The retreating sea-ice cover has powerful feedbacks on regional albedo, ocean warming, and cloud conditions. These influences contribute to a strong amplification of climate warming in the Arctic, making it one of the most sensitive and rapidly changing regions on Earth. Because of the geopolitical and environmental ramifications, there is tremendous interest in reliable climate change and sea-ice forecasts for the Arctic region. The complexity and scale of sea-ice processes and ice-ocean-atmosphere exchanges, as well as the relative dearth of subsurface observational data, make this a challenging problem for climate models.

Over the past decade, various studies have attempted to estimate the future trajectory of Arctic climate and have proposed projections of the disappearance of summer Arctic sea ice ranging from the end of this decade to the end of this century. The majority of GCMs, including those participating in the IPCC AR4, have not been able to adequately reproduce satellite-observed Arctic sea-ice extent variability and trends (Stroeve et al., 2007), however, in particular the extent of late-summer ice loss in the past decade. Model representation of sea-ice thickness presents additional challenges because it involves not only thermodynamic interaction with the ocean below but also the dynamic and thermodynamic effects from the atmosphere above.

The inability of climate models to adequately reproduce the recent states and trends of Arctic sea ice diminishes confidence in their accuracy for making future climate predictions. It suggests a great need for improved understanding and model representation of physical processes and interactions specific to polar regions that are omitted from, or poorly represented in, most current-generation GCMs. These processes include the following: oceanic eddies, tides, fronts, buoyancy-driven coastal and boundary currents, cold halocline, dense water plumes and convection, double diffusion, surface/bottom mixed layer, sea-ice thickness distribution, concentration, deformation, drift and export, fast ice, snow cover, melt ponds and surface albedo, atmospheric loading, clouds and fronts, ice sheets/caps and mountain glaciers, permafrost, river runoff, and air-sea ice-land interactions and coupling. There are also a number of important limitations in the way sea ice and ocean models are coupled in current-generation GCMs, which can contribute to pycnocline displacement via Ekman pumping, freshwater water exchange between ice and ocean, or thermohaline coupling at the ice-ocean interface.

To facilitate a better understanding of interconnectivity within the Earth system (Doherty et al., 2009; Rind, 2008; Roberts et al., 2010) work is under way to (a) improve the fidelity and number of polar-centric processes represented within Earth system models, (b) refine coupling channels between them, and (c) expand the hierarchy of available models and observations to help quantify sources of uncertainty and skill in sea-ice simulations. Model development is being targeted toward physical and biogeochemical processes that are suspected of strong interconnectivity with the surface Arctic Ocean energy and mass budgets. By increasing the number of interconnected processes in models, the degrees of freedom of the simulated Earth system expand, which poses problems for understanding causal climatic links and is likely to increase apparent model uncertainty in the next decade (Hawkins and Sutton, 2009). At the same time the need for high-fidelity regional ensemble projections has grown, especially in the Arctic, where economic, social, and national interests are rapidly reshaping the high north in step with regional climate change (e.g., Arctic Council, 2009; Proelss, 2009).

Roberts et al. (2010) proposed the creation of an Arctic System Model (ASM) based around a core climate model configuration comprising an ocean circulation model, atmospheric model, sea-ice model, and terrestrial model. Such a model has been recently developed (Maslowski et al., 2012), and it is currently being evaluated for physical performance. It will have high spatial resolution (5 -50 times higher than currently practical in global models) to advance understanding and modeling of critical processes and determine the need for their explicit representation in global Earth system models. More opportunities for advancing ASMs are under way with the development of a variable-resolution or unstructured-grid approach (Ringler et al., 2010), which shows great promise for bridging the gap and enabling high-resolution regional Arctic climate change exploration within the context of the global climate system model framework. Subject to further progress with its development, including space-dependent physical parameterizations, an improved framework for robust regional Arctic climate system modeling should become available within the next several years. Overall, these different modeling methodologies and results point to the ongoing need for a hierarchical approach (as discussed in Chapter 3) to better understand the past and present states and estimate future trajectories of Arctic sea ice and climate change.

What Is the Potential for Abrupt Change in the Climate System?

Various mechanisms have been identified for abrupt climate change, where the climate state undergoes a regime shift over a period of a decade or less on regional to global scales. Candidate processes include large-scale destabilization and release of methane hydrates from shallow marine and permafrost environments, disruption or reorganization of ocean circulation patterns, loss of sea ice, loss of coral reefs, and desertification (i.e., sustained regional droughts, dieback of tropical rainforests, etc.). These events are thought to be threshold processes where, beyond a certain point, gradual climate change might trigger a nonlinear response. It is not known exactly where the thresholds lie, and whether 21st-century climate change is likely to incite such nonlinear responses, but climate models are the best available tool to address this question.

Many of the abrupt climate change instabilities identified here involve Earth system interactions and feedbacks as discussed in Chapter 3. Examples include cryosphere-climate interactions (permafrost thaw, sea-ice retreat) and the combined impacts of changes in the hydrologic cycle, ocean temperature and salinity, sea-ice formation and melt, and freshwater runoff from rivers, glaciers, and ice sheets on ocean stratification and deepwater formation. The expansion of model complexity and improvements in two-way coupling strategies in Earth system models will help to address and quantify some of these feedbacks and threshold processes. For instance, increasingly more sophisticated sea-ice and Arctic Ocean models allow a better assessment of interannual to interdecadal sea-ice variability and the "reversibility" of recent, dramatic reductions in late-summer sea ice (Armour et al., 2011). Similarly, the addition of more sophisticated models of permafrost thermodynamics, including soil biogeochemistry and vegetation, will enable a better assessment of methane release from thawing permafrost.

Other aspects of abrupt climate change involve improvements to the fundamental representation of tropical convection and rainfall patterns, as discussed above with respect to climate sensitivity. Of particular concern here are patterns of tropical and subtropical aridity, including those of North Africa and the Amazon Basin. Agricultural, ecological, and water resource stresses in these two regions have the potential for global-scale impacts (e.g., Betts et al., 2008). Sustained, systematic drying of the Amazon Basin is predicted in some modeling studies, and the likelihood of such high-impact climate shifts needs to be quantified and constrained, requiring improvements in modeled tropical convection, representation of the ITCZ, and possibly land-surface coupling (i.e., for transpiration fluxes and land-cover changes).

How Will Marine and Terrestrial Ecosystems Change?

Ocean warming, acidification, and changes in salinity all affect biogeochemical cycles and marine ecology on local to global scales, threatening ecological integrity and biological diversity in the oceans, which are intrinsically valuable to the planet. This threat has significant implications for the fishing industry and global food security. Marine biological activity also plays a large role in carbon uptake from the atmosphere, with important feedbacks to climate warming. Climate models capable of assessing marine ecology are needed to examine this.

Models of ocean biogeochemistry have been developed and coupled in GCMs, but details of ocean mixing and coastal upwelling are integral to nutrient cycles; these need to be resolved to enable consideration of marine ecosystems and ecological response to changing ocean temperature, salinity, and pH. The anticipated progression to eddy-resolving and multigrid ocean modeling will improve model simulations of mixing, mesoscale eddies, and coastal ocean dynamics, permitting coupling of models of ocean dynamics, ocean biogeochemistry, and marine ecology.

Terrestrial ecosystems are important in the Earth system because they influence the climate through physical, chemical, and biological processes that affect the hydrologic cycle and atmospheric composition. Warming and drying of the climate will potentially induce a shift of plant zones to more drought-resistant varieties and species, alter pest and predator patterns, and shift forest fire regimes in time and space. Climate change will also interfere with the timing of various temperature-related events (e.g., blooming or egg laying) and the cold end of species' ranges (e.g., toward the poles or higher elevations; NRC, 2011b). Linkages between species that are temperature, moisture, or annual cycle dependent will also be disrupted.

Climate models capable of assessing terrestrial ecology are also needed. These models should represent the drivers and feedbacks from global and regional interactions of climate, ecosystem processes, plant function (e.g., photosynthesis and respiration), carbon and nitrogen dynamics of soils, and ecosystem disturbances (e.g., drought, flooding, and insect outbreak; NRC, 2010b).

How Will Society Respond to and Feed Back on Climate Change?

Future climate evolution will be impacted by human choices in a number of ways, including future emissions scenarios (e.g., through population, energy intensity, and sources of energy), land-use changes, agricultural activities, and potentially through deliberate interventions in the climate system, so-called geoengineering activities (e.g., injection of reflective aerosols in the stratosphere to reduce insolation). Emissions, land-use changes, and patterns of development are presently prescribed in climate simulations through predetermined scenarios, without allowing for feedbacks or societal "reactions" in response to the patterns and extent of climate change. A great deal of thought goes into these scenarios (e.g., the Representative Concentration Pathway scenarios of the Coupled Model Intercomparison Project, Phase 5 (CMIP5)/IPCC AR5 [Moss et al., 2010]), but they are not exhaustive and are not always consistent with the internally modeled land-surface changes and atmospheric chemistry. The prescribed scenarios also neglect interactive feedbacks with respect to climate mitigation policy or societal choices concerning things like land use or energy systems.

There is increasing interest in introducing interactive human influences in climate models. Increasingly more sophisticated dynamic vegetation models are now being employed in GCMs, but it is difficult to accommodate the influence and impact of human land-use choices in future climate projections. Agricultural practices (i.e., crop selection) depend on the climate, but they also feed back on climate and hydrologic conditions. Forestry and fishery practices, urbanization, and energy systems all have similar two-way implications within the climate system. Many of these effects are implicitly included in future emissions scenarios, but there is an opportunity to develop coupled, dynamic models of human interactions with the climate system to better capture these feedbacks and interactions. Early attempts in that direction are currently under way, including the addition of algorithms for different crop types that simulate changes in crop planting, growth, and harvesting due to human land-surface management in a changing climate (Levis et al., 2012).

Can the Evolution of the Climate System over the Next Decade Be Predicted?

It is not yet known whether climate models can predict climate system evolution on annual to decadal time scales (Meehl et al., 2009). Sensitivity to radiative forcing is reasonably well modeled, but climate evolution is also sensitive to initial conditions and internal variability. This is a challenging problem because of sensitivity to imperfectly known initial conditions, and because internal, natural variability that occurs within models (e.g., ENSO) does not necessarily arise at the same time as similar variability that occurs in nature. The future timing of other climatic influences, such as volcanic events, is also unknown. Thus, the extent to which annual to decadal predictive skill can be reasonably expected in climate models is limited, and at present it seems unlikely that, even in a decade, climate models will have high skill in predicting societally relevant deviations from "normal" climate over lead times of 2-10 years (i.e., the interval between ENSO and the effect of climate change trends). However, ensemble forecasts that span a statistical space of possibilities are not precluded. Work is needed to understand and quantify the uncertainty associated with such forecasts. To improve forecasts, specific research goals should be set for improving understanding of sources of predictability (NRC, 2010c).

Given the uncertainty in many initial and boundary conditions, particularly with respect to ocean and sea-ice conditions (see section above), model forecasts lay out a range of possible futures, even for a single climate model with the same set of physics and future emissions scenarios (e.g., Laprise et al., 2000; Wu et al., 2005). This manifests particularly strongly in regional climate models, which take large-scale climate fields as boundary forcing. Some of this sensitivity to initial and boundary conditions may be numerical (i.e., model inaccuracies that result in drift), and some is intrinsic to climate dynamics.

Over a long enough period, e.g., 30 years, it may be insignificant that modeled El Niño years differ from reality, because ENSO cycles are relatively short lived. Some patterns of internal climate variability are decadal in nature, however (e.g., the Atlantic Multidecadal Variability [AMV] and Pacific Decadal Variability [PDV)]). Models can reproduce much of this decadal variability (e.g., Meehl et al., 2009; Troccoli and Palmer, 2007), but there is considerable intermodel variability in the timing and duration of such internal variability. Even within the same model, multiple realizations with different initial conditions can give divergent timing of modeled decadal variability, indicating potential limits to decadal-scale regional forecast skill (Meehl et al., 2009; Murphy et al., 2008). Improvements may be possible through data assimilation methods of climate modeling, and through expanded observational data on ocean conditions for model initialization. Such methods show promise for seasonal forecasts using numerical weather prediction models, with demonstrable predictive skill on seasonal time scales for ENSO, for instance (e.g., Tippett and Barnston, 2008).

On a global scale, decadal projections may be less problematic. Patterns of internal variability, such as the AMV and PDV, result in regional-scale redistribution of energy and moisture but lesser impacts on global mean conditions. Predictions of global average temperature depend more on, for example, external forcing; for a given global scenario, however, some regions will warm more than others and some will be less affected, as a result of internal variability and the response of circulation systems to the cumulative climate forcing. The degree of irreducible uncertainty in decadal-scale projections is therefore greater on regional scales than it is for global means. Feedbacks arising from a given circulation pattern (e.g., cloud feedbacks or sea-ice conditions) can in fact influence radiative forcing and global average temperatures, so the effects of internal, interannual variability have the capacity to influence global conditions.

MECHANISMS FOR CLIMATE MODEL IMPROVEMENTS

As discussed in Chapter 3, model improvements to address these research frontiers will be achieved through three main mechanisms: (i) development of Earth system models (increasing model complexity); (ii) improvements to the existing generation of atmosphere-ocean models through improved physics, parameterizations, and computational strategies, increased model resolution, and better observational constraints; and (iii) improved coordination and coupling of models at global and regional scales, including shared insights and capabilities of modeling efforts in the climate, reanalysis, and operational forecast communities. Progress is likely through a combination of these three mechanisms. The climate modeling community is already pressing on the first two points, advancing Earth system models and refining model physical parameterizations and resolution, and continued progress is needed on both of these fronts, perhaps more strategically focused on high-priority questions. In the committee's opinion, the third point, coordination of global and regional modeling efforts, as well as "research-oriented" versus operational models, is a weak spot in the U.S. national climate modeling effort, and also an opportunity for advances.

Earth System Models

Several research frontiers can be explored through development of more sophisticated, interactive, and complete Earth system models. A number of examples are discussed above, such as coupling of climate models with models of ice sheets, land-surface hydrology, aerosols, permafrost, and human interactions. In these examples, additional complexity is needed and justified to address high-priority questions. Earth systems model development may yield significant progress in the next 20 years for a number of scientific questions. In some cases this development is a matter of improved coupling between systems (i.e., coupling schemes that conserve energy, mass, and momentum; two-way coupling, where possible, to include feedback processes), as the component models are already quite sophisticated. Model components (e.g., land-surface hydrology and ice-sheet models) need to be resolved and coupled at the natural scale of the relevant processes, where possible.

In general, there is a tension between increasing model complexity and the ability to interpret model results, or even the ability of coupled models to generate meaningful results. There is experience in this from ocean-atmosphere modeling. For instance, if modeled wind fields are unrealistic in a region, such errors will propagate in the modeled ocean dynamics, including critical features like coastal upwelling, mixing, or ENSO simulations. Such errors can grow and feed back, causing a cumulative drift from reality. Meaningful projections of sea-level rise cannot be justified by adding an ice-sheet model into a climate model; the climate models must be able to generate realistic mass balance fields (snow accumulation and melt) over the ice sheets, and the critical ocean-ice processes have to be understood and included. The building of Earth system models requires extensive testing and adaptive code development, and progress can be slow.

Paleoclimate simulations are one avenue of research to exploit Earth system models and deepen understanding about climate dynamics. Climate variations in the past, such as the Pleistocene glacial cycles, offer insights into the inner workings of the climate system, including important questions such as climate sensitivity, the sign and strength of different climate feedbacks, and processes involving (for example) ice sheets, sea level, aerosols, marine ecology, and the carbon cycle. More subtle climate events in the recent past, such as the Medieval Warm Period and the Little Ice Age, also provide examples of natural variability that can aid in understanding climate dynamics. These events are not fully understood, and they offer exceptional targets for climate modeling studies; lessons from the past can inform process representation in climate models that are used for future projections.

Multimillennial problems such as glacial cycles may be difficult to tackle with full climate models in the next 10 years due to the long integration times, but there are many potential insights from Earth system models of intermediate complexity and reduced Earth system models (see Chapter 3). The last glacial cycle is a particularly good modeling target because it involves numerous important feedbacks and processes, including important fluctuations in the global carbon cycle. Carbon sinks during the glaciation provided an important feedback to the orbitally triggered cooling and ice-sheet advance, but the exact mechanisms of carbon storage on land and in the ocean are not yet understood. Similarly, there is an incomplete understanding of the roles of permafrost, the hydrologic cycle, and changes in large-scale ocean and atmospheric circulation during glacial-deglacial transitions, millennial-scale climate variability, and potentially abrupt (decadal-scale) climate transitions during the glacial period; improving this understanding is a superb modeling target for Earth system models.

Climate changes over the past two millennia have been more modest, but they are relatively well understood, spatially and temporally, and they provide another good target for Earth system models. Climate variability over this period is largely associated with fluctuating solar and volcanic activity, but land-use changes and internal (ocean-atmosphere-ice-biosphere) climate dynamics may also play a role in both climate forcing and positive and negative feedbacks that amplify or buffer such forcing. Climate models need to be able to provide realistic representations of large-scale events such as the Medieval Warm Period and the Little Ice Age before we can be confident in their ability to replicate natural climate variability. Such representations would provide assurance that the critical processes and Earth system components that give rise to natural variability are adequately represented in future projections, so that natural and anthropogenic forcing can be separated. Model studies of these periods in recent Earth history can also provide an observational constraint on modeled climate sensitivity.

Finding 4.1: Earth system model development over the next 20 years is expected to provide a more complete representation of climate system interactions and feedbacks. This will improve the physical representation of several critical features of climate, such as sea-level rise, sea ice, carbon-cycle feedbacks, ecosystem changes, and the hydrologic cycle.

Ongoing Improvements

In addition to new model capacity created through Earth system model development, increased resolution and improved physics in GCMs will drive progress on a number of longstanding scientific problems in the ocean-atmosphere system. Some of this will occur through incremental, "business-as-usual" advances, although progress on some fronts requires strategic investments and prioritization. It is important to recognize that some longstanding problems may not be resolved because of complex, non-deterministic, or poorly understood physics as well as the reality that some essential processes occur at the molecular scale (e.g., cloud physics) and are not amenable to global-scale modeling.

Progress in modeling clouds offers a good example of how advances may be possible in model parameterizations and scale issues. Such examples are found in many other aspects of climate modeling as well (e.g., sea-ice dynamics). Cloud-related parameterizations, like other major parameterizations in climate models, contain multiple numerical parameters not fully constrained by process modeling and observations, for example, the "lateral entrainment rate" at which air is turbulently mixed into cumulus updrafts, or fall speeds of ice and snow particles. These parameters are typically "tuned" via trial and error to optimize the quality of overall global and regional simulations of cloud cover/depth/thickness, precipitation, and top-of-atmosphere radiative fluxes.

Using clouds as a testbed, some promising new approaches to improving parameterizations are being explored, including perturbed parameter ensembles to explore the range of simulated climates possible by changing parameters within an individual climate model, uncertainty quantification to systematically optimize uncertain parameters, and stochastic parameterization. Traditional parameterizations give a single best-guess estimate of the aggregate effect of a subgrid process such as turbulence or clouds averaged over a grid cell. Stochastic parameterization instead provides a random plausible realization of that aggregate effect, drawn from an appropriate probability distribution function. A conventional parameterization of subgrid fractional cloud cover might specify it in terms of the grid-mean relative humidity, while a stochastic parameterization will randomly choose a cloud cover scattered around that deterministic value. This can help maintain grid-scale variability that conventional parameterizations may artificially damp. Stochastic parameterization has been successfully demonstrated in numerical weather prediction (e.g., Buizza et al., 1999; Palmer et al., 2009; Shutts and Palmer, 2007) and monthly to seasonal prediction (Weisheimer et al., 2011).

A nonstochastic parameterization of a random subgrid process such as cumulus convection cannot produce statistically robust results unless there are many cumulus clouds in each grid cell. As the spatial and temporal resolution in climate models is refined, this "scale-separation" assumption breaks down well before a single cumulus cloud is well resolved by the model grid, creating a "grey zone" in which neither the parameterization nor an explicit simulation of the process is theoretically justified. Many global weather prediction models are approaching that resolution for cumulus convection, and climate models are likely to do so within the next 20 years. Designing parameterizations that can function through this range of resolutions is an important challenge for the next decade. Stochastic parameterization may be a particularly useful strategy in the grey zone.

While a revolution in computational approaches or capabilities is not impossible, in simulating clouds and in the broader challenges of climate modeling, incremental improvements are more likely. Improvements are possible by tapping into model capabilities that already exist in some cases, through strategic cooperation of the sometimes disparate global and regional modeling streams, as well as increased cooperation of global, regional, research-based, and operational modeling efforts. Such improvements will involve unified, scale-invariant physical treatments of key processes, conservative coupling schemes, and, in some cases, two-way coupling.

Finding 4.2: Progress is likely on a number of important problems in climate modeling over the coming decades through a combination of increasing model resolution, advances in observations and process understanding, improved model physical parameterizations and stochastic methods, and more complete representations of the Earth system in climate models.

THE WAY FORWARD

There is generally a tension between different lines of progress in climate modeling. For instance, do we allocate resources to increased resolution or to increased model complexity (i.e., Earth system model development)? There is no one-size-fits-all answer, but instead the approach should be problem driven. Some problems that are of great societal relevance, such as sea-level rise and climate change impacts on water resources, require increased model complexity, and progress is likely through the addition of new model capabilities (ice-sheet dynamics and land-surface hydrology, in these examples). In other cases, such as improved model skill in regional precipitation and extreme weather forecasts, increased resolution and "scalable" physical parameterizations are the highest priorities for extending model capabilities. Other problems, such as water resource management, require both increased resolution and complexity.

The committee finds that an important direction forward is for Earth system models to be developed with realistic representations of ice-sheet dynamics and ice-ocean-atmosphere interactions in order to provide improved projections of sea-level rise. Such models will also improve understanding of glacial-interglacial cycles and millennial-scale climate variability during glacial periods. Coupled with sophisticated models of terrestrial and marine carbon cycles, investigations of glacial cycles could shed light on natural carbon sources and sinks and the future evolution of the atmospheric carbon pool.

A number of important scientific and societal questions require detailed and meaningful climate projections at local to regional scales. The committee recommends that the U.S. climate modeling community pursue high-resolution model runs in the coming decades. Specifically, at least one national modeling effort in the next decade should aim to simulate historical and future climate change (i.e., the period 1900-2100) at a resolution of less than 5 km, to enable eddy- and cyclone-resolving models of ocean dynamics and more realistic representation of land-surface exchanges with the atmosphere. In addition, at least one national modeling effort in the next 20 years should aim for century-scale simulations at resolutions of 1-2 km, to allow cloud-resolving physics. There is ample evidence that resolving these highly interactive, nonlinear, and thermodynamically irreversible processes provides for qualitatively better simulations of Earth's climate. Such a resolution will permit improved representation of many features of the climate, such as explicit resolution of mesoscale ocean eddies and the spatial scales of land-surface and hydrologic variability.

The committee recognizes that these suggested efforts are not trivial and will require a substantial investment in manpower, computing power, and financial capital. It is also not certain that increases in resolution will reduce uncertainty. However, improvements in model capability and resolution can be expected to advance understanding of the high-priority climate science questions discussed in this chapter. The "grand challenges" outlined here all refer to societally relevant questions where progress can be anticipated in the next 10-20 years, with highest priority given to the questions of climate sensitivity, regional climate change, climate extremes, and sea-level rise. Each of these is central to provision of critical information for climate policy decisions and climate change adaptation.

Recommendation 4.1: As a general guideline, priority should be given to climate modeling activities that have a strong focus on problems that intersect the space where (i) addressing societal needs requires guidance from climate models and (ii) progress is likely, given adequate resources. This does not preclude climate modeling activity focused on basic research questions or "hard problems," where progress may be difficult (e.g., decadal forecasts), but is intended to allocate efforts strategically.

Recommendation 4.2: Within the realm where progress is likely, the climate modeling community should continue to work intensively on a broad spectrum of climate problems, in particular on longstanding challenges such as climate sensitivity and cloud feedbacks that affect most aspects of climate change (regional hydrologic changes, extremes, sea-level rise, etc.) and require continued or intensified support. Progress can be expected as resolution, physical parameterizations, observational constraints, and modeling strategies improve.

Recommendation 4.3: More effort should be put toward coordinated global and regional climate modeling activities to allow good representation of land-surface hydrology and terrestrial vegetation dynamics and to enable improved modeling of the hydrologic cycle and regional water resources, agriculture, and drought forecasts. This will require better integration of the various national climate modeling activities, including groups that focus on models of surface hydrology and vegetation dynamics. The annual climate modeling forum discussed in Chapter 13 might provide a good vehicle for a working group with this focus.

Recommendation 4.4: At least one national modeling effort in the next decade should aim to simulate historical and future climate change (i.e., the period 1900-2100) at a resolution of less than 5 km, to enable eddy-resolving models of ocean dynamics and more realistic representation of cumulus convection and land-surface exchanges with the atmosphere. Parallel efforts need to aim for century-scale global atmospheric simulations at 1-2 km, to enable cloud-resolving physics. These national efforts would be facilitated by advances in climate model software infrastructure and computing capability discussed in Chapter 10.

CHAPTER FIVE

Integrated Climate Observing System and Earth System Analysis

Observations are critical for monitoring and advancing understanding of the processes driving the variability and trajectory of the climate system. The evaluation and improvement of climate and Earth system models is thus fundamentally tied to the quality of the observing system for climate. The observational assessment of model performance is an important prerequisite for credible climate predictions and projections and for articulating their uncertainties. Climate observations and model assessment have become increasingly important and urgent because climate change is progressing rapidly.

A longstanding issue is the adequacy of the observational record for the purpose of model evaluation and advancement. Numerous Earth observations are made, but many are not of sufficient quality to evaluate models or meet other climate needs (e.g., NRC, 2007). In the atmosphere, most observations are made to initialize weather forecasts. Because the amplitude of weather fluctuations is large, high measurement accuracy and low bias have historically not been a priority. In contrast, climate change must discern relatively small changes over time, which requires stable calibrated measurements of high accuracy. Knowing how the measurements of today relate to those of years or decades ago is a very important component of climate science.

Another challenge for a climate observing system is that monitoring climate involves measuring many more variables than for monitoring weather. Space and time scales are also more extreme for climate—clouds vary rapidly while ice sheets and the deep ocean vary very slowly. The shortage of reliable and consistent data on the interactions between climate, environmental systems, and humans limits our ability to understand and model how humans affect climate and vice versa.

Observational data sets contain inherent limitations such as measurement uncertainties, gaps in spatial or temporal coverage, and the lack of continuity of calibrated records over extended periods of time (e.g., NRC, 2004; Trenberth et al., 2006). A proliferation of observational data sets, including retrospective reanalysis products and newly available satellite measurements, has enhanced understanding of the climate system and its processes but has also led to a bewildering number of similar data sets. This proliferation thus demands an assessment of the various observational products and their usefulness for different purposes, as well as documentation of the differences and uncertainties among the data sets. Users, including modelers, often do not have sufficient information to appreciate the strengths and weaknesses of different data products describing the same variable, and how they may be reliably used.

The high number of important climate variables suggests there is a need to prioritize observational requirements within the climate observing system. Such prioritization is fraught with difficulty, however, because of the underlying assumptions and the fact that observations are used for multiple purposes. The Observing System Simulation Experiment (OSSE) methodology can potentially be used to advance the rigor of both climate model testing as well as climate observations (e.g., Norton et al., 2009). Although model spatial resolution and errors currently limit the utility of OSSEs, OSSEs will become more effective and powerful at prioritizing climate observations as models improve.

Although the existing collection of in situ observations covers most high-priority and currently feasible measurements, their spatial and temporal coverage is incomplete, and many improvements to the current climate observing system can be envisioned. Such improvements would be based on technical innovations in measurement techniques, the recognition of new needs for observations, and improved integration of variables for societally relevant topics. There is also a general need for integration and synthesis of satellite and in situ observations, which is partly met by reanalysis. Observations from multiple sources are not necessarily redundant, because they can complement each other and allow calibration and validation.

Some observation systems critical for model evaluation and improvement are at risk, either because they require substantial investments that cannot be done incrementally, or because budget constraints and aging equipment have gradually reduced capabilities or data quality to unacceptable levels. While nations have continued to recognize the importance of climate observations, for example through acceptance of the Global Climate Observing System (GCOS) Implementation Plans, in many cases funding commitments have not yet been made by GCOS member nations to provide or improve key components of the climate observing system. The risk of major satellite and in situ observing system holes is already present, and it may well grow in the future. As discussed by Trenberth et al. (2011), there are many good aspects of the current GCOS, but much remains to be done in order to provide the climate-quality products required to develop and test the next generation of climate models and Earth system models (ESMs). Process-oriented observations require further attention and prioritization as well. These and other issues are explored in more detail in the following sections.

STATUS OF SYSTEMATIC CLIMATE OBSERVATION

A thorough summary of the organizational framework and status of systematic climate observations, including by satellite, is provided by Trenberth et al. (2011). The lead international organization for advisory oversight of systematic climate observations is GCOS.[1] Its goal is to provide comprehensive information on the total climate system, involving a multidisciplinary range of physical, chemical, and biological properties, and atmospheric, oceanic, hydrologic, cryospheric, and terrestrial processes. One of the most important roles of GCOS is to produce regular assessments of the adequacy of climate observations, including suggestions for needed improvements. Recent GCOS reports provide an excellent reference point for discussing the status of climate observations.

Among other points, GCOS (2009) concluded that developed countries had improved many of their climate observation capabilities, but there was little progress in ensuring long-term continuity for several important observing systems and in filling gaps in the in situ observing networks, with some evidence of decline. On the positive side, GCOS (2009) concluded both operational and research networks and systems were increasingly responsive to needs for climate data and information, including the need for timely data exchange, and that space agencies had improved mission continuity observational capability, data reprocessing, product generation, and access. Overall, GCOS judged that the international climate observing system has progressed significantly, but it still falls short of meeting all the climate information needs of the United Nations Framework Convention on Climate Change (UNFCCC) and broader user communities.

The Third World Climate Conference (WCC-3 in 2009) underscored the importance of systematic observations (Karl et al., 2010; Manton et al., 2010) and recommended strengthening GCOS in several ways. Of particular note were the WCC-3 recommendations to sustain the established in situ and space-based components of GCOS; enhance existing observing systems (e.g., fill gaps in spatial coverage, improve measurement accuracy and frequency, and establish reference networks); apply the GCOS

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[1] http://www.wmo.int/pages/prog/gcos/ (accessed October 11, 2012).

Climate Monitoring Principles (GCMPs[2]); improve the operation and planning of observing systems; and rescue, exchange, archive, and catalog data, and recalibrate, reprocess, and reanalyze long-term records, working toward full and unrestricted access to data and products. High priority in WCC-3 was also given to the observational needs for adaptation planning and to assisting developing countries to maintain and strengthen their observing networks.

The 2010 update (GCOS, 2010) also noted advances in observational science and technology, an increasing focus on adaptation, and the demand to optimize mitigation measures. It reaffirmed the importance of the GCMPs, emphasizing the need for continuity and stability of measurements. GCOS (2010) also provided a current listing of "essential climate variables" (ECVs) (Table 5.1) and called for collocated measurement of ecosystem variables along with the ECVs that influence or are influenced by them.

Finding 5.1: Observational networks and systems are increasingly responsive to needs for climate data and information, but still fall short of meeting information needs for climate and Earth system modeling.

CHALLENGES, GAPS, AND THREATS

Observational Needs for Earth System Models

The climate modeling enterprise differs from operational weather forecasting in several significant ways. With respect to observations in support of modeling, one important difference is the need for long-term, accurate measurements of a broad range of Earth system components, including the oceans, land surface, biosphere, and cryosphere as well as the atmosphere (GCOS, 2010, Table 1). The list of ECVs may increase as climate models embrace increasingly more sophisticated treatments of the Earth system (e.g., ice sheets, permafrost, land-surface hydrology, and the carbon cycle). Because coupled climate models can drift if one component of the system is poorly represented, subsystems that are poorly initialized, modeled, or constrained can compromise the full climate solution. Moreover, feedbacks that are often controlled by small-scale processes may cause such errors to grow and propagate in long-term (i.e., multidecadal) climate projections.

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[2] http://www.wmo.int/pages/prog/gcos/index.php?name=ClimateMonitoringPrinciples (accessed October 11, 2012).

TABLE 5.1 Essential Climate Variables (ECVs) That Are Both Currently Feasible for Global Implementation and Have a High Impact on UNFCCC Requirements (GCOS, 2010)

Domain	Essential Climate Variables
Atmospheric (over land, sea, and ice)	**Surface:** Air temperature, wind speed and direction, water vapor, pressure, precipitation, surface radiation budget. **Upper-air:** Temperature, wind speed and direction, water vapor, cloud properties, Earth radiation budget (including solar irradiance). **Composition:** Carbon dioxide, methane, and other long-lived greenhouse gases; ozone and aerosol, supported by their precursors.
Oceanic	**Surface:** Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, surface current, ocean color, carbon dioxide partial pressure, ocean acidity, phytoplankton. **Subsurface:** Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers.
Terrestrial	River discharge, water use, ground water, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire disturbance, soil moisture.

For observational data sets to be most useful to climate model validation and verification, or as boundary and initial conditions for modeling studies, most climate fields need to be gridded and reasonably complete (i.e., without major geographic and temporal gaps). The spatial density of required data depends on the application and on the resolution of climate models in the coming decades (see below). As improved understanding and model representation of physical processes and feedbacks involved in regional climate variability elevates in importance, more detailed and complete regional observations will be required.

Specific examples of ECVs that are not routinely or globally available at present include sea-ice thickness, deformation, drift and export, soil moisture, land carbon stocks, the surface radiation budget, and stratospheric water vapor. Recommended monitoring strategies for these and many other climate variables are provided in Karl et al. (2010) and GCOS (2010). In other cases, climate variables may be well monitored at present, but accuracy and continuity of the observations must be ensured, as well as calibration and homogenization of data products that originate from different platforms or instruments. All these data characteristics are essential to evaluation of temporal trends, which provide some of the main "targets" for climate modeling.

Process Studies

The number of physical processes included in climate and Earth system models is increasing, and those occurring below the model grid scale are typically parameterized. The observations needed to develop and calibrate the parameterization schemes are most often obtained through intensive field campaigns of limited duration (e.g., months to a year or two). These campaigns are often referred to as process studies (Cronin et al., 2009).

The timely transfer of information from process studies into climate and Earth system models is critical, and within the United States this has been facilitated through multiagency funding of the Climate Process Team (CPT) concept. The key aim of a CPT is to bridge gaps among field and remote sensing observation programs, process modelers, and global modelers by building new communities, in which those with observational expertise and data, those with highly detailed process models, and those building global models work together to address systematically the issues that most limit progress in improving global climate models. The CPT concept has been successful in supporting cross-institutional collaborations, an important concept because it is rare to find single institutions with sufficient expertise in all of these areas. They are also designed around "best practices" for process studies (Cronin et al., 2009), for example:

- modelers and observationalists should be integrated in the study from the planning stage onward;
- integrated and synthesized data sets should be generated from the process study observations to provide model-comparable data that can be used as benchmarks for assessing and validating models; and
- broad use of the data should be encouraged through open data policies, centralized access to all components of the experiment, and data archiving in a user-friendly format.

Recent examples of process studies that followed these tenets include the U.S. CLIVAR Variability of the American Monsoon Systems (VAMOS) Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx), the Kuroshio Extension System Study, the CLIVAR Mode Water Dynamic Experiment, and the North American Monsoon Experiment. Web sites for each of these are given in Cronin et al. (2009).

The first round of pilot CPTs began in 2003 with National Science Foundation and National Oceanic and Atmospheric Administration (NOAA) funding, and they resulted in several significant achievements (U.S. CLIVAR Office, 2008). New ocean parameterizations were developed, for instance, for both mesoscale and submesoscale eddies in the upper ocean in one CPT, while another produced new parameterizations for the shear-driven mixing in overflows, mixing in the frictional bottom layer, and representations of dense water transport through ocean straights and down slopes. These parameterizations were included in the ocean models at both the National Center for Atmospheric Research (NCAR) and the Geophysical Fluid Dynamics Laboratory (GFDL), and they would likely not have been developed without the CPT framework.

The principal legacies of the CPTs to date are the improved global models, but they also initiated several new field experiments, trained early career scientists, and resulted in a large number of peer-reviewed publications, including several synthesis and review articles. Continued interaction between the team members from diverse fields is another lasting, but perhaps less tangible, legacy.

The major challenge identified by the pilot CPTs was the manpower resources available at the national modeling centers. The full implementation and testing of highly sophisticated parameterizations into coupled global models requires significant effort extending beyond those supported by the CPT funds, which can be a difficult task given competing demands such as Intergovernmental Panel on Climate Change (IPCC) assessments. Also, in the absence of newly funded field campaigns, full integration of observationalists can be a challenge.

Nevertheless, the CPT framework has proved effective, and a second CPT solicitation in late 2009 is currently funding several new efforts. For a CPT to lead to model improvements, several criteria need to be met (U.S. CLIVAR Office, 2008):

- Relevance: The process should be one that is currently poorly represented in climate models, but where improvement in representation could lead to better and more credible climate simulations.
- Readiness: The process should be one where recent theoretical developments, process modeling, and observations are readily transferable into climate models.
- Focus: The topic needs to be focused and well defined so as to lead to concrete results within the duration of the project.
- Model independence: The process should be of interest to developers of more than one climate model.

There are many candidate processes to be considered by future CPTs, for example: tropical convection, radiative transfer processes, aerosol indirect effects, cloud microphysics, land-surface processes including soil moisture and ice, ocean mesoscale eddy processes, sea-ice processes, equatorial ocean upwelling and mixing, Southern Ocean ventilation and deepwater formation, atmospheric gravity waves, air-sea fluxes, and ice-sheet dynamics.

Finding 5.2: By bridging gaps among field and remote sensing observation programs, process modelers, and global modelers, the Climate Process Team framework has proven to be an effective mechanism to systematically address the critical issues that limit progress in improving global climate models.

High-Resolution Models

High-resolution regional climate studies (ca. 1-10 km) are already common, and global simulations at such resolutions will become commonplace over the next decade or two. Some applications at these resolutions will be limited by the data that are available to initialize, calibrate, and evaluate models. For instance, improved observations of precipitation frequency and intensity and of snow water equivalence in most of the world's mountain regions are needed to constrain high-resolution modeling of precipitation patterns and snowline altitudes in complex topography (Nesbitt and Anders, 2009). Details of sea-ice thickness and its variability are required to validate model simulations of the dramatic changes being observed in polar regions (Vavrus et al., 2012). Similar constraints apply to many aspects of coupled atmospheric and land-surface models, such as flood forecasting (Booij, 2005; Dankers et al., 2007), estimation of carbon fluxes due to thawing permafrost (Schuur et al., 2008), and quantification of the climate impacts of land-use changes such as urbanization or deforestation.

Other applications may lend themselves to high-resolution regional atmosphere-ocean modeling, but detailed data sets are needed to advance understanding of processes involved as well as to provide accurate boundary conditions. One example is modeling of ice-sheet mass balance in Greenland and Antarctica. Sea ice and open water conditions affect heat and moisture advection to the ice sheets, affecting snow accumulation and melt, so sea-ice concentration and coastal wind patterns need to be well resolved and constrained, as do the larger-scale cyclonic systems that deliver heat and moisture to the ice sheets. In addition, ocean mesoscale circulation patterns that move warm water from depth into contact with sea ice, marine-based outlet glaciers, and ice shelves play a leading role in interannual sea- and land-ice mass balance variability (e.g., Holland et al., 2008). Regional and coastal ocean models that simulate this process require high-resolution boundary forcing from three-dimensional data sets for ocean temperature, salinity, and currents as well as boundary-layer wind fields. Similar constraints apply to simulation of nutrient and carbon fluxes in coastal ocean waters.

Requirements for Sustained Data Collection and Synthesis

Data collection through satellite, airborne, radiosonde, ground-based, and marine-based observing platforms needs to be sustained and, in some cases, enhanced. Much of this can be leveraged off of the routine observations being done for weather and marine forecasts, but climate modeling also has different needs. This includes decadal-scale stability and continuity, the inclusion of some "slow-varying" parts of the climate system (e.g., ice-sheet dynamics, subsurface ocean waters, forest/peatland carbon stocks), and homogenization of data sets from different generations of instruments. The latter includes changes in measurement standards and spatial/temporal sampling density. The accuracy required for climate studies (e.g., 0.1 K for temperatures) requires careful attention to data set homogenization.

There are numerous different climate reanalysis products, both within the United States and globally (next section). Because these are continuous, gridded products, they provide an essential "data set" for model calibration and validation over climatic (multidecadal) time scales, for both the mean state and for temporal trends in different meteorological variables over the past ~60 years. One challenge for climate model validation is to know which of the various reanalyzed data products is closest to "truth": that is, which product is most appropriate to evaluate a particular variable for a particular part of the planet. There are significant discrepancies in the different products (Trenberth et al., 2011) that need to be reconciled. In addition, there is a need for more high-resolution or regional reanalysis products to validate high-resolution models.

Similarly, there are multiple renditions of many variables, and the climate research community needs to evaluate and synthesize these alternative data sets. A single or limited number of recommended data sets that best represents each ECV would be helpful for climate model validation and intercomparison exercises. One example highlighting data set differences and the need for data assessment and intercomparison is the study of 20th-century sea-surface temperature (SST) trends (Deser et al., 2010). Sea-surface temperature is a fundamental physical parameter of the climate system and hence is a critical variable for models to simulate well. It is also well suited for monitoring climate change due to the oceans' large thermal inertia compared with that of the atmosphere and land. Accurate determination of long-term SST trends is hampered, however, by poor spatial and temporal sampling and inhomogeneous measurement practices (Hurrell and Trenberth, 1999; Rayner et al., 2009). As a result, 20th-century SST trends are subject to considerable uncertainty, limiting their physical interpretation and utility as verification for climate model simulations. This uncertainty is especially evident in the tropical Pacific where even the sign of the centennial trend is in question (Vecchi et al., 2008). Similarly, Reynolds and Chelton (2010) show results from six different SST products and highlight a number of significant differences among them.

Ongoing improvements to measurement capability and resolution for a number of climate fields will also facilitate improvements in the climate models. Many of these innovations are recent, and the data being acquired create new opportunities for climate modeling. For instance, sea-ice altimetry from ICESat, launched in 2003, provides the capability to estimate sea-ice thickness (Kwok and Rothrock, 2009), allowing for more rigorous testing and calibration of sea-ice models. The Argo float network, initially deployed in 2000 and now more than 3,300 strong, provides unprecedented global-scale data of the upper 2,000 m of the ocean (e.g., Douglass and Knox, 2009). Together with continuous and accurate top-of-the-atmosphere radiation measurements, the Argo float network is critical to constraining climate models and understanding changes in the global heat budget. Satellite-based precipitation radar offers the promise of exceptional spatial density and coverage (e.g., Nesbitt and Anders, 2009), an important supplement to ground-based precipitation networks. Such observations need to be sustained for decades for climate applications; this requires foresight and international cooperation, given the need for global coverage, the cost of satellite missions, and the inevitability of occasional failures (e.g., ADEOS, Cryosat, Glory).

Finding 5.3: To be useful for evaluating climate and Earth system models, observations need to be regionally comprehensive, global in scope, and internationally coordinated in a way that ensures consistency and transparency across measurement standards, spatial and temporal sampling strategies, and data management protocols (metadata standards, quality control, uncertainty estimates, processing techniques, etc.).

Gaps and Threats

Long-term continuity of in situ and satellite-based observations is essential to provide the data that are needed to advance climate science and to test, evaluate, and advance models. Two of many examples are the satellite-based observations from Ice, Cloud, and Land Elevation Satellite II (ICESat II) and Gravity Recovery and Climate Experiment II (GRACE II). The former, scheduled for launch in 2016, will provide the continuous high-quality measurements of sea-ice and ice-sheet thickness essential to understanding of interannnual variability versus decadal-scale trends in the cryosphere. Similar urgency attends the continuity of satellite gravity measurements with the GRACE II mission. Over the past several years GRACE data have provided important insights into many features of the global climate, including the hydrologic cycle, sea-level rise, and mass balance of the polar ice sheets. The prognostic capability of climate models and ESMs hinges on the quality of such observational data sets and their ability to provide insight into these and other essential Earth system processes.

The NRC Decadal Survey (NRC, 2007) reiterated the need to obtain "long-term, continuous, stable observations of the Earth system that are distinct from observations to meet requirements … in support of numerical weather prediction." It also articulated a strategy for continuing and enhancing the U.S. Earth observing satellite system, including recommended future missions to observe key processes in the Earth system that would ultimately improve predictive capacity of both weather and climate events. It is thus critical for the climate modeling community to have a coherent and active voice in the planning of new space-based missions and instruments. Unfortunately, however, the implementation of the Decadal Survey recommendations has been slow, in part because of poor budgets but also because of launch failures and delays. In the past 2 years, for instance, two climate satellites that would have provided critical data on climate forcing (OCO and GLORY) crashed at launch. Further, NOAA has made significant reductions in the scope of some future environmental satellite missions, eliminating observational capabilities assumed by the Decadal Survey to be part of NOAA's future capability (NRC, 2012b).

Thus, despite some notable successes, the nation's space-based observing capability is in decline, with significantly fewer space-based observations than at any time in recent decades. Earth observations face considerable challenges today (AMS, 2012), and the continuity and stability of climate observations from satellites is thus seriously threatened at just the time weather extremes are exceeding historical records. Overall, the number of in-orbit and planned NASA and NOAA Earth observing missions will decline by more than a factor of 3 by 2020, with a similar dramatic reduction in the number of space-based Earth observing instruments (Figure 5.1; NRC, 2012b). Included in this is also a looming gap in observations by polar orbiting satellites, for instance between the expiration of NPP (National Polar-orbiting Operational Environmental Satellite System [NPOESS] Preparatory Project; NPOESS was launched on October 28, 2011) and the launch of JPSS-1 (Joint Polar Satellite System; rescheduled for 2016). The data gap could be six months with an optimistic estimate of the lifetime of NPP, but could exceed two years if NPOESS lasts only 3 years. As discussed in GAO (2011), such "a data gap would lead to less accurate and timely weather prediction models used

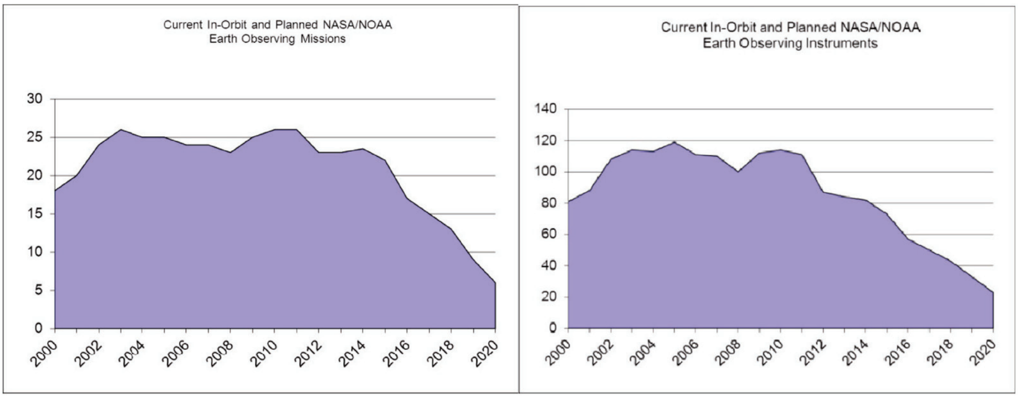


FIGURE 5.1 The number of current and planned Earth observing missions and instruments from NOAA and NASA showing a significant decline by 2020. Figure is courtesy of Stacey Boland, Jet Propulsion Lab (personal communication).

to support weather forecasting, and advanced warning of extreme events—such as hurricanes, storm surges, and floods—would be diminished," potentially placing lives, property, and critical infrastructure in greater danger.

Another issue with climate data from all sources is that there are significant differences in the metadata, availability, and provision of error and uncertainty estimates for different climate data sets. Although it is difficult to make this globally conformable, climate model validation and intercomparison exercises require a thorough understanding of the available data and their limitations. The climate observing and modeling communities are not optimally integrated, so observations are not always used appropriately.

There needs to be more emphasis on detection and analysis of extreme weather in both the observing and modeling communities, including hydrologic events (flood, drought), severe storms (cyclones, tornadoes), snow and freezing rain events, and persistent extreme temperatures (e.g., heat waves). These are the meteorological events that impact society the most and, thus, are needed for informed decision making, but the observing system and climate models themselves are ill equipped to capture and simulate extreme conditions.

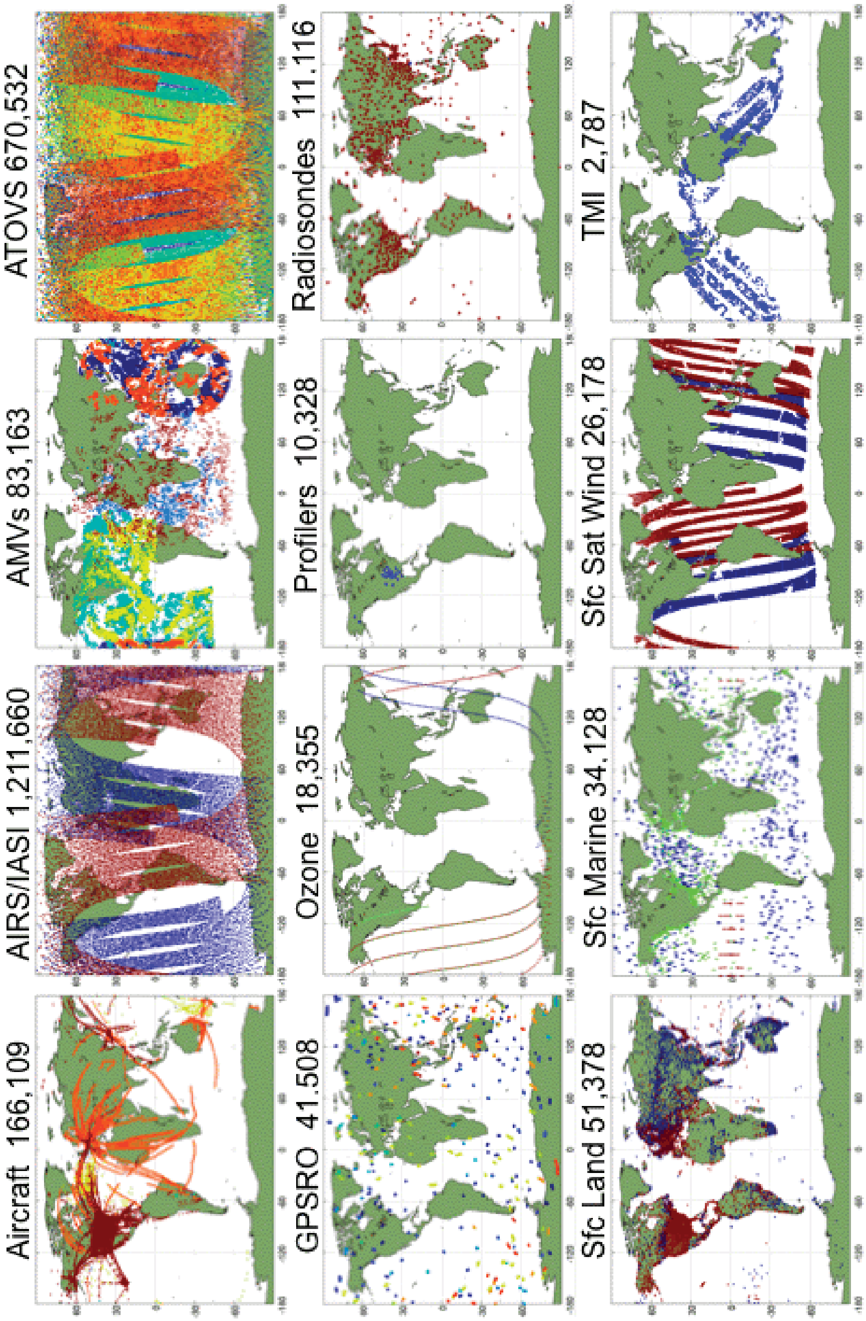
The timely availability of some climate observations may be at risk because of funding shortfalls, data-sharing issues, gaps or unforeseen failures in current and future satellite missions, or transitions between systems (Sullivan, 2011; Zinser, 2011). Parties to the UNFCCC approved the GCOS (2010) recommendations in principle, but funding commitments at a national level are not in place in many cases. Budget cuts are eroding the monitoring network in some GCOS member states.

Finding 5.4: Satellite-based observations are essential for the evaluation and advancement of climate and Earth system models. The U.S. space-based observing system is now in peril, and the timely availability of some climate observations may be at risk because of funding shortfalls, data-sharing issues, gaps or unforeseen failures in current and future satellite missions, or transitions between systems.

ANALYSIS, ASSESSMENTS, AND REPROCESSING

Climate observations come from a diverse system of instruments and are spatially and/or temporally incomplete (Figure 5.2). Meshing them with global climate models to produce a best estimate of the state of the climate at a given point in time can enhance the value of diverse climate observations. The past decade has seen a proliferation of efforts to synthesize these diverse observations into a common framework to produce global synoptic data sets for evaluating the atmospheric, oceanic, and terrestrial components of climate and Earth system models. Such global analyses of climate fields have supported many needs of the research and climate modeling communities. Because they are primarily produced by operational forecasting centers, which are less concerned with long-term data consistency, many changes are made to both the models and the assimilation systems over time. These changes produce spurious "climate changes" in the analysis fields, which obscure the signals of true short-term climate changes or interannual climate variability.

For the atmosphere a solution has been to redo the assimilation of the historical collection of diverse atmospheric observations using a constant state-of-the-art numerical weather prediction model. These "reanalysis" efforts have produced fairly reliable atmospheric climate records that have enabled (i) climatologies to be established, (ii) anomalies to be calculated, (iii) empirical and quantitative diagnostic studies to be conducted, (iv) exploration and improved understanding of climate system processes, and (v) model initialization and validation to be performed (Trenberth, 2010). These products provide the essential foundation for an accurate assessment of current climate, diagnostic studies of features such as weather systems, monsoons, El Niño/Southern Oscillation and other natural climate variations, seasonal prediction, and climate predictability. Importantly, the reanalyses have also provided a vitally needed


Aircraft 166,109
AIRS/IASI 1,211,660
AMVs 83,163
ATOVS 670,532
GPSRO 41.508
Ozone 18,355
Profilers 10,328
Radiosondes 111.116
Sfc Land 51,378
Sfc Marine 34,128
Sfc Sat Wind 26,178
TMI 2,787

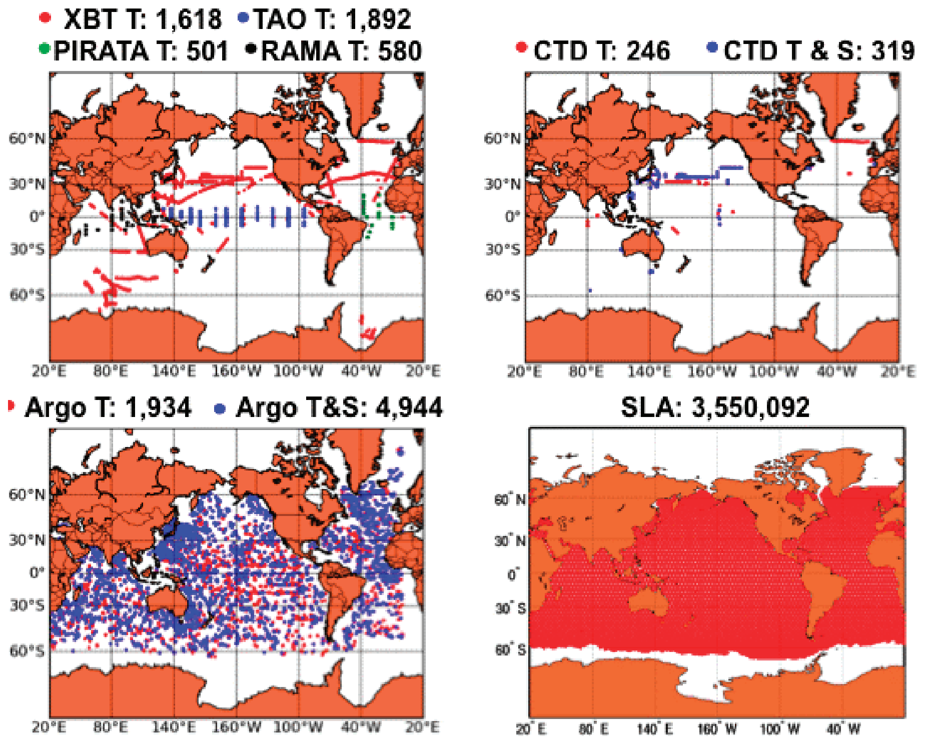


FIGURE 5.2 Climate observations come from a diverse system of instruments and are spatially and/or temporally incomplete. Meshing them with global climate models to produce a best estimate of the state of the climate at a given point in time can enhance the value of diverse climate observations. The top image shows atmospheric observations assimilated into GEOS-5 for a typical 6-hour assimilation window. The bottom image shows the daily distribution of ocean observations throughout 1 month (September 2011). AIRS/IASI, Atmospheric Infrared Sounder/Infrared Atmospheric Sounding Interferometer; AMV, Atmospheric Motion Vector; ATOVS, Advanced TIROS (Television Infrared Observation Satellite) Operational Vertical Sounder; GPSRO, Global Positioning System Radio Occultation; TMI, TRMM (Tropical Rainfall measuring Mission) Microwave Imager; XBT, expendable bathythermograph; TAO, Tropical Atmospheric-Ocean; PIRATA, Prediction and Research Moored Array in the Atlantic; RAMA, Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction; CTD, conductivity temperature depth; SLA, sea-level anomaly. SOURCE: Courtesy of Michele Rienecker, NASA.

testbed for model improvement on all time scales, especially for seasonal-to-interannual forecasts. Moreover, the basic assimilation and prediction systems are improved as deficiencies are identified and corrected by applying them both in reanalysis and routine weather and climate prediction. Besides improvement in the assimilating model and much better resolution, the data sets that have been analyzed have also evolved. Nonetheless, a serious problem is effects of changes in the observing system that produces spurious changes in the perceived climate. As a result, estimates of trends and low-frequency variability have been unreliable, and this problem is exacerbated by model bias.

Analysis and reanalysis are being extended to support research on other aspects of the climate system too. Data assimilation efforts have grown in the United States, for instance, and now include assimilation of data for weather (e.g., National Centers for Environmental Prediction), seasonal-to-interannual climate variability (e.g., Climate Prediction Center), satellite data (e.g., GMAO MERRA), ocean circulation (e.g., GODAE), and land surface (e.g., GLDAS). Moreover, as assimilation techniques for observations of atmospheric trace constituents (e.g., aerosols, ozone, and carbon dioxide) are refined, reanalysis should eventually provide the means to develop consistent climatologies for the chemical components of the atmosphere, including the carbon cycle, and thus help to quantify key uncertainties in the radiative forcing of climate (IPCC, 2007c). Analysis of ocean data has led to novel data products based on the historical ocean data, so that there are now about 20 different analyses of ocean temperatures and ocean heat content (see Lyman et al., 2010; Palmer et al., 2011). However, there are large discrepancies among them, similar to the many atmospheric analysis and reanalysis products.

Thus, as well as assessments of data sets of individual variables, assessments of reanalyses are also essential, especially with the recent proliferation of atmospheric and ocean reanalysis data sets. Many are created for specific purposes but all differ, often substantially, and the strengths and weaknesses or assumptions are currently neither well understood nor documented. Consequently, assessments are required to evaluate these aspects and help improve the data sets. Moreover, continuous reprocessing is essential. Reprocessing can account for recalibration of satellite data, take advantage of new knowledge and algorithms, and rectify problems and errors that have become evident. As stated by Trenberth et al. (2011), "repeat reprocessing and assessment should be hall marks of a climate observing system."

Finally, promising developments are occurring in sea-ice and land-surface reanalysis, and coupled data assimilation systems are beginning to be developed. Coupled analysis and reanalysis products are necessary to provide the physically consistent initial conditions for developing decadal prediction systems, which have the potential to advance adaptation and mitigation planning. Improvements in reanalysis depend on continued support for the underpinning research and required observations, the development of comprehensive Earth system models to expand the scope of reanalysis, and the infrastructure for data handling and processing.

Finding 5.5: Assessments of data sets, of individual variables, and of reanalyses are essential to ensure quality data for the evaluation and development of climate models.

THE WAY FORWARD

Earth is observed more extensively today than at any other time, but many of the observations are not of sufficient quality to monitor long-term climate variability and change. Moreover, some observation systems critical for process-level understanding and model evaluation and improvement are at risk, with declines in both quality and coverage. Gaps also exist in important Earth system observing systems, both in terms of existing systems and new types of observations necessary for improving our capacity to predict future changes in climate especially on regional scales. The U.S. space-based observing system is now in peril, with an anticipated 75 percent reduction in the number of NOAA and NASA missions over the next decade, and an associated reduction in the number of observing instruments from approximately 90 today to 20 or so by the end of the current decade.

The committee thus strongly supports the findings and recommendations from a number of previous relevant National Research Council reports on the status of the climate observing systems and the importance of reanalysis efforts:

- NRC (2009): "A U.S. climate observing system … should be established to ensure that data needed to address climate change are collected or continued. [This includes] augmenting current satellite and ground observing systems … and support [for] new types of observations, including human dimensions observations that are needed for developing mitigation and adaptation strategies."
- NRC (2009): "[E]xpand and maintain national observation systems to … fill critical gaps [and support] modeling and process studies."
- NRC (2010b): "Redouble efforts to develop, deploy, and maintain a comprehensive climate observing system that can support all aspects of understanding and responding to climate change."

- NRC (2009): "[The United States] should sustain production of atmosphere and ocean reanalyses, further develop and support research on coupled data assimilation techniques … , and improve coordination with similar efforts in other countries."

In addition, several major recommendations have emerged from this report. First, the diverse suite of climate observations should continue to be scrutinized in order to diagnose the state of the changing climate and understanding the evolving dynamics of the system. Both confrontation of climate model simulations with climate observations and enhanced communication between the modeling and observational communities are critical for assessing model performance, for improving the representation of physical processes in the models, and in some cases for identifying problems with observational data sets. The assimilation of observations into models exploits known relationships among the different climate variables to select or reject the observations and to propagate and/or extrapolate the observations into data gaps in space or time. Data assimilation efforts in the United States and elsewhere, however, operate independently and use separate models. They therefore have not taken full advantage of the entire suite of observations for the Earth system.

A way to rectify this situation would be the establishment of a national Earth system data assimilation effort that simultaneously merges weather observations, satellite radiances or retrievals for precipitation and various trace constituents, ocean measurements, and land and other observations into a full Earth system model, such as one used for climate projections, so as to make full use of the coupled and interactive nature of the Earth system to constrain the data analysis products.

Hand in hand with the Earth system data assimilation effort is the renewed and continued analysis of the available observations, especially in terms of climate variability at regional scales. Regional-scale climate variability is inherently greater than large-scale variability, and many aspects of it are poorly simulated in the current generation of global climate models. Furthermore, the causes and signatures of decadal and multidecadal variability need to be extracted from the observations and used to assess climate model simulations on these scales. The committee believes that the nation should continue to sustain its effort in the analysis and comparison of different data sets, including reanalysis products, to improve documentation of their strengths, weaknesses, uncertainties, and utility for different purposes, including model development and evaluation, as well as renew its effort in the analysis of available observations, especially in terms of the nature and causes of climate variability at regional scales. One effort in this direction is the web-based informed guide to selected climate data sets of relevance to the evaluation of Earth system models, available from NCAR.[3] The two main objectives of this work are to (1) evaluate and assess often-used climate data sets and (2) provide "expert-user" guidance and advice on the strengths and limitations of selected observational data sets and their applicability to model evaluations. Another effort in its early stages is "Obs4MIPs," which is an attempt to provide modeling groups with a limited collection of well-established and documented data sets that have been organized according to the CMIP5 model output requirements.[4] More activities along these lines should be supported, because they are vital to the integrity of observational, modeling, and prediction studies of climate variability and change.

Climate data archives are scattered among federal agencies, laboratories, universities, and other repositories (also discussed in Chapter 10). While data catalogs exist, it is not easy for the scientific investigator or the decision maker to access and/or download the multidisciplinary data sets in various formats, subset them, "regularize" them (put them onto common grids, time spacing, units, etc.), and analyze them to advance understanding of the Earth system. The advances of information technology (e.g., OpenDAP3, Goddard Giovanni4) have enabled the remote analysis of subsets of the climate data. These information technology (IT) advances need to be brought to bear on the entire climate data holding, linking all the data repositories (regardless of agency) with a user-friendly nonexpert interface to the data that makes it easy and fast to find variables. This interface would support the ability for interactive standard analyses of the data sets and the download of subsets of the data and the analysis results. The formatting and gridding of the various data sets should not be an issue to the user. Such a national IT infrastructure for Earth system data could facilitate and accelerate advances in data display, visualization, and analysis and could be regarded as a natural philosophical extension of the community software infrastructure proposed in Chapter 10. Ideally, the development of such an infrastructure would be primarily community organized and well coordinated with model intercomparison efforts (which require exactly this kind of product, but then also generate model outputs on the same grid). It would be useful if an entity that has the ability to coordinate the efforts of multiple agencies, laboratories, and universities were to endorse this effort and help achieve an interagency agreement for how to support it. While other organizations could perhaps fill this coordinating role, the U.S. Global Change Research Program (Box 2.1) is the most obvious possibility.

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[3] http://climatedataguide.ucar.edu (accessed October 11, 2012).

[4] http://obs4mips.llnl.gov:8080/wiki/ (accessed October 11, 2012).

Recommendation 5.1: The committee reiterates the statements of previous reports that call on the United States to continue and to augment the support for Earth observations and to address the potential for serious gaps in the space-based observation system. A particular priority should be maintaining fundamental climate-quality observational data sets that have been gathered for 20 years or longer.

Recommendation 5.2: To better synthesize the diversity of climate-relevant observations, the United States should establish a national Earth system data assimilation effort that builds from existing efforts and merges weather observations, satellite radiances or retrievals for precipitation and various trace constituents, ocean measurements, and land and other observations into the same Earth system model simultaneously.

Recommendation 5.3: Building from existing efforts, the United States should develop a national IT infrastructure for Earth system data so as to facilitate and accelerate data display, visualization, and analysis.

CHAPTER SIX

Characterizing, Quantifying, and Communicating Uncertainty

This chapter discusses uncertainty (Box 6.1) both in the context of climate modeling of long-term climate change (decades to centuries) and of seasonal forecasting (intraseasonal to interannual time scales). Many of the uncertainties are similar in the two different contexts, except for uncertainties regarding longer-term future forcing that are relevant mainly to the long-term climate change problem. This chapter discusses different types of uncertainty related to climate modeling, reviews how uncertainty has been quantified, discusses the complex issue of communicating uncertainty, and, finally, provides findings and recommendations.

TYPES OF UNCERTAINTIES IN THE CLIMATE SYSTEM

From the point of view of developing projections of long-term climate change from results of climate model simulations, there are three major uncertainties: (1) future emissions and concentrations of greenhouse gas and aerosols (forcing); (2) the re-

BOX 6.1 UNCERTAINTY

Uncertainty is fundamental to all scientific investigations, and many scientific experiments are designed solely to quantify the uncertainty (e.g., in order to place bounds on observational requirements). Many enterprises have embraced the fact that uncertainty exists and have developed methods for operating and decision making under uncertainty. Uncertainty, in its most general definition, refers to lack of knowledge, or imperfect knowledge about specific quantities (e.g., speed of light), or the behavior of a system (e.g., the climate system). Because there is often a random component to uncertainty, it is usually broken down into two basic types: aleatory (randomness) and epistemic (lack of knowledge about something that is in principle knowable). With respect to climate modeling, both types of uncertainty are highly relevant. Uncertainty in climate modeling has been discussed in many contexts (e.g., Hawkins and Sutton, 2009; IPCC, 2007c; Palmer et al., 2005). The main uncertainties discussed are value uncertainty (e.g., uncertainty in data such as observations needed for model development and evaluation), structural uncertainty (e.g., incomplete understanding of processes or how to model them), and unpredictability (chaotic components of the complex system).

sponse of the climate system to the forcing; and (3) the internal (stochastic) variability of the climate system. In the seasonal-to-decadal prediction context , uncertainties of types 2 and 3 are relevant, but, in addition, there are also uncertainties in the initial conditions of the climate system. The latter arise due to observational errors and errors in the assimilation systems used to generate the initial conditions.

Uncertainty in Future Climate Forcing

The energy balance of Earth provides the engine that powers the planet's climate. That energy balance in turn is shaped by, among other things, the composition of Earth's atmosphere, which is being altered by emissions of greenhouse gases, aerosols, and short-lived species. Future climate forcing will be shaped by

- emissions of greenhouse gases, aerosols, and short-lived species into the atmosphere;
- processes that control the composition of the atmosphere, such as atmospheric chemistry, terrestrial and marine components of the carbon cycle, and nitrogen cycles; and
- climate processes, including interactions among the atmosphere, ocean, land, and cryospheric systems.

The future of each of these processes is subject to important uncertainties. Human emissions of greenhouse gases, aerosols, and short-lived species are sufficiently large (and growing) that they are significantly changing the composition of the atmosphere. Historical emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) from fossil fuel use and industrial processes are reasonably well known. Emissions of CO_2 and other compounds resulting from land-use and land-cover change are smaller and less well measured. Future projections of all these sources of anthropogenic emissions will be subject to important uncertainties.

The annual global emissions of CO_2 can vary by more than an order of magnitude in nonclimate policy intervention scenarios (see, for example, Reilly et al., 1987, 2001; Scott et al., 1999). However, the cumulative nature of the carbon cycle means that variation in the concentration of CO_2 in the atmosphere is more constrained. Factors that influence the scale of future anthropogenic emissions include the scale of economic activity, the technologies with which human societies generate and use energy, and the public policy environment in which human activities are conducted. Hence, predicting emissions of GHGs and aerosols requires being able to predict how the entire human world will develop in the future, a truly daunting task fraught with multiple profound uncertainties.

Natural systems involving dynamical and biogeochemical processes that proceed at both large and fine scales are subject to different, though overlapping, uncertainties. There is some confidence associated with descriptions of the very long term (1,000+-year) processes that determine the average abundance of carbon in the atmosphere, but the forces shaping decadal to century atmospheric composition are less well understood (Kheshgi et al., 1999). Uncertainty in the carbon cycle is such that the maximum annual emissions that would limit long-term CO_2 concentrations to 550 ppm are uncertain by ±20 percent (Smith and Edmonds, 2006).

Finally, there are also uncertainties in the natural forcing of the climate system, namely fluctuations in solar irradiance and aerosol emissions due to volcanic activity. Although there is some periodicity to solar irradiance that can be estimated (Lean and Rind, 2009), it is not precise, and future forcing from volcanoes is currently completely unpredictable. The latter can substantially reduce receipt of solar radiation for short periods (e.g.,1-2 years).

Uncertainty in the Climate System Response to Radiative Forcing

Climate system uncertainty is explored through the application of global and regional climate models. While most of these models are carefully constructed to incorporate many climate-related processes and are carefully evaluated, they do not necessarily respond in the same way to a given future forcing scenario. These differences are due to scientific uncertainties about how the climate system works, differences in the way various subsystems are modeled (e.g., land-surface processes), and differences in how unresolved processes are parameterized (e.g., convection). These uncertainties are explored and characterized by analyzing the results of different types of ensembles of climate model simulations. The most common is the multimodel ensemble (MME) based on simulations with different climate models that are subjected to the same future radiative forcing. These MMEs play a central role in the analyses that contribute to the Intergovernmental Panel on Climate Change (IPCC) assessments (e.g., IPCC, 2007c). There are also ensembles developed from a single climate model whose parameters are varied in systematic ways, which are referred to variously as parameter permutation experiments or perturbed physics ensembles (PPEs) (e.g., Murphy et al., 2007).

A primary integrated metric of uncertainty related to the climate system response to radiative forcing is the value of the climate sensitivity of the climate system. Equilibrium climate sensitivity is defined as the average annual change in global mean temperature that results from forcing a climate model with the radiative equivalent of doubled concentration of CO_2. For many years, this sensitivity was described as a range between 1.5°C and 4.5°C, but it has now been quantified using probabilistic approaches (Meehl et al., 2007).

Uncertainty also arises because certain processes or features are not included in most climate models or are modeled poorly or incompletely. These include ice sheets, interactions of sea ice and ocean circulation, aerosols and aerosol-cloud interactions, complexities in the carbon cycle (e.g., role of methane clathrates), interactions between the stratosphere and troposphere, and tropical convection; see Chapter 4 for more details. Note that because ensembles composed of current climate models do not represent many of these processes, these ensembles do not take into account these structural uncertainties and thus do not represent all the known uncertainties. It is very likely that progress in including these aspects of climate in models will be made over the next 10-20 years, thereby reducing structural uncertainty in models.

Finally, there is uncertainty due to the spatial scale of simulations (see Chapter 3) due not only to the fairly coarse resolution of global climate models, but also to that introduced in downscaling the results of the atmosphere-ocean general circulation models (AOGCMs) to even higher resolutions. These downscaling methods include dynamical downscaling with regional climate modeling or variable resolution techniques as well as statistical downscaling techniques. Regional climate models (RCMs), like general circulation models, are subject to uncertainty related to grid resolution and physics parameterizations but also introduce additional uncertainty associated with the lateral boundaries (including their placement) and large-scale boundary conditions and methods to assimilate them (Kerr, 2011). Statistical downscaling makes use of statistical relationships between local climate and the large-scale climate to infer changes at the local level from climate change projections from AOGCMs (Wilby et al., 1998). It adds uncertainty to the regional climate projections by assuming that these statistical relationships do not change over time (Schmith, 2008).

The regional climate modeling approach has been applied particularly frequently in recent years, and a number of programs have been developed to compare the responses of different RCMs to boundary forcing from different AOGCMs (e.g., ENSEMBLES over Europe [Christensen et al., 2009], NARCCAP over North America [Mearns et al., 2009], RMIP over China [Fu et al., 2005], and CLARIS over South America [Boulanger et al., 2010; Menendez et al., 2010]). A new global framework, the Coordinated Regional Climate Downscaling Experiment (Giorgi et al., 2009), should provide a more rigorous evaluation of downscaling products and the uncertainty associated with them, which is much needed because the high demand for regional climate projections (Kerr, 2011).

Internal Variability of the Climate System

Climate predictions and projections are subject to uncertainty resulting from the internal variability of the climate system. The relative role of this type of uncertainty, compared to other sources of uncertainty, is a function of the future time horizon being considered and the spatial scale of analysis (Hawkins and Sutton, 2009, 2011). Hawkins and Sutton note that internal variability dominates on decadal or shorter time scales and is more important at smaller (e.g., regional) space scales. Natural variability is usually explored by running ensembles of climate model simulations using different initial conditions for each simulation. Traditionally the number of ensemble members has not been large (e.g., around three in the Coupled Model Intercomparison Project, Phase 3 [CMIP3] data set), nor has it been based on rigorous statistical considerations. In addition, estimation of natural variability using models is limited by inherent uncertainty in the models because of parametric and structural uncertainty.

In this regard, the role of internal variability has been underinvestigated in the exploration of future climate change, although recent research on larger ensembles (e.g., Deser et al., 2010) has developed improved measures of natural variability and underscored how substantial it can be particularly on regional scales (Deser et al., 2012).

Uncertainty in Intraseasonal to Interannual (ISI) Climate Predictions

Intraseasonal to interannual (ISI) climate predictions, which have recently been extended to lead times of a decade or longer (CMIP5; Taylor et al., 2012), rely on two important sources of predictability—processes or variables such as upper ocean heat content and soil moisture that have memory relevant to the ISI time scale, and predictable patterns of variability, such as teleconnection patterns associated with the El Niño/Southern Oscillation, which involve complex dynamics of atmosphere-ocean feedback. Incomplete knowledge of all the relevant long-memory reservoirs, as well as the imperfect ability of models to accurately simulate patterns or modes of variability, and intrinsic loss of predictability due to chaotic behavior of the Earth system, all contribute to uncertainty in ISI predictions. Last, ISI predictions are limited by our inability to accurately initialize the climate system, as a result of instrumental and algorithmic uncertainty in measurements, as well as uncertainty in synthesizing these measurements using data assimilation systems used to derive the initial conditions.

Finding 6.1: There are important uncertainties in the response of the climate system to future forcings, including uncertainties due to inadequate representation

and spatial resolution of some processes and features in current climate models, and uncertainties inherent in both dynamical and statistical downscaling methods for making local climate projections. Climate predictions and projections are subject to uncertainty resulting from the incomplete knowledge of initial conditions of the relevant components and internal variability of the climate system, which depends on the time scale being considered.

QUANTIFYING UNCERTAINTIES

Quantitative estimates of uncertainty are often required by users of climate model-based information and are also important in the developing and improving climate model predictions and projections. Among the several types and sources of uncertainty described above, some are more quantifiable than others.

Weighting of Models

One of the important further developments since the IPCC Fourth Assessment Report is the consideration of the relative value of simulations from different (global) climate models in, for example, MMEs. Most prior work assumed that all climate models have the same value for producing information regarding climate change (Meehl et al., 2007), and thus models should be equally weighted (i.e., taking the simple average of all simulations). However, some work has been produced that allowed for the weighting of models differentially based, for example, on the magnitude of model biases (Christensen et al., 2007; Giorgi and Mearns, 2003), the exclusion of "poor performing" models (e.g., Dominguez et al., 2010; Smith and Chandler, 2010), or other criteria (e.g., Watterson, 2008). Others assert that understanding of the models or the climate system is inadequate to make such distinctions (Gleckler et al., 2008; Knutti, 2008; Pincus et al., 2010), while still others have suggested that the ensembles and/or the record lengths are too small to robustly establish weights that are significantly different from each other (DelSole et al., 2011; Deque and Somot, 2010; Knutti, 2010; Pierce et al., 2009). There is some question about how different models are from one another (Palmer et al., 2005; Pennell and Reichler, 2011).

Some uncertainties, such as structural uncertainty due to incomplete or poor representation of processes in climate models, do not readily lend themselves to quantification. This is a very important issue, because without recognition of structural uncertainty, the probability distribution functions derived from ensembles can be seriously misinterpreted. Neither MMEs nor PPEs includes consideration of all the known uncertainties, which could lead to overconfidence about the characterization of uncertainty (Curry and Webster, 2011). There remains an important research topic in how to combine quantifiable uncertainties (e.g., from ensembles) with unquantifiable uncertainties (e.g., incomplete representation of processes).

MMEs are also used in ISI prediction as a simple approach for quantifying forecast uncertainty (Kirtman and Min, 2009; Palmer et al., 2004). Some studies using MME from the DEMETER (Development of a European Multimodel Ensemble System for Seasonal to Interannual Prediction) seasonal prediction archive showed that MME often outperforms any individual model (e.g., Jin et al., 2008). Besides MME, PPE and stochastic physics have also been used to quantify ISI forecast uncertainty, but it is not clear how different methods compare or whether combining different methods or different ways to combine models within MME and PPE may further improve prediction skill.

Advances in Probabilistic Methods

There has been considerable recent development in quantifying uncertainty using probabilistic methods. Generally these methods are applied either to MMEs (i.e., simulations based on different models but that used the same external forcings) or to PPEs. Some studies have sought to determine unequal weights for different models (Brekke et al., 2008; Buser et al., 2009; Furrer et al., 2007; Greene et al., 2006; Pitman and Perkins, 2009; Smith et al., 2009; Suppiah et al., 2007; Tebaldi et al., 2005; Watterson, 2008). Other studies have eschewed weighting (Giorgi, 2008; Ruosteenoja et al., 2007). With the development of ensembles of regional climate model simulations, methods particularly adapted to that context are emerging (e.g., Deque and Somot, 2010; Sain et al., 2011). These studies are being used in impacts analysis; for example, Tebaldi and Lobell (2008) adopted the methods of Tebaldi et al. (2005) for rendering probabilities of climate change and adapted it to generate probabilities of crop yield magnitudes under future climate.

There has also been considerable progress in generating methods for presenting joint probabilities, typically of temperature and precipitation (e.g., Tebaldi and Lobell, 2008; Tebaldi and Sanso, 2009; Watterson, 2012; Watterson and Whetton, 2011). This approach is particularly useful for application to impacts of climate change, because temperature and precipitation are the two most fundamental variables used for calculating many impacts.

Applying weightings to MME or PPE have also been explored in ISI prediction using, for example, a superensemble technique (Krishnamurti et al., 1999) and Bayesian combination (Rajagopalan et al., 2002; Robertson et al., 2004). An important distinction between uncertainty quantification for climate change and ISI prediction is that hindcasts play a more important role in the latter; models that perform better in hindcast are more likely to perform better in forecast on shorter time scales when the effects of nonstationarity are more minor, for example, as in ISI versus decadal to century time scales. In this sense, optimal selection and weighting of models can be an important piece of an overall strategy not only for quantification, but also for reduction, of uncertainty, leading to improvement in ISI prediction skill.

Uncertainty in weather and climate model parameterizations of subgrid-scale physical processes is being addressed through stochastic parameterization methods, which have been reported to improve the probabilistic reliability of seasonal forecasts by some climate models (see Chapter 4).

There are nascent efforts to reduce the climatological biases of models through multivariate optimization of uncertain parameters. Stainforth et al. (2005) randomly perturbed a set of uncertain parameters in a version of the UKMO climate model and compared 2,017 resulting models against a suite of climatological error metrics; the best of the perturbed models had a modest 15 percent error reduction over the control model. Jackson et al. (2008) used a more systematic multivariate sampling and optimization approach on the CAM3 atmospheric general circulation model, finding 6 configurations of more than 500 tested that improved an overall measure of climatological error by 7 percent compared to the regular model. These improvements are significant but modest, and the parameter optimization needs to be repeated each time a new model version or a change in grid resolution is introduced. This experience suggest that, as models get more complex, periodic automatic parameter optimization may be valuable, but perhaps more as a device to save human effort involved in trial-and-error optimization (at the cost of more computer time) rather than as a method to make a model of substantially higher fidelity. Furthermore, it suggests that the systematic errors related to uncertain parameters in climate models are heavily compensating, such that improvements in one field are balanced by degradation in another so that the overall result is something of a wash.

Hence, it seems likely that structural errors in parameterizations or inadequacies in grid resolution not correctable by parameter tuning are probably a larger driver of systematic errors and projection uncertainty than suboptimal choices of existing uncertain parameters. In this environment, there is a tradeoff between maintaining fluidity of the model development process and the huge investment of computer time needed to apply the rigorous principles of uncertainty quantification and optimization. Some modeling groups, such as the Geophysical Fluid Dynamics Laboratory, are experimenting with some automatic parameter tuning as a routine part of model development; what is needed is developing pragmatic methodologies that get most of the benefit with a minimum of time waiting for simulations to finish.

While there has been considerable development in quantifying uncertainties regarding climate models, uncertainty quantification (UQ) is a field important to many different disciplines, particularly those that use models (NRC, 2012a). The climate modeling community could benefit from assessing new methods being developed in other disciplines (NRC, 2012a). Certain government agencies, such as the Department of Energy, are supporting multiple research efforts in such topics as advancing UQ in modeling, simulation, and analysis of complex systems.[1]

In general, more careful consideration of uncertainty can serve multiple purposes of model improvement and better utilization of model predictions and projections.

Reducing Uncertainties in the Climate Change Problem

Although there has been much progress in characterizing and quantifying uncertainty about future climate change, less progress has been made in the arena of reducing uncertainty. This is a complex issue, because it depends on what type of uncertainty is being reduced and how that particular uncertainty is quantified.

There has been steady reduction in uncertainty about the causes of current climate change, as expressed in the series of IPCC reports, such that in the 2007 report (IPCC, 2007d) it is stated that "[m]ost of the observed increase in global temperatures since the mid-20th century is very likely (i.e., 90% confidence) due to the observed increase in greenhouse gas concentrations." This is primarily due to observation of continuing global warming and many of its anticipated corollaries consistent with the range of climate model predictions.

However, uncertainty in projections of future climate change is reducing more slowly. Before 2070, uncertainty about climate sensitivity is most important for projection of global-mean climate change. IPCC assessments suggest this uncertainty has not significantly decreased since 1990. It is unclear by how much this metric of uncertainty will be reduced over the next decade. Large regional projection uncertainties, especially in subtropical and summertime midlatitude precipitation, are added to this uncertainty in climate sensitivity; again, more research may beat these uncertainties down, but this may take time. Past 2070, uncertainty about GHG concentrations due to emissions uncertainty (which is difficult to reduce) is more important to projection of

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[1] http://science.energy.gov/ascr/funding-opportunities/faq-for-math/ (accessed October 11, 2012).

global surface air temperature than is climate model uncertainty (IPCC, 2007c, Figure 10.29). Morgan et al. (2009) has noted that "in some cases, all the research in the world may not eliminate key uncertainties on the timescale of decisions we must make."

Finding 6.2: The climate science community has made considerable progress in quantifying uncertainty in climate simulations, but progress in reducing certain types of uncertainty has been slow, and further reduction may not be possible for certain aspects of long-term projections.

COMMUNICATING UNCERTAINTY

Communicating uncertainty is a relevant topic for advancing climate modeling because it relates to decision making (see next section) for adaptation, mitigation, and regarding what aspects of a model may be most important to improve. The appropriate approach to communication depends on the particular audience and on the purpose of the communication. Moreover, the appropriate approach to communication partially depends on the purpose of the communication. Is it for general education, making people aware of important issues, or is it to inspire specific actions regarding managing climate resources, or is it for the sake of shaping the needs for future climate model development? Communications of scientists to scientists about uncertainty are very different from their communication with the lay public.

Review of Communication Approaches

There has been a steady increase in the attention that communicating about climate and climate change has received, and this communication has been carefully considered within the community of scientists. For example, in IPCC (2007c) there were descriptions of scientific understanding and likelihood of specific results. A standard language was developed with narrative terms; for example, "likely" was linked to quantitative statistics, >66 percent probability. An entire Synthesis and Assessment Report (SAP) of the Climate Change Science Program (CCSP, 2009) was dedicated to establishing best practice approaches of characterizing and communicating uncertainty (Morgan et al., 2009). In *Advancing the Science of Climate Change* (NRC, 2010b), considerable effort is devoted to describing the terminology of uncertainty, the nature of uncertainty in the culture of science, and the use of uncertainty in decision making. This section emphasizes and discusses some issues associated with the communication of uncertainty that have evolved or emerged since these earlier works and that are relevant to climate modeling.

The primary focus of the works cited above is how scientists can communicate uncertainty about climate change. From these, it is apparent that there is no simple formulaic way to communicate uncertainty, and in order to develop effective communication strategies, social-science based empirical studies are needed.

Lemos and Morehouse (2005) introduce another element of communication in their study of the effective use of climate information. They document that teams of both scientists and nonscientists working in a problem-solving environment to cogenerate solution strategies are effective. The communication of uncertainty of climate change involves not only scientists providing their descriptions to decision makers, but also learning what is usable information for the decision makers. The question becomes: does what we are doing make sense to and for the decision maker?

As stated in the SAP on transportation (CCSP, 2008):

> Transportation decision makers are well accustomed to planning and designing systems under conditions of uncertainty on a range of factors—such as future travel demand, vehicle emissions, revenue forecasts, and seismic risks. In each case, decision makers exercise best judgment using the best information available at the time. In an ongoing iterative process, plans may be revised or refined as additional information becomes available. Incorporating climate information and projections is an extension of this well developed process.

With this in mind, uncertainty about climate change is often not the most important or largest uncertainty faced by the decision maker. This suggests that descriptive statements about climate change uncertainty that are appropriately placed in the context of these other uncertainties could constitute effective communication that would accelerate the use and effectiveness of climate change knowledge in decision making.

The ways decision makers use information about climate change uncertainty complicate the problem of effectively communicating that information. Common, intuitively communicative language is necessary, but not sufficient. How decision makers view the definition and role of uncertainty must be taken into account. A model developer will identify uncertainties associated with comparisons of models to observations and uncertainties from processes not included in the model. A user of climate information will have uncertainty associated with its perception of the process of model evaluation or validation. As discussed above, other sources of uncertainty referred to by climate modelers include boundary conditions, initial conditions, formulation of physics, parametric, numerical formulation, downscaling, and so on. These different ways of describing sources of uncertainty are all useful, perhaps definitive, in their context, but collectively they amplify the challenges of communication.

This complex texture of types of uncertainty suggests the need for multiple strategies of communication. Above, uncertainty communication was implicitly framed as communication to nonscientist decision makers. However, when developing a strategy for improving the U.S. climate modeling enterprise, the communication to and subsequent use of information by scientific program managers is also important. It may seem attractive to pose scientific programs guided by uncertainty reduction, but this may not be realized in a systematic way in complex problem solving. Similarly, it is consistent with scientific culture to work toward quantification of uncertainty, reducing the definition of uncertainty to a small set of numbers that does not express the complexity of the climate. Again, this might be necessary, but it certainly is not sufficient. It does not represent the "expert judgment" form of uncertainty.

Finding 6.3: There is no simple, formulaic way to communicate uncertainty. To develop effective and consistent communication strategies, social science-based empirical studies are needed.

Examples of Current Approaches to Communicating Uncertainty

It is hoped that approaches to communicating uncertainty will become much more sophisticated in the coming decades, that the different needs for quantification in different science and policy communities will be well recognized, that means of presenting uncertainties will have greatly advanced so as to match the needs of the particular community, and that more creative ways of communicating uncertainty to the lay public and policy makers alike will be developed. These advances will entail greater interdisciplinarity—embracing climate modelers and climate analysts, experts in quantifying and communicating uncertainties and in decision making under uncertainty, and the target audiences themselves. More strategic approaches in communication are needed as summarized by Pidgeon and Fischhoff (2011):

> Communications worthy of climate change will require sustained contributions from cross-disciplinary teams, working within an institutional framework that provides support for their efforts. Such teams would include, at minimum, climate and other experts, decision scientists, social and communications specialists, and program designers. Once assembled, these teams must be coordinated so that experts stay focused on their aspect of the communication process. For example, subject-matter experts should edit for fact, not style; they should also check that social scientists have not garbled the facts when trying to make them clearer. That coordination must maintain

a rhetorical stance of non-persuasive communication, trusting the evidence to speak for itself, without spin or coloring.

These advances could be facilitated through the creation of resource centers to provide climate modelers with support in designing and empirically evaluating communications, including communication of uncertainty. There are fledgling activities that have begun to emerge that have focused on effective communication of climate science, such as the Yale Project on Climate Change Communication,[2] a nonprofit science and outreach project called Climate Communication,[3] and the commentary site RealClimate.[4] This effort could also be furthered by more actively engaging the media through agencies dedicated to the reporting of science such as the Society of Environmental Journalists,[5] the Yale forum on Climate Change and the Media,[6] and Climate Central.[7]

Although these and other resources (Somerville and Hassol, 2011; Ward, 2008) are starting to become more available, there are very few programs aimed at training climate scientists in lay communication or in targeting groups of scientists or professionals (such as weather forecasters) who play large roles in communicating to the public. One of the most prominent programs is the Climate Change Education Partnership (CCEP) Program from the National Science Foundation. CCEP "seeks to establish a coordinated national network of regionally- or thematically-based partnerships devoted to increasing the adoption of effective, high quality educational programs and resources related to the science of climate change and its impacts."[8] This program, begun in 2010, brings together climate scientists, learning scientists, and education practitioners, to work on issues focused on regional or thematic climate change impacts.

Finding 6.4: The issue of communication of uncertainty to a wide range of audiences has received more attention over the past few years—at annual scientific meetings, for example—but further progress in developing well-formulated communication strategies is needed.

Finding 6.5: Communication of uncertainty is a challenge within the climate modeling community: more sophisticated approaches that include the involvement of experts across disciplines and the consideration of communication from

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[2] http://environment.yale.edu/climate/about/ (accessed October 11, 2012).

[3] http://climatecommunication.org/ (accessed October 11, 2012).

[4] http://www.realclimate.org/ (accessed October 11, 2012).

[5] http://www.sej.org/ (accessed October 11, 2012).

[6] http://www.yaleclimatemediaforum.org/ (accessed October 11, 2012).

[7] http://www.climatecentral.org/ (accessed October 11, 2012).

[8] http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503465 (accessed October 11, 2012).

the beginning of any particular climate model-based research project or program could help address this challenge.

UNCERTAINTY AND DECISION MAKING

Although the focus in this report is on advances in climate modeling, it is important to consider what the results of climate models are used for. Many statements are made about the importance of location-specific information to inform decision making regarding coping with climate change. But the decision-making landscape is highly complex and varied. It is difficult to come up with a small collection of robust statements about the needs of decision makers (NRC, 2010d).

There may be major differences regarding how resource managers manage uncertainty about climate now and what will be needed for managing uncertainties about climate and other important elements in the near and long-term future. There is also substantial variability in how uncertainty is managed based on which resource is being managed (e.g., water resources, human health, and transportation infrastructure), the spatial scale of the decision frame (within a municipality, regional, or national), and the time horizon relevant for the decision (annual versus half-century).

There has been rapid development of new approaches to decision making and application of modes of decision making to new contexts. In these contexts it is well recognized that management decisions involve uncertainty and that in many cases significant uncertainty cannot be eliminated (NRC, 2010d). There has been considerable research about robust decision making (RDM; Lempert et al., 2004). In this approach decisions are made that are robust against the uncertainties to be faced about the future (e.g., climate, population, governance structures, etc.) (Lempert and Groves, 2010). The RDM approach has particularly been applied in the context of water resources, because the infrastructure associated with water resource management is particularly long lived (e.g., dams with lifetimes of 100 years). A related approach is iterative risk management (IRM), wherein it is recognized that we will learn more about the future as the future unfolds, and thus decisions made now may be revisited and perhaps altered as new information about the future becomes available (NRC, 2010d). How important it is to reduce uncertainty of regional climate change depends closely on the approach being used for decision making under uncertainty. The RDM or IRM approaches may be much less in need of a rapid reduction in uncertainty than an approach that needs a high degree of certainty to make any decision at all. The promise of uncertainty reduction, when not realized, stands as a metric of poor management, poor scientific method, or outright scientific failure. A meaningful codification of uncertainty for specific applications (e.g., model development) and alignment of development priorities with addressing those uncertainties stands to improve the communication of climate change to political decision makers and to organize model development priorities. There is new appreciation for involving decision makers directly in both discussions of uncertainty about climate change, and of their decision-making needs for quantification of uncertainties. For example, in work with the integrated Regional Earth System Model (iRESM), regional decision makers and other stakeholders from the pilot region have been engaged in the modeling process to guide, among other things, uncertainty characterization relevant to their decision making (Rice et al., 2012).

The development of the shared socioeconomic pathways that will be related to the representative concentration pathways used for the IPCC Fifth Assessment Report may provide a new opportunity for quantifying uncertainties in possible future socioeconomic conditions. There may also be means of reducing uncertainty regarding future concentrations of greenhouse gases by better characterization of surface processes (including land-use change) contributing to the concentrations of greenhouse gases and aerosols.

Finding 6.6: Resource managers and decision makers have diverse and evolving methods for handling climate change uncertainty.

THE WAY FORWARD

Knowledge about future climate has increased rapidly over the past two decades, and a number of facts about future climate are robust, such as that global temperature will increase, that greater increases in temperature will occur over land than ocean, that sea level will rise, and that substantial changes in the hydrologic cycle will occur. Nonetheless, important uncertainties remain, particularly regarding climate sensitivity, GHG emissions, and regional details about climate change. As new components of the Earth system are included into models, they may in fact (especially over the short term) increase the spread of certain predictions between models, as uncertainty previously not encompassed within the modeling framework is internalized (e.g., removing flux adjustment from coupled models). Some uncertainties are unlikely to be reduced over the next decade or so (for example, uncertainty in future emissions, a very important component of long-term climate change). But uncertainty due to model inadequacy or incompleteness should be reduced in the next 15-20 years. In addition, adding new components to the model helps reduce uncertainty about their response to a perturbed climate. For instance, adding a well-tested sea-ice representation to a climate model is a good strategy for reducing uncertainty about how fast sea ice might be lost during a climate change, even if it does not reduce uncertainty about the accompanying global-mean warming. The committee's strategy for climate modeling in the United States is intended to facilitate these advances and improve the understanding of the uncertainties in climate model projections (Chapter 14).

Although improvements in uncertainty characterization and quantification will proceed, particularly in the context of various kinds of climate model ensembles, it is less clear that convincing means of combining known qualitative (i.e., structural) uncertainties with these quantitative methods will be developed. Moreover, while much attention has been paid recently to developing means of differentially weighting different ensemble methods, we are not yet at a point where a consensus on how to proceed has been reached. Obviously limits to predictability constrain reduction in uncertainty, a possible issue for decadal forecasting. A probabilistic framework, rather than methods used in deterministic prediction, better characterizes uncertainty. Work on better characterizing uncertainty will need to be done on an ongoing basis. The committee suggests that a working group in the proposed annual climate modeling forum would be an appropriate venue to explore these issues (see Chapter 13).

Recommendation 6.1: Uncertainty is a significant aspect of climate modeling and should be properly addressed by the climate modeling community. To facilitate this, the United States should more vigorously support research on uncertainty, including

- **understanding and quantifying uncertainty in the projection of future climate change, including how best to use the current observational record across all time scales;**
- **incorporating uncertainty characterization and quantification more fully in the climate modeling process;**
- **communicating uncertainty to both users of climate model output and decision makers; and**
- **developing deeper understanding on the relationship between uncertainty and decision making so that climate modeling efforts and characterization of uncertainty are better brought in line with the true needs for decision making.**

CHAPTER SEVEN

Climate Model Development Workforce

The current workforce of climate model developers is insufficient to meet the growing need for climate model development work (Jakob, 2010). Most modeling centers have only a small number of people directly involved in climate model development. It is difficult to quantify the number of climate model developers in the United States, because a systematic study on the climate modeling workforce has never been done. The committee estimates that the number of full-time employees who work on climate model development is on the order of a few hundred.[1]

CURRENT CHALLENGES IN THE CLIMATE MODEL DEVELOPMENT WORKFORCE

Climate models had their origins in both weather forecast models and very simple models describing the radiative balance of the planet that streamlined representations of the ocean and atmosphere. The earliest climate models (ca. 1980) had many simplifications, such as fixed cloudiness or oceans with no currents. Since that time the complexity of modeling has increased, including not only much greater spatial resolution and realism in the representation of the ocean-atmosphere-land-ice system, but also the inclusion of new component models, such as atmospheric chemistry and aerosols, sea ice, the terrestrial and marine carbon cycles, and ocean biogeochemical cycles. These changes have increased the demands on model development and

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[1] The National Research Council (NRC) report *Improving the Effectiveness of U.S. Climate Modeling* (NRC, 2001b) estimated that there were approximately 550 full-time employees dedicated to weather and climate modeling in the United States. The current committee requested information from several modeling centers regarding their workforce. The National Centers for Environmental Prediction has about 63 full-time employees who work on the Global Forecast System and the Climate Forecast System. The National Aeronautics and Space Administration's (NASA's) Global Modeling and Assimilation Office has about 7 full-time employees who work on climate modeling for the Goddard Earth Observing System Model, Version 5. NASA's Goddard Institute for Space Studies has about 10 scientist-level people who work on the full Earth system model, with many of those people not working on the model full time. Of the 169 employees at the Geophysical Fluid Dynamics Laboratory (including federal employees, contractors, and National Oceanic and Atmospheric Administration Cooperative Institute), about 70 percent work on model development, application, analysis, and interpretations. These numbers are difficult to analyze and compare, because it is challenging to make distinct categories of people doing only model development, experiments, or analysis. In many cases the same person is doing all these activities, but at different points in time, and not necessarily full time.

analysis, but the human resources have generally not kept pace with the rapid growth in model complexity.

The development and use of comprehensive climate models in the United States requires a large number of talented individuals in the following areas:

- scientists engaged in understanding the climate system, leading to the development of new parameterizations and other model improvements (distinct cadres of scientists are often needed for various model components, such as the ocean or terrestrial ecosystem models);
- scientists engaged in using the models for well-designed numerical experiments and conducting extensive diagnostics of the models to better understand their behavior, ultimately leading both to model products and to scientific insights that provide the impetus and context for model improvements;
- scientists studying the regional details provided by the archived results from global model simulations and related downscaling efforts, and how these vary across various models;
- support scientists and programmers to conduct extensive sets of numerical simulations in support of various scientific programs and to ensure their scientific integrity;
- software engineers to create efficient and portable underlying codes, including the development and use of common software infrastructures;
- software engineers and scientists to facilitate easy and open access to model output through modern networking technologies;
- hardware engineers to maintain the high-end computing facilities that underpin the modeling enterprise; and
- climate interpreters to translate climate model output for decision makers.

The U.S. institutional and funding system has addressed some of these areas better than others; in particular, the U.S. scientific effort on model diagnostics and region-specific analyses has kept up better than the effort devoted to model improvement. The result is that many climate modeling efforts are subcritical in some aspects. In particular, there are longstanding problems in the simulation of the atmosphere-ocean-land-ice system that are not yet solved, and yet these have been somewhat neglected in the desire to add additional complexity into models. One example of a longstanding problem is the tendency for virtually all climate models to simulate an unrealistic structure of the Intertropical Convergence Zone in the eastern Tropical Pacific. Another such example is the tendency for virtually all models to simulate sea-surface temperatures in the equatorial Atlantic that increase from west to east, instead of the observed increase from east to west. These errors in the simulation of the basic state of the tropical climate can distort the overall simulation of the climate system.

One important objective is to develop a pathway that can lead to modeling efforts in the United States that have sufficient human resources to meet their challenges in all critical areas, including both persistent and longstanding problems such as those mentioned above. Efforts are needed to address the emerging scientific frontiers discussed in Chapter 4, such as the effects of aerosols on clouds (the indirect aerosol effect) or the terrestrial and oceanic carbon cycles, which are major sources of uncertainty in climate change projections. In addition, continuing model development will be required to provide the high-quality climate simulations that can provide information to decision makers at the regional and local levels, as discussed in Chapter 10.

Finding 7.1: The level of human resources available for climate modeling has not kept pace with the demands for increasing realism and comprehensiveness of the models, leading to subcritical efforts in multiple areas of core modeling efforts. This is a serious impediment to progress.

ESTABLISHING AND MAINTAINING A PIPELINE IN CLIMATE MODEL DEVELOPMENT

Current Pipeline

Workers in climate model development have primarily received postgraduate degrees. In order to maintain a pipeline of human capital to sustain the climate modeling efforts, the United States will need to ensure the current and future availability of fellowship funding for graduate students and postdoctoral researchers, including expansion of programs at national laboratories and research facilities.

Data on the numbers of students involved in climate model development do not exist.[2] As a proxy for understanding trends in the training of climate model developers, the committee examines data on related fields of computer science, geosciences, mathematics, and physics. Current trends in the education pipeline in fields related to climate modeling (Figure 7.1) show that the overall number of Ph.D. degrees being awarded in some fields related to climate modeling is growing, but numbers of master's degrees and bachelor's degrees are not growing. The percentages of females and minorities are low and have not been growing substantially over the past decade. As stated, although none of this information is specific to the pipeline of climate model developers, the committee infers that it is indicative of a pipeline that is not growing in a robust fashion.

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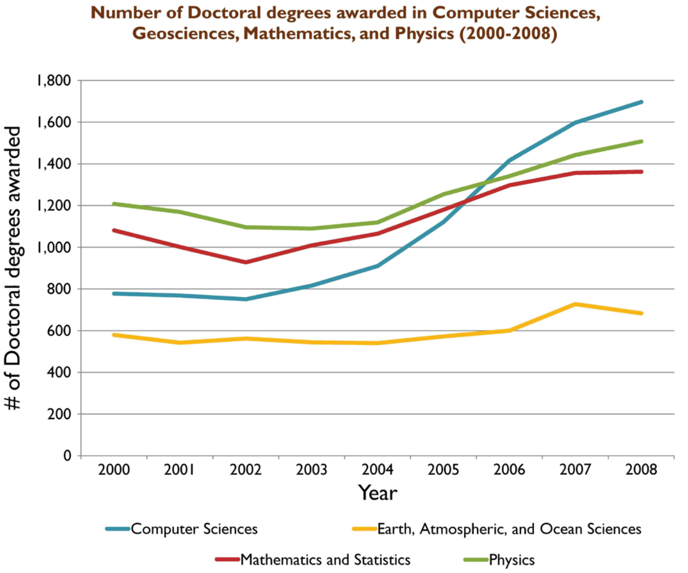
[2] Jill Karsten, National Science Foundation (NSF), personal communication, 2011.



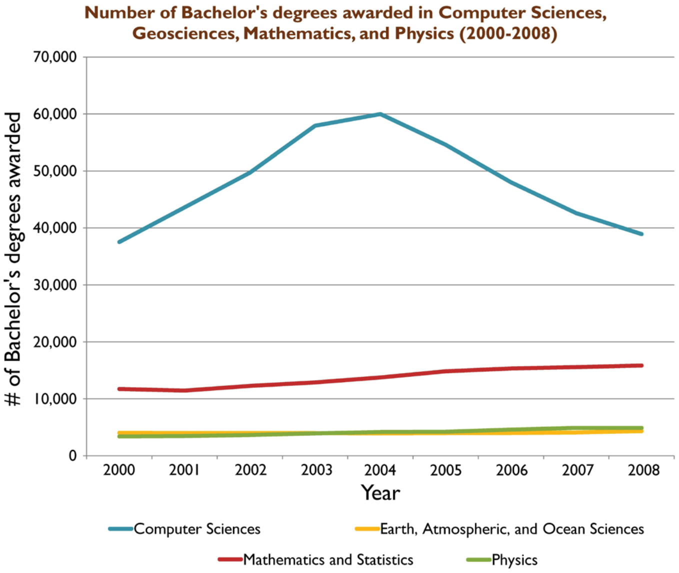
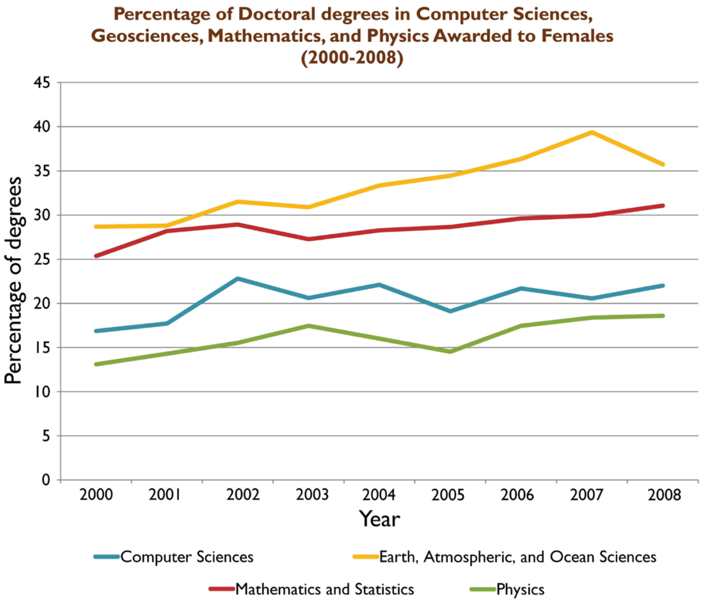
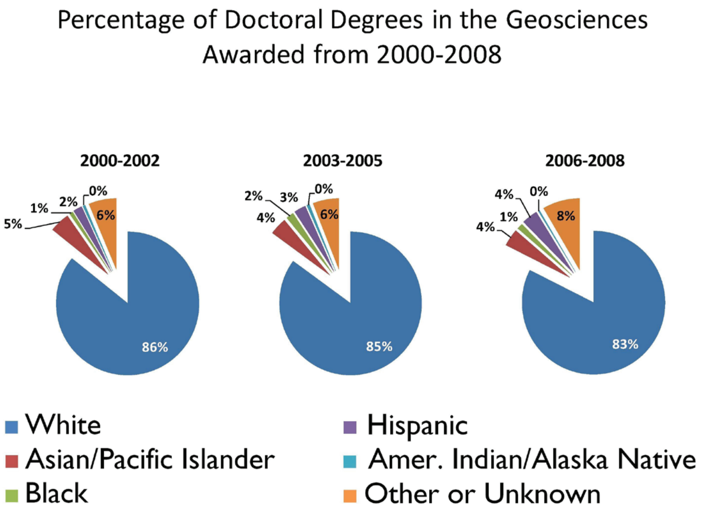


FIGURE 7.1 Education data for scientific disciplines related to climate model development indicate that the pipeline for climate model developers is not flowing robustly. The upper two panels show the trend in Ph.D. degrees (first panel) and bachelor's degrees (second panel) awarded over the past decade, showing no increase for the category of "Earth, Atmospheric, and Ocean Sciences." The third panel shows the percentage of females awarded doctorates over the past decade, showing relatively low percentages (less than 50 percent) for several fields related to climate modeling. The fourth panel shows the percent-





age of bachelor's degrees awarded in geosciences by ethnicity, showing the relative lack of diversity; the percentages are similar at higher education levels. For these figures, even though only one set of data is shown, the trends among doctorates, master's degrees, and bachelor's degrees are all similar. SOURCE: NSF, Division of Science Resources Statistics, special tabulations of U.S. Department of Education, National Center for Education Statistics, Integrated Postsecondary Education Data System, Completions Survey, 2000-2008.

Finding 7.2: From the limited data available, it is surmised that the pipeline of climate modelers being trained is not growing robustly in overall numbers or in diversity within the United States.

Overcoming Obstacles

Climate model development is a challenging job. It involves synthesizing deep and broad knowledge, working across the interface between science and computational algorithms, and working well in a team. Thus, it is important to hire the most talented available people into this field. One obstacle to getting more students who are interested in climate science and other related fields to go into climate model development comes from the current incentive system for U.S. early-career scientists, which heavily favors those who produce more first-authored peer-reviewed journal articles. Students are disinclined from undertaking model development projects because of the fear of a "black-hole syndrome" wherein climate model development projects take long time periods (longer than a typical Ph.D. length) and do not result in many journal publications.[3] This is a systemic issue within the field—the credibility of climate change science is heavily dependent on the fidelity of the climate models used, and yet the process of improving such models is often not particularly rewarding to a young scientist's career. For example, a scientist who spends 2 years analyzing the output of existing simulations and writing papers on the findings may be more likely to advance in his or her career than a scientist who spends 2 years working on the details of a physical parameterization in a model. From the perspective of the entire field the efforts of the second scientist may well be more important in the long run, and yet the personal rewards will likely accrue more to the former scientist. One mechanism to combat this bias would be an enhanced recognition and reward system for climate model computer code writing and for the production of modeling data sets, including the recognition of such effort through stronger requirements for citation and coauthorship, both within modeling institutions and by academic users and collaborators.

A significant challenge is the entraining of top students interested in software engineering or computational science to work on developing climate models in comparison to other career tracks. Promising young computer programmers may have other more lucrative career opportunities at large software companies or startups. Climate modeling groups must compete by marketing relatively stable career tracks and the opportunity for stimulating cross-disciplinary interactions with a variety of scientists. A

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[3] This is a conclusion largely drawn from anecdotal evidence; further quantification is needed to determine how pervasive student bias is against tackling model development projects.

positive step is the development of computational (as opposed to computer) science programs at a number of U.S. universities that provide applied training well suited to a career in computational aspects of climate model development.

Finding 7.3: The current professional recognition system that heavily weights journal publications is a barrier to entraining more young scientists into climate model development.

The European Centre for Medium-Range Weather Forecasts as an Example

One potential example of how to entrain more people in climate model development work is from the European Centre for Medium-Range Weather Forecasts (ECMWF). ECMWF is an intergovernmental organization supported by 34 countries dedicated to operational medium- and extended-range forecasts combined with an extensive scientific research program. In these roles of operations and research, the Center employs about 150 staff members and 80 consultants coming from member and cooperating states. Rather than strictly a technician staff, members and consultants are generally highly reputed scientists who not only serve to deliver the end-use product to the member institutions, but also employ the supercomputing facilities and myriad data services of cooperating institutions to provide cutting-edge science with regard to the Center's many research projects. The utility of the modeling is more directly coupled with research and provides justification for the latter. ECMWF appoints model developers for 5-year terms, which is longer than typical research grant cycles in the United States (3 years). ECMWF offers strong incentives to attract top scientists such as access to excellent facilities, excellent tools (e.g., the best numerical weather prediction [NWP] model in the world), and high, tax-free salaries.

THE WAY FORWARD

In order to ensure a capable and robust workforce in climate modeling in the future, it is crucial that young scientists and software engineers entering this field be appropriately trained and have highly attractive career paths. This involves a partnership between funding agencies, universities, and national laboratories. Universities can offer innovative coursework, degree pathways, and research opportunities for students and postdoctoral researchers combining climate and computational science. National laboratories can also host postdoctoral researchers and partner with universities in graduate student training. They can create stable career paths and change the current system of professional recognition and incentives to favor important contributions to team projects with long development cycles and more risk. In order for these efforts to succeed, funding agencies will need to nurture training activities and provide adequate opportunities for stable funding to those who choose climate model development careers both in national laboratories and in academia, so that the best scientists and engineers do not seek greener pastures.

As described above, there are limited data on the existing climate model development workforce or future needs. More information on gaps in the workforce pipeline and future workforce needs could help inform better planning by universities, national laboratories, and funding agencies.

Recommendation 7.1: The United States should attempt to entrain top students into choosing climate model development as a career by providing more graduate and postgraduate training opportunities, enhanced professional recognition and career advancement for participation in climate model development projects, and adequate incentives to attract software engineers who could also choose private-sector careers.

Recommendation 7.2: In order to assess future needs on the climate model development workforce, the United States should obtain quantitative information about the workforce needs and required expertise base to support climate modeling.

CHAPTER EIGHT

Relationship of U.S. Climate Modeling to Other International and National Efforts

The field of climate modeling has grown tremendously over the past several decades, and much of that growth has occurred in the international community. In the first Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 1990), only three coupled ocean-atmosphere models were used for estimates of the transient evolution of global temperature in response to changing greenhouse gases. Those models were all from the United States (the Geophysical Fluid Dynamics Laboratory [GFDL], the National Center for Atmospheric Research [NCAR], and the Goddard Institute for Space Studies). Since that time the growth in climate modeling has been substantial—for the IPCC Fourth Assessment Report in 2007, 23 models were used from 11 countries around the world (Table 10.4 of the Fourth Assessment Report), and even more will likely be used in the upcoming Fifth Assessment Report, scheduled for completion in 2013. These include climate modeling centers in a wide range of countries, including Canada, the United Kingdom, Germany, France, Norway, Russia, Italy, China, Japan, Korea, and Australia. Computational resources associated with these international centers have likewise grown, including facilities such as the Earth System Simulator in Japan.[1]

INTERNATIONAL COORDINATION, ESPECIALLY AS IT RELATES TO THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

Systematic comparison of simulations using these models has proved highly beneficial. Since the 1990s the leading climate modeling efforts around the world have exchanged information and coordinated their efforts under the umbrella of the World Climate Research Programme (WCRP), an activity of the World Meteorological Organization of the United Nations. A number of working groups have sought to facilitate interactions and coordination of modeling activities. The Working Group on Numerical Prediction (WGNE) has coordinated activities involving weather prediction models. The Working Group on Seasonal to Interannual Prediction (WGSIP) has coordinated

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[1] http://www.jamstec.go.jp/esc/index.en.html (accessed October 11, 2012).

efforts in developing and using coupled ocean-atmosphere models for seasonal to interannual prediction, with its primary focus on the El Niño/Southern Oscillation phenomenon. The Working Group on Coupled Modeling (WGCM) has coordinated coupled ocean-atmosphere models that are primarily developed and used for the study of decadal to centennial climate change projections. A subset of the WGCM, the Working Group on Ocean Model Development, has fostered the development worldwide of the ocean component of coupled models to improve the representation of the ocean component of coupled models.

The community as a whole, under the aegis of the WGCM and the WGNE of WCRP, with links to the International Geosphere-Biosphere Programme, comes to consensus on a suite of experiments, which they agree would help advance scientific understanding. The WGCM sponsors the Coupled Model Intercomparison Project (CMIP), a project that seeks to foster and coordinate the design and execution of simulations using models around the world that are subjected to a common experimental protocol. Meehl and Bony (2011), Stouffer et al. (2011), and Doblas-Reyes et al. (2011) describe the current protocol and how it has evolved. All the major modeling groups participated in defining the experiments and protocols and have agreed to the CMIP5 suite[2] as a sound basis for advancing the science of secular climate change, assessing decadal predictability, and so forth (Taylor et al., 2012). The use of this common protocol is designed to facilitate the comparison of the various models used. Model output is freely available over the Web. The Program for Climate Model Diagnosis and Intercomparison (PCMDI), sponsored through the U.S. Department of Energy, has played a key role in archiving this model output and facilitating its wide public dissemination.

These common experiments have evolved significantly over the years. The first experiments were performed in the early 1990s with atmosphere-only models as part of the Atmospheric Model Intercomparison Project (AMIP). A key aspect of this early effort that set the tone for future success was an emphasis on making model output available for use by a wide community of users. This early AMIP effort then spawned a number of model intercomparison projects, including an Ocean Model Intercomparison Project, the Paleoclimate Model Intercomparison Project, and the widely known CMIP.

In addition to the output of such coordinated experiments, the various working groups serve as important mechanisms for exchange of information and ideas among modeling scientists around the world. U.S. scientists have benefited greatly from such interactions. These working groups sponsor internationally coordinated experiments

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[2] Currently ongoing at the time of this report.

with climate models, diagnostic projects across models, and international workshops to synthesize model results and foster increased understanding.

The intraseasonal to interannual community agrees on similar multimodel approaches for seasonal forecasting, for example, through the WCRP WGSIP and its Climate System Historical Forecast Project.[3] A globally coordinated suite of experiments is then run, and results are shared for a comparative study of model results.

The data archives that result from all of these coordinated campaigns have spawned an entire new field of research in the interpretation of multimodel ensembles (e.g., Reichler and Kim, 2008; Santer et al., 2009), including studies of model genealogy and cladistics (see, e.g., Masson and Knutti, 2011) and uncertainty quantification (Tebaldi and Knutti, 2007). The data are stored in petabyte-scale (and soon exabyte-scale; see Overpeck et al., 2011) distributed archives. Providing access to these data, especially for users who may not be climate experts, is one of the primary challenges of the decade.

Finding 8.1: U.S. climate modelers are extensively involved in internationally coordinated activities, including the Coupled Modeling Intercomparison Project, the IPCC, and a suite of observational and modeling programs that are designed to advance climate models by improving processes-based understanding of important aspects of the climate system, such as clouds and their feedback on the climate system.

Finding 8.2: The U.S. involvement in such international activities contributes significantly to advances in U.S. climate modeling through leveraging international resources that are applied to climate modeling.

Finding 8.3: Modeling intercomparison projects create vast amounts of data that need to be curated, managed, made readily available, and analyzed.

INTERNATIONAL ACTIVITIES IN PROCESS-BASED STUDIES AND OBSERVING SYSTEMS THAT CAN LEAD TO IMPROVED MODELS

Under the auspices of WCRP, there are also numerous international activities aimed at testing the fidelity of model simulations of various specific physical processes, for instance sea ice, carbon dioxide (CO_2) fluxes from vegetated surfaces, aerosol transport, or tropical cirrus clouds. Examples of such activities are the Global Atmospheric System Study coordinated through the Global Energy and Water Cycle Experiment

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[3] http://www.wcrp-climate.org/wgsip/index.shtml (accessed October 11, 2012).

(GEWEX), the GEWEX Atmospheric Boundary Layer Study, and the Year of Tropical Convection (YOTC).

Typically, such activities evaluate how well a process is simulated by comparing a relatively new data set with data from a suite of participating models (e.g., from a field experiment, a ground observing network, or a satellite instrument). Participation is voluntary; usually a case leader will specify details of how the models are to be run (what days, boundary conditions, what fields to output) and then process all the model output for direct comparison with the observations.

This process is rarely as straightforward as it may appear. A focus on a single process (e.g., cirrus microphysics) requires other related processes to be constrained (e.g., cumulonimbus convection that first creates the cirrus) using observations or a best guess at the related meteorology; often the model results themselves suggest how to better do the comparison. An international intercomparison leverages the effort involved in setting up both the observations and the modeling protocol; most modeling groups can participate with relatively minor effort once the case is defined, and they get valuable analysis of their results essentially for free.

Many recent U.S.-led field experiments have from the start been designed in part for such an intercomparison. A partial list of such projects includes DYCOMS-II (the Second Dynamics and Chemistry of Marine Stratocumulus field study); the Rain in Cumulus over Ocean project, sponsored by the National Science Foundation (NSF); the North American Monsoon Experiment (NAME); the Tropical Warm Pool International Cloud Experiment; and the VAMOS Ocean-Cloud-Atmosphere-Land Study, a part of the Variability of the American Monsoon Systems (VAMOS) project. Intercomparisons have also been based around observation networks such as the Atmospheric Radiation Measurement sites, the AERONET aerosol monitoring network (AEROsol robotic NETwork), or the AMERIFLUX array of CO_2 monitoring sites, or using new satellite data sets (e.g., the CFMIP Observation Simulator Package, within the Cloud Feedback Model Intercomparison Project [CFMIP] project).

U.S. funding agencies have supported these types of projects (e.g., as part of the NAME and VOCALS science plans) because of their potential for speeding the pace at which new observations are used to test and improve process representation in models. In some cases (e.g., National Oceanic and Atmospheric Administration/NSF Climate Process Teams), U.S. climate modeling groups such as GFDL, NCAR, and the National Centers for Environmental Prediction (NCEP) also have received dedicated funding to aggressively use such intercomparisons to improve their models.

Model intercomparisons allow modelers to see weaknesses of their simulations in focused settings, and also to see whether other parameterization approaches clearly work better. They are only one part of the road to actual model improvement because different process parameterizations can strongly interact so that a change in one parameterization (e.g., cumulus convection) may not have the same effect on overall results when applied to different climate models. However, leading modeling groups such as GFDL and NCAR in the United States and the U.K. Met Office, Max Planck Institute, and the European Centre for Medium-Range Weather Forecasts in Europe are typically participating in many intercomparisons at any one time. Their model development teams see great merit in this approach. NCEP has participated less, perhaps because of a lack of available manpower. Overall, the committee's assessment is that voluntary process-oriented international intercomparisons greatly benefit U.S. climate models rather than being a distracting drain on resources.

Finding 8.4: International model intercomparison projects have proven to be effective mechanisms for advancing climate models because they leverage the effort involved in setting up both the observations and the modeling protocols used for testing, and they allow modelers to see weaknesses of their simulations in focused settings.

CURRENT CMIP/IPCC EFFORTS

In support of the Fifth Assessment Report of the IPCC, the CMIP has established an extensive suite of common modeling experiments that many centers around the world are executing. A goal is to make the output from such experiments widely and easily available so that scientists from around the world can analyze that model output in time for the results of such analyses to inform the Fifth Assessment Report of the IPCC (as of this writing, any paper that will be cited in the next IPCC report must be submitted by July 31, 2012). However, the CMIP archive will be available for many years to come, so that additional studies using this archive will likely occur well after the IPCC. The previous (CMIP3) suite of simulations from 2005-2006 had been used in 595 publications as of January 2012[4] and is still heavily utilized. There are more than 6,700 registered users of the CMIP3 archive, with new users continually registering for access; data are being downloaded from the archive at a rate of approximately 160

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[4] http://www-pcmdi.llnl.gov/ipcc/subproject_publications.php (accessed October 11, 2012).

TB per year, with over 1 PB of data downloaded since the start of the CMIP3 project in 2005, corresponding to 3 million files.[5]

The CMIP activity has evolved from common experiments using models of just the atmosphere to models of the full Earth system, including oceans, interactive aerosols, and biogeochemical cycles. As described below, the current suite of CMIP experiments involves models of differing levels of complexity; these span a range from atmosphere-only models to more comprehensive coupled ocean-atmosphere models that include representations of ecosystems and various biogeochemical cycles, including the carbon cycle. In addition to model comprehensiveness, the suite of experiments conducted under CMIP has grown in diversity over the years. While the initial protocols consisted of very simple, idealized experiments, the full protocol for CMIP5[6] is extremely complex, entailing many thousands of years of model simulations (note, however, that there are several tiers of simulations of different priority levels, of which the highest-priority tier is less computationally demanding, and there is no requirement for even a leading modeling center to perform all requested simulations). This allows a much fuller examination of simulations but also entails significant costs. This general issue is discussed below. The experimental protocol entails designs for both long-term and near-term climate change predictions and projections, as well as a focused effort on evaluating the role of biogeochemical cycles and changes in the climate system and their potential future change. The model output from this archive is used to investigate a host of issues. These range from detailed analyses of the physical processes that operate in models in order to assess their credibility, to using this model output to assess the impact of projected climate change for various regions to estimate climate vulnerability and adaptation.[7]

Finding 8.5: CMIP outputs, including model outputs from models outside the United States, are a valuable resource for a wide range of activities, including estimating climate change impacts and adaptation planning.

BENEFITS AND COSTS OF INTERNATIONAL COLLABORATIVE EFFORTS

One of the fundamental challenges in the use of climate models for projections of future change is the very limited understanding of the uncertainties embedded within

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[5] Karl Taylor, PCMDI, personal communication, 2011.

[6] http://cmip-pcmdi.llnl.gov/cmip5/experiment_design.html?submenuheader=1 (accessed October 11, 2012).

[7] See, for example, http://www-pcmdi.llnl.gov/ipcc/diagnostic_subprojects.php for a list of projects using CMIP3 output (accessed October 11, 2012).

any single model projection. The construction and use of a climate model represents a series of choices on many topics, including physical parameterizations and scenarios of future changes in emissions of radiatively active atmospheric constituents. Each of these is highly uncertain, and yet climate modelers are constrained in our choices due to various resource limitations. Thus, a projection based upon one model represents a single point within a very large parameter space.

A more robust assessment of future climate change arises with fuller coverage of this parameter space of uncertainty in model formulation and scenarios of future radiative forcing changes. Thus, many recent assessments of future climate change draw not only on the output of a single simulation, but also on the full suite of possible outcomes as drawn from the archives of past CMIP experiments. Although this assessment is still very far from a satisfactory estimate of the full range of possible future climates, it represents an invaluable guide. Thus, participation of modeling centers around the world in the CMIP suites of experiments contribute both to better estimates of future climate change and to model development and improvement. Such international coordination and exchange of information provide a vital exchange of ideas and techniques that improve climate modeling in the United States and around the world.

Model intercomparison programs, such as CMIP, provide timelines for model development and the execution of coordinated experiments. The process of climate model development is one in which there are often not obvious ending points. Models can be changed in an almost continuous fashion, with each change producing new simulations that must be carefully evaluated. This process often has no natural closure points and generally becomes longer as models become more comprehensive. However, participation in activities such as CMIP can provide clear schedules for the conclusion of such model development processes that can be used very effectively by modeling centers to define completion of the model development cycle. In fact, many of the model development cycles at centers around the world are now timed to the schedule of IPCC assessment reports. Although such a schedule can be a benefit by providing firm deadlines for concluding model development cycles, it can also be a serious detriment by artificially constraining the model development process and placing enormous strain on already underresourced model development efforts.

Participation in CMIP-like activities can also produce a healthy sense of competition among national and international modeling centers. The output from such coordinated experiments is routinely made available to researchers around the world, who provide evaluations and comparison among the models. Such activities often show which models are among the world's elite, and this can produce a very positive feedback in the ongoing model development process.

Finding 8.6: There are many benefits to the participation of U.S. climate models in the CMIP process, including defining timelines for model development and creating healthy competition among modeling centers.

However, there are also costs to participation in such efforts. Bringing closure to the model development process on any timeline is a difficult task, especially because modeling centers want to have the best possible physics and numerics in their models. These typically involve recently developed physical parameterizations based on new observational and theoretical research, and their behavior in complex models can be difficult to predict. The often unpredictable nature of newly developed model processes can create an environment of intense pressure to finalize a model with simulation characteristics that are superior to its predecessor model and to competitor models. This pressure can be exacerbated by the CMIP-derived timelines for coordinated model experiments and can lead to model decisions being heavily influenced by artificial time pressures rather than the best possible science. The effect of this process can lead to "burn out" among those most deeply involved in the model development process.

In addition, as described in Chapter 7, model development is an enormous task requiring substantial human and computational resources, yet the vast majority of this effort, including the production of model runs for CMIP activities, does not lead to peer-reviewed publications. Because such publications are usually the metric by which scientists are evaluated, participation in the model development process can sometimes hurt a young scientist's career, at least in the short term as measured by publications. As noted in Chapter 7, a culture of coauthorship with model developers and the careful citation of model development papers could change this.

The benefits of CMIP-related model experimentation also have to be weighed against some lost opportunity costs, especially for the scientists directly involved in model development. Fundamental advances and new findings are often the result of research that is curiosity driven or inspired by an idea or question. The more time that a scientist devotes to large-scale science, as embodied by programs and activities such as CMIP, the less time is available for small-scale or curiosity-driven research. In addition, the full suite of CMIP simulations requires an enormous computational effort that can consume a substantial fraction of the computational resources available to a modeling center for a year or longer.

Finding 8.7: One cost associated with the effort and time pressure of participating in the CMIP/IPCC is the reduction of time and computational resources that model developers have to devote to fundamental research that produces results on longer time scales.

THE WAY FORWARD

For decades, the United States has sustained the largest climate research enterprise in the world. The first climate simulation model was developed in the United States, and the United States continues to support a diverse range of approaches to better understanding future extreme weather and climate on all space and time scales. A robust international climate modeling community has evolved, including state-of-the-art efforts in Europe in regional and global modeling, as well as growing efforts in Asia supported by large new investments in computing. This has led to Earth system models that simulate the current climate more accurately and comprehensively than in the past, and the application of these and finer-scale, more specialized regional models to many societal and scientific problems, although model-related uncertainties in future climate projections remain substantial. In response to IPCC-type assessments, the international community, led by the United States, has pioneered mechanisms for distributing an ever-growing set of standardized outputs from international suites of models. These are a major resource for the U.S. climate community.

On balance the CMIP activities are a clear positive for U.S. climate modeling activities. These activities help to keep U.S. models and model-based research at the leading edge of activity around the world. However, the costs associated with these activities imply a need for balance among the various sorts of activities in modeling centers to achieve some optimal outcome, especially in light of the rapidly growing scope of CMIP experiments. These activities are important enough to be considered an expected part of the model development process and thus warrant sustained support. This includes support for participation in the CMIP/IPCC activities and for the systems to archive model output in a way that is freely and easily available to users. Such support would include (a) software specialists for the development and maintenance of data storage and distribution systems that meet the needs of the climate community and (b) the required hardware, including storage, transmission, and analysis capabilities. This support would likely include resources at the modeling centers that run the climate model simulations, as well as support for a centralized capability that coordinates this activity within the United States.

In addition, it is anticipated that over the coming decades climate change assessments will be conducted in the United States that focus on both national and regional scales, with an increasing emphasis on adaptation. The utility of such assessments is greatly enhanced through the active use of climate models both from the United States and from institutions around the world. The utility of a large number of models enhances the credibility of any such assessments by providing the potential for an improved assessment of the uncertainty of climate change projections. The U.S. participation in CMIP and related activities greatly facilitates the use of multimodel ensembles incorporating U.S. and international models.

U.S. modeling centers should be encouraged to participate in international activities, including the execution of internationally coordinated numerical experiments such as CMIP, and to make that data publicly available. In addition, there should be sustained support and encouragement for the participation of U.S. scientists in international activities in support of climate modeling and the use of climate models, such as those organized by WCRP, and for the systems to archive model output from leading U.S. climate models, and to make that output freely and easily accessible (this is discussed in Chapter 10).

Recommendation 8.1: To advance in the next 10-20 years, U.S. climate modeling efforts should continue to strive for a suitable balance among and support for

- **the application of current generation models to support climate research activities, as well as national and international projects such as CMIP/IPCC;**
- **near-term development activities that lead to incremental but meaningful improvements in models and their predictions; and**
- **the investment of resources to conduct and capitalize on long-lead-time research that offers the potential for more fundamental and transformational advances in climate modeling.**

Recommendation 8.2: The United States should continue to support the participation of U.S. scientists and institutions in international activities, such as model intercomparisons, including support for systems to archive model output, because such activities have proven effective in robustly addressing user needs for climate information and for advancing U.S. climate models.

Recommendation 8.3: To enhance their robustness, national and regional climate change/adaptation assessments should incorporate projections from leading international climate models as well as those developed in the United States.

CHAPTER NINE

Strategy for Operational Climate Modeling and Data Distribution

The ability to dynamically simulate climate has existed for a little over 50 years (Phillips, 1956), even less if climate simulation is viewed as requiring coupled ocean-atmosphere models (Manabe and Bryan, 1969). Attempts to apply climate simulation to the problem of seasonal to interannual climate prediction, using dynamical ocean-atmosphere models with initial conditions based on observations, have been made for only the past quarter century (Cane et al., 1986). In contrast to the relative youth of climate prediction, the demand for weather forecast information in the United States officially dates to the 1870s when a national weather service was called for by Congress during the Grant Administration. Since then, the weather service mission has grown to include a multitude of products, including climate monitoring and outlooks, which are used daily by citizens, companies, and researchers. User sophistication has grown as well from a rudimentary expectation for advance warning of impending storms to the ability to ingest and interpret gigabytes of raw data from numerical models of the atmosphere and ocean (Chapter 12). Within the past two decades, the demand for future climate information has grown to include long-lead forecasts, seasonal outlooks, and climate change projections. These products are valuable to a wide range of sectors and regions.

Given the growing demand for climate prediction products, and the maturation of climate simulation and prediction to demonstrably useful levels of skill, a strategy for operational climate prediction is needed. Furthermore, given the sophistication of the user community and the rapidly growing number and complexity of potential climate prediction data products based on climate models with ever-increasing complexity and resolution, the strategy needs to take into account the distribution of data to the user community for application in a variety of socioeconomic sectors and for basic research.

CLIMATE MODEL DEVELOPMENT FOR OPERATIONAL PREDICTION

For the past several decades, increasingly complex climate models of increasing spatial resolution were developed as research tools to study scientific questions regarding the processes responsible for climate variability, change, and predictability (e.g., Delworth et al., 2006; Gent et al., 2011; Kiehl et al., 1998). Other than the development of seasonal prediction tools, the motivation for these advancements was primarily, until recently, to improve understanding of processes and reduce biases, not to address any particular societal need for climate predictions, although researchers realized that the results might have societal implications (NRC, 1979). More recently climate model development has been driven more by a desire to better understand the general impacts of anthropogenic climate change, and several recent reports (e.g., NRC, 2010b, *Advancing the Science of Climate Change*) and the U.S. Global Change Research Program 2012-2021 strategic plan (USGCRP, 2012) have noted that both scientific advancement and addressing specific societal needs should be viewed as drivers of climate model development.

The user community needs easily accessible and comprehensible climate information updated on a regular basis. One resource for users interested in decadal and longer time scales has evolved from a series of climate model comparison (or intercomparison) projects (MIPs), organized by the international research community primarily for the purpose of advising international assessments of climate change that are conducted periodically by the Intergovernmental Panel on Climate Change (IPCC, 2007a,b,c). These MIPs are described in more detail in Chapter 8. They encourage the participating model development groups to conduct a series of numerical climate change simulations that conform to a prescribed protocol, with standardized outputs placed in a distributed quasipublic archive. These simulations are increasingly used not only by IPCC and the research community but by a broad range of users as source material for assessments of climate variability and change and as inputs to other models specialized to particular applications.

A second resource for users is "operational" climate forecasts (see Box 9.1) for lead times of months to a few years. Several weather services around the world have developed climate models specifically to provide scheduled, real-time, forecast products. For example, the U.S. National Weather Service has developed the Climate Forecast System (Saha et al., 2006, 2010) to produce operational climate predictions with lead times of up to 9 months. The second generation of this system went into operation in March 2011. The European Centre for Medium-Range Weather Forecasts has developed a seasonal climate prediction system, soon to be in its fourth generation

BOX 9.1 OPERATIONAL PREDICTION

As in operational numerical weather prediction, several characteristics of operational climate prediction make it distinct from climate model research and development. First, the goals of operations are driven by a user community rather than scientific advancement. There is no value judgment implied by this, but the implication is that the needs of the user community have to be assessed regularly, operational products must respond to users' needs, and there is an expectation for improvement over time in various aspects of users' experience. Second, operations must conform to a specified schedule of generation and delivery of products. Users expect products to be available in time, on time, every time, which requires a mindset and a working protocol that is not necessarily appropriate in a research and development setting. Third, operational prediction requires dedicated resources and contingency (failsafe) planning. Model developers often work with resources that have been obtained through a competitive process, on an ad hoc basis, or through windfall opportunities, but those modes are far too undependable for operational requirements. Operations must have a platform for product generation that is fully functional when needed and a plan in place for utilizing backup resources when that platform is out of order. Finally, operational computer code should conform to rigorous standards of software engineering that may or may not apply to research codes. While many climate prediction research groups are shifting to a more formal software engineering approach (Chapter 10), primarily motivated by the need for including the input from a wide community of researchers and model developers, there remains a more informal methodology in most model development groups that enables and even encourages risk taking, as is appropriate in a research and development enterprise.

(System4[1]), and other nations have similarly developed seasonal climate prediction systems that include a climate model developed specifically for this purpose.

There is a desire within the research community to migrate experimental climate prediction models into operational use (e.g., the National Oceanic and Atmospheric Administration [NOAA] Climate Test Bed effort to build a multimodel ensemble [NOAA, 2011]) and to improve on operational models by transitioning model components and/or parameterization schemes from experimental models developed in the broader community, motivated by the growing expectation for governments to provide climate services (e.g., Dr. Jane Lubchenco's testimony before Congress during the hearings to confirm her as Undersecretary of Commerce for Oceans and Atmosphere and Administrator of the National Oceanic and Atmospheric Administration

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[1] http://www.ecmwf.int/products/changes/system4/ (accessed October 11, 2012).

[Lubchenco, 2009]). This migration of experimental models into operational use has the potential of efficiently leveraging the U.S. climate research community to provide more skillful and comprehensive climate predictions. Effecting this transition is difficult, because of gaps between research goals and operational imperatives (e.g., that changing an operational model requires a more careful and elaborate process than for a research model) and mismatches between resource requirements needed to maintain an operational model and the current distribution of resources between research, development, and operations. There is clearly a need for adequate support for research on climate modeling, operational climate prediction, and an effective interface between the two.

Finding 9.1: Some operational seasonal-to-interannual prediction efforts are already under way, and there are archives of model output from research-oriented international climate model intercomparisons focused on multidecadal to centennial climate simulation; these archives do not cover all of the needs of climate information users.

ISSUES RELATED TO OPERATIONAL CLIMATE MODELING

The current practice of configuring and running climate models is primarily done by a relatively small number of developers and programmers with insufficient support for robust code development and support. Many aspects of climate model development and usage (e.g., setting up model experiments and "tuning" climate model parameterizations) cannot be made routine when model configuration and execution demands such large efforts from a small number of people. This practice also does not facilitate rigorous attention to reproducibility, which is needed to ensure credibility. Finally, singular efforts such as are the current practice do not adequately support the sustained two-way conversation that must take place between developers and user communities[2] regarding requirements, expectations, use cases, etc. Interactions between model developers and other communities of researchers, practitioners, and decision makers are beginning to be encouraged; for example, the Community Earth System Model project recently added a working group on societal dimensions.[3]

Finding 9.2: The current collection of efforts for research in climate model development is not well positioned to perform operational climate modeling.

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[2] Individuals and groups interested in applying climate model outputs to the management of the societal effects of climate change.

[3] http://www.cesm.ucar.edu/working_groups/Societal/ (accessed October 11, 2012).

For decades there has been a mismatch between the expectations of the operational numerical weather prediction (NWP) and climate prediction community and the model research and development community. The principal measure of success of work that is supported by a typical short-term (e.g., 3-year) research grant is the number, quality, and impact of the research publications that result from any project. Researchers receive no reward for developments that become "operational," so there is little incentive to do what is viewed as extra work to transform research results into operational methods or procedures. There is a view that the scholarly publications speak for themselves, which has been described as a "loading dock" approach—the research results are made available to the operational prediction community via peer-reviewed publications (left on the loading dock), and it is up to users to figure out how to use the results. There are some nascent efforts in which the transition to operations is the objective rather than a by-product of research, e.g., the NOAA Climate Test Bed activity.[4]

From the operational community point of view, there are a great many constraints imposed by operations that should be taken into account by the researchers who seek to improve the operational predictions. In order to effect a transition from research to operations, they argue, the research community needs to modify its developments to conform to the constraints of operations so that their results can become useful, and the operational center needs to provide infrastructure support for the research community to use the operational model to conduct its research. The mismatch between the two communities' expectations has been called the "valley of death," that is, a communication and interaction gap. There is clearly a need to better align the two communities and provide adequate resources so that good ideas can be more rapidly and effectively transformed into operational practice.

Finding 9.3: The expectations of the research community and the operational prediction community are not well aligned.

As indicated throughout this report (Chapters 1 and 10), a market for climate model information already exists. Given the growing need for information about future climate from climate models, involvement of the private sector could be beneficial. The private sector is already engaged through consulting companies that provide customized and downscaled climate information. A number of private companies successfully sell climate information that depends on climate models. Examples include Prescient Weather, Ltd.,[5] Atmospheric and Environmental Research Inc.,[6] Risk Management

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[4] http://www.cpc.ncep.noaa.gov/products/ctb/ (accessed October 11, 2012).

[5] http://www.prescientweather.com/ (accessed October 11, 2012).

[6] http://www.aer.com/ (accessed October 11, 2012).

Solutions Inc.,[7] Stratus Consulting,[8] and ICF International.[9] An important question to resolve is the appropriate balance between the private sector and government organizational structures, such as a national climate services operation.

Is there a potential benefit of involving the private sector more directly in climate modeling? Could a market be created for climate model information? How much is happening already?

Such a balance has been struck in the weather community. Since the inception of the weather enterprise in the 1800s, it evolved to include three sectors: the National Weather Service, academia, and the private sector. Each plays a vital and unique role in weather services, and the competition between the sectors led to a flourishing and extensive set of valuable weather services. However, friction and conflict also abounded. Policies were initiated in the latter part of the 20th century to try to identify the roles and missions of the various sectors, but the boundaries were never as crisp as some wanted and the conflicts continued.

A 2003 NRC report, *Fair Weather: Effective Partnerships in Weather and Climate Services*, concluded that it is more effective to define a *process* for evaluating and adjusting the roles of the private, public, and academic sectors than to rigidly define such roles. Such a process entails the American Meteorological Society (AMS)—a neutral party—hosting a forum for civil interactions and discussion among the three sectors. AMS formed the Commission on the Weather and Climate Enterprise, which consists of three boards and several committees devoted to the various aspects of the partnership. The existence of the commission has resulted in a significantly reduced atmosphere of conflict among the three sectors and has helped introduce an era of cooperation. The joint participation of the private, public, and academic sectors has resulted in better data coverage, wider information dissemination, more realistic and scalable models, increased infusion of cutting-edge technology, and a greater number of specialized products (NRC, 2003).

Finding 9.4: The private sector already has at least some role in providing climate modeling information. There is precedent for this, for example, in how the National Weather Service interacts with the private sector.

As described in Chapter 10, standardized model outputs from the leading international climate models are routinely combined through the Coupled Model Intercomparison Project (CMIP) efforts. These CMIP outputs have heavily contributed to the

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[7] http://www.rms.com/ (accessed October 11, 2012).

[8] http://www.stratusconsulting.com/ (accessed October 11, 2012).

[9] http://www.icfi.com/markets/climate (accessed October 11, 2012).

IPCC assessments, as well as provided accessible climate model simulations to a wider community of users and researchers. A centralized data archive was initially developed by the Program on Climate Model Diagnostics and Intercomparison at Lawrence Livermore National Laboratory in the United States, but as the volume of model output has grown, an internationally coordinated collaboration was developed, referred to as the Earth System Grid. As described in Chapter 2, self-organized grassroots efforts such as the Global Organization of Earth System Science Portals (GO-ESSP)[10] and the Earth Systems Grid Federation (ESGF),[11] as well as short-term grant-funded projects such as Metafor[12] and ExArch,[13] are responsible in large part for building the data infrastructure underlying CMIP5. These CMIP efforts are a vital backbone for efficiently providing current climate model output to diverse user communities. However, despite these efforts, the data sets are growing in size and complexity, and users require even more sophisticated access methods than are currently available. The demands being placed on these networks far exceed the capacity of volunteer energy: it is high time that the global data infrastructure was recognized as "operational" and resourced as such.

Finding 9.5: The global infrastructure for modeling and data distribution is currently a community-owned federation without formal governance.

The climate modeling community increasingly recognizes the need to focus on the reproducibility of results, and of traceability from results back to the methods and models used to produce them. For instance, the CMIP5 project records model provenance using a questionnaire developed by the Metafor project. It is in fact quite possible to record provenance, provide codes that produce specific results, etc., such that third parties can in fact attempt to reproduce or vary them (Balaji and Langenhorst, 2012), aided by software tools such as OLEX,[14] but these methods still need enthusiastic adoption by the community.

Finding 9.6: Climate modeling groups have not universally put a high priority on workflow provenance, i.e., documented steps from model configuration to a given output data set or graphic that make the process transparent and reproducible.

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[10] http://go-essp.gfdl.noaa.gov/ (accessed October 11, 2012).

[11] http://esgf.org/ (accessed October 11, 2012).

[12] http://metaforclimate.eu/trac (accessed October 11, 2012).

[13] http://proj.badc.rl.ac.uk/exarch (accessed October 11, 2012).

[14] http://olex.openlogic.com (accessed October 11, 2012).

THE WAY FORWARD

Taking the best advantage of research findings for operational climate prediction requires a tight linkage, with shared goals, shared decision making, and shared resource allocation, between the research and development community and the operational prediction community. The transition of research advances to operations requires dedicated resources for external scientists to work on operational models and for the operational center to accelerate the transition to operations. There is a large benefit of confronting models with observations (e.g., through operational data assimilation and prediction) for advancing and potentially transforming climate model development.

A strategy for enabling a more rapid and effective transition from research to operations that can take best advantage of recent research advances and model developments in the academic community will require more sophisticated interactions among climate model developers, climate simulators, data assimilation experts, and climate analysts. This strategy should include a closer alignment of the goals and expectations of the research and development community with the goals and expectations of the operational prediction community and changes in the rewards system that recognize the value of contributions to operational climate prediction. A systems approach is needed that takes into account (1) the rigor needed for scientific advancement, (2) society's needs for information from climate models, (3) the complexity and volume of data generated by climate models, and (4) the complex relationships among government laboratories, university research groups, the private sector, and potential users of climate model information. A meaningful and robust personnel exchange, whereby research scientists spend a significant period of time visiting operational centers to help advance prediction science, would be a beneficial part of such a strategy. Operational centers would best promote these advances by providing operational models, supporting data sets, and a user-friendly model testing environment that allows external researchers to test experimental parameterizations and/or model components in an operational setting.

Closing the gap between research and development and operational prediction will require the capability to establish workflow provenance and automate analysis where feasible and reasonable, for which research and development are needed.

This committee judges that data management of the large and complex data sets that are regularly produced by climate modeling research and operations should be viewed as on par, in terms of importance and resource provisioning, with the research and development, simulation, and prediction efforts themselves. Data distribution, including robust technical support for remote analysis to the large and diverse stakeholder community, needs to be viewed as an operational imperative rather than a research project, with appropriate management and resource allocation.

The vision of the committee is that over the next 20 years climate modeling for interannual to decadal to centennial time scales will develop a stronger operational component. The model predictions will be substantially more robust and provide a considerably richer and more comprehensive set of products that are closely tied to recent scientific research developments in climate modeling. Although there have been previous calls for the United States to commit to the production of operational climate data products for model-based global climate projections (Chapter 2), the committee feels that it is too soon to make such a commitment for decadal to centennial prediction. Considerable research and dialogue among stakeholder communities is needed to determine if there is any overlap between what can be predicted and what needs to be predicted, in particular for decadal time scales.

Recommendation 9.1: To better address user needs for short-range climate predictions, the U.S. and international modeling communities should continue to push toward a stronger operational component for prediction of seasonal climate and regular experimental simulation of climate change and variability on decadal time scales.

PART 3

Strategy for Advancing Climate Modeling

This final section of the report examines several key issues in the U.S. climate modeling enterprise where the committee presents novel recommendations and an overarching national strategy for advancing climate modeling in the United States over the next two decades.

CHAPTER TEN

Computational Infrastructure—Challenges and Opportunities

It is in the nature of infrastructures to be ignored when they are functioning. When they crumble, it can cause major disruptions or collapse of the enterprises and communities that depend on them. Computational infrastructure underpins the entire climate modeling enterprise. This chapter reviews the risks posed to the current climate modeling infrastructure by changes in technology and proposes an expansion of the infrastructure that could dramatically alter the landscape of climate modeling. (Definitions of selected terms used throughout this chapter are provided in Box 10.1.)

Future generations of climate simulation models will place an ever-increasing demand on computational infrastructure. There are compelling scientific needs for higher levels of spatial resolution (e.g., cloud-resolving atmospheric component, eddy-resolving ocean component, landscape-resolving land-surface component), more extensive vertical domains (e.g., whole atmosphere), increased model complexity (e.g., treatments of parameterized processes as well as the addition of other simulation component models, such as marine and terrestrial ecosystem components), and larger simulation ensembles (e.g., 50-100 members). All these developments are seen as essential for more accurate, reliable, and useful climate projections and predictions. The current generation of supercomputer systems deployed partly or mostly to support climate modeling, such as the National Oceanic and Atmospheric Administration's (NOAA's) Gaea supercomputer and the National Center for Atmospheric Research's (NCAR's) Yellowstone system, provide an important capability that enables progress toward these goals, but they are only a first step in deploying rapidly evolving computational capabilities. Scientific advances and applications will motivate the national climate modeling enterprise to exploit these new computational capabilities; the complexity and diversity of climate model codes coupled with the expected nature of hardware advances will make this an increasingly challenging task over the next two decades.

As a rough guide, the ability to simulate 5-10 years per wall clock day of computing time continues to be regarded as necessary to make the climate modeling problem tractable.[1] With the current generation of high-performance computing systems,

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[1] Climate model runs often simulate time spans of hundreds of years, meaning that a single run can take days or weeks to complete.

BOX 10.1 GLOSSARY OF SELECTED TERMS USED IN THIS CHAPTER

Computational infrastructure: the software basis for building, configuring, running, and analyzing climate models on a global network of computers and data archives. See Edwards (2010) for an in-depth discussion of "infrastructure" and software as infrastructure.

Refactoring: rewriting a piece of software to change its internal structure without in any way altering its external behavior. This is often undertaken to increase the efficiency or ease of use and maintenance of legacy software.

Core: an element of computational hardware that can process computational instructions. Some current computers bundle several such "cores" onto a single chip, leading to "multicore" (typically 8-16 cores per chip) and "many-core" systems (tens of cores per chip).

Node: an object on a network. In the context of high-performance computing (HPC) architecture it is a unit within a distributed-memory supercomputer that communicates with other nodes using network messaging protocols, i.e., "message passing." It is the smallest entity within the cluster that can work as an independent computational resource, with its own operating system and device drivers. Within a node there may be more than one, indeed many, integrated but distinct computational units ("cores") that can communicate using more advanced fine-grained communication protocols ("threading").

Concurrency: simultaneous execution of a number of possibly interacting instruction streams on the same computer.

Flops: floating-point operations per second, a unit of computational hardware performance. Prefixed by the usual metric modifiers for orders of magnitude; a petaflop is 10^{15} flops and an exaflop is 10^{18} flops.

Exascale: computers operating in the exaflop range, coupled to storage in the exabyte range.

Threads: a stream of instructions executing on a processor, usually concurrently with other threads in a parallel context.

this allows global resolutions of 50 km. Each additional 10-fold increase in resolution leads to a more than 1,000-fold increase in operation count, before considering additional complexity. As recent history has demonstrated, the testing, debugging, and evaluation (e.g., participation in formal model evaluation processes, like the Coupled Model Intercomparison Project, Phase 5 [CMIP5]) required for any given model version continues to require ever-greater amounts of computing time as the model becomes more complex. Overall, the climate modeling enterprise relies on sustained improvements in supercomputing capabilities and must strategically position itself to fully exploit them.

Finding 10.1: As climate models advance (higher resolutions, increased complexity, etc.), they will require increased computing capacities.

PREVIOUS HARDWARE TRANSITIONS

As discussed in Chapters 3 and 4, higher spatial resolution is an important element of improving the fidelity and usefulness of climate models, but also dramatically increases their computational requirements. Thus, climate models have historically been among the principal drivers of HPC. The first coupled ocean-atmosphere model (Manabe and Bryan, 1969) was recognized as a landmark in scientific computing in a *Nature* survey (Ruttimann, 2006).

Coding models to take advantage of advanced and novel computational architectures has always been a significant activity within the climate and weather research and operations communities. During the 1980s and early 1990s, the climate simulation enterprise benefited greatly from computer architectures focused on high-performance memory systems, mainly in the form of vector computing, a technique of fine-grained array concurrency pioneered by Seymour Cray. Several models from many institutions were able to deliver sustained computing performance operating near the theoretical limits of these computing architectures. In the late 1990s, proprietary vector supercomputing architectures began to be supplanted by commodity off-the-shelf architectures. This was partly a result of market forces driving U.S. manufacturers of proprietary architectures out of this field. At least one company (NEC) soldiered on, with the SX series of machines successfully operating in subsequent generations until the present in this field in Japan, Australia, and Europe.

A disruptive transition in the late 1990s pushed climate modeling toward parallel and distributed computing implementations. Although this was viewed with trepidation at the time (NRC, 1998, 2001b; USGCRP, 2001), it is possible to see from the hindsight of 2011 that the community in fact weathered the transition with distinction. While actual sustained performance of climate codes relative to the theoretical peak hardware performance fell by an order of magnitude, time to solution continued to be reduced through exploitation of the aggregate performance of massively parallel machines. Adapting to parallel computing architectures did require pervasive refactoring of highly mature codes. This recoding process necessarily started prior to the establishment of a programming environment standard (e.g., shared memory parallel directives that evolved to SHMEM (Barriuso and Knies, 1994) and distributed-memory approaches (like Parallel Virtual Machine [Geist et al., 1994] that eventually evolved into the Message Passing Interface standard [Gropp et al., 1999]). Being out in front of the development of a programming model has been essential to navigating previous architectural transitions. But rather than insert these new methods throughout model codes, climate and weather modelers began to see these methods as part of *infrastructure*. Most institutions developing high-end models resorted to high-level libraries where the standard and highly reusable computational methods were encapsulated. Scientists and algorithm developers were able to use abstractions that were scientifically intuitive, and the gory details of parallel programming were effectively hidden from those developing the scientific aspects of climate models. When the underlying hardware changed, the infrastructure changed with it, and the scientific codes remained largely intact.

Finding 10.2: The climate modeling community adapted well to the previous hardware transition by moving toward shared software infrastructure.

A similarly disruptive moment is now upon us. As described in the next section, all indications are that increases in computing performance through the next decade will arrive not in the form of faster chips, but more of them, with considerably more complex embodiments of concurrency. Deep and abstruse memory hierarchies, and processing element counts that push the limits of current parallel programming standards, both make for a challenging environment for application programmers. In this chapter, the committee argues that a renewed and aggressive commitment to shared software infrastructure across the climate and weather communities will be needed to successfully navigate this transition, which may prove to be even more disruptive than the vector-to-parallel transition. Indeed, conventional wisdom in the HPC community (see Zwieflhofer [2008] and Takahara and Parks [2008] for examples) is that the next generation conversion will be significantly more complex and unpredictable than previous changes, given the absence of a clear technology path, programming model, performance analysis tools, etc. The ratio of sustained performance to theoretical hardware peak may once again fall precipitously, as it once did during the vector to distributed-memory-parallel transition.

A second element of infrastructure that now pervades the field is the global data infrastructure for models. While this "vast machine" networking the globe is historically associated with the global observing networks, it now encompasses models as well (Edwards, 2010). The committee argues below that this infrastructure too is invisible and taken for granted, but that without proper provisioning for the future, it may be overwhelmed by projected growth and demand for access to data.

NEW ARCHITECTURES AND PROGRAMMING MODELS

This section summarizes trends in HPC hardware, the programming model for using such platforms, and the system software expected to be in place over the next two decades.

Hardware Assessment: Architectural Prospects for the Next 10-20 Years

Conventional high-end multicore microprocessor technology is approaching multiple limits, including power consumption, processor speed, per-core performance, reliability, and parallelism. Hardware assessments such as Kogge (2008) have shown that extrapolating current technologies such as those used in Oak Ridge National Laboratory's (ORNL's) Jaguar machine or NOAA's Gaea leads to exascale machine configurations that can be ruled out on the basis of power consumption alone, which would reach the 100-megawatt range. Alternate technology paths in the next generation of machines include the Blue-Gene system-on-chip design. Using flops/watt as a key metric, this technology path scores better on the power efficiency front. However, the newest and largest machine of this class, the 20-petaflop *Sequoia* platform at Lawrence Livermore National Laboratory,[2] will still require 6 megawatts of power to operate.

A second technology track aims at exploiting the fine-grained parallelism employed in contemporary graphics chips. Graphics processing units (GPUs) have been used to achieve very high concurrency for specialized graphics operations (such as rendering three-dimensional objects on a two-dimensional screen). More recently GPUs have become a viable alternative to conventional high-end microprocessors (CPUs), in part because of their high performance, programmability, and efficiency at exploiting parallelism for use in scientific and other nongraphics applications. This accelerator approach has been extended to allow for general-purpose computing on graphics processing units (GPGPUs) using a technique that combines programmable stages and high-precision arithmetic with the fine-grained parallelism for which GPUs were designed. This approach allows mapping of standard computational concepts onto the special-purpose features of GPUs (Harris, 2005). The Intel Knights Corner chip, released at the 2011 Supercomputing Conference, is the latest extension of GPGPU technology called Many Integrated Core (MIC) architecture, utilizing many parallel lower-power cores. Such computer architectures as GPUs and MICs are expected to be an important step toward the realization of exascale-level performance in the next one to two decades.

Other novel technologies under consideration such as field-programmable gate arrays have not proved very suitable to complex multiphysics applications such as Earth system models: they are more intended for applications where a single set of operations is repeated on a data stream. Even more experimental approaches, based on biology, nanotechnology, and quantum computing, are not expected to be suitable for con-

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[2] http://nnsa.energy.gov/blog/sequoia-racks-arriving-llnl (accessed October 11, 2012).

ventional codes and will almost certainly require complete and radical rethinking of computational Earth system modeling if they are to be exploited.

Although there are architecturally different solutions to enhancing system performance, they share the characteristic that the increase in performance will come from exploiting additional concurrency at the node level. Extrapolating to an exaflop (10^{18} flops) with single thread clock speed of 10^{10} Hz leads to a required concurrency factor of 10^{8}-10^{9}. (Gaea, the largest machine today entirely devoted to climate modeling, is rated at ~1 petaflop to 10^{15} flops.)

There is no current comprehensive climate model (as opposed to process study model) operating anywhere remotely close to that level of concurrency. The best examples of parallel concurrency exhibit about 10^{5} based on maximum processor counts reported for models in the CMIP5 archive (model descriptions are online[3]). The level of concurrency in comprehensive climate models lags the hardware concurrency of the leadership-class machines by at least a factor of 100. Based upon the community's experience with the previous disruptive technology transition, where the ratio of sustained to theoretical peak performance dropped from ~50 percent to ~10 percent for typical climate codes, it would not be surprising if this ratio dropped again during the coming transition. This cannot be made up without a very substantial investment in research into basic numerical approximations and algorithms, which must then be adopted quickly by the simulation community.

Finding 10.3: Climate models cannot take full advantage of the current parallel hardware, and the gap between performance and maximum possible performance is likely to increase as the hardware advances.

Programming Models for the Next 10-20 Years

At this time the many emerging architectures do not adhere to a common programming model. While new ways to express parallelism may well hold the key to progress in this decade, from the point of view of the developer of scientific applications, a transition path is far from evident.

Assessments undertaken by the Defense Advanced Research Projects Agency (DARPA) and the Department of Energy (DOE) (e.g., DOE, 2008; Kogge, 2008) indicate profound uncertainty about how one might program a future system that may encompass many-core chips, coprocessors and accelerators, and unprecedented core counts requiring the management of tens of millions of concurrent threads on next-generation

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[3] http://q.cmip5.ceda.ac.uk/ (accessed October 11, 2012).

hardware. The President's Council of Advisors on Science and Technology (PCAST) has called for the nation to "undertake a substantial and sustained program of fundamental research on hardware, architectures, algorithms and software with the potential for enabling game-changing advances in high-performance computing" (PCAST, 2010). This challenge will grow to a billion threads by the end of this decade. The standard *du jour* programming model for parallel systems is based on MPI (Lusk and Yelick, 2007), shared-memory directives (e.g., OpenMP [Chandra et al., 2001]), or a hybrid of both. These are likely to fail at the scales projected for next-generation systems. Several new approaches are being proposed: for instance, Partitioned Global Address Space languages (Yelick et al., 2007), which grew out of the DARPA High Productivity Computing Systems (HPCS) program to develop "high-productivity" programming approaches (Lusk and Yelick, 2007). In some instances they are entirely new languages such as X10 (Charles et al., 2005) and Chapel (Chamberlain et al., 2007), and in other instances extensions to existing languages, like Co-Array Fortran (Numrich and Reid, 1998) and Unified Parallel C (Carlson et al., 1999).

On longer time scales the exploitation of fine-grain parallism that minimizes data movement will be necessary. For certain hardware directions such as GPUs, a fine-grained parallelism approach is immediately needed. A new programming standard suitable for GPUs and many-core chips is being proposed (OpenCL: see, e.g., Munshi, 2008). Experiments with hardware-specific programming models such as CUDA for Nvidia graphics chips indicate a potential for significant speedups at very fine grain (see, e.g., Michalakes and Vachharajani, 2008) but very extensive intervention is needed to translate these speedups to the entire application. There are efforts under way to introduce a directive-based approach that could potentially be unified with OpenMP. The most promising avenue at the moment appears to be OpenACC,[4] but it is still early in its development.

The climate/weather modeling community has never retreated from experimenting with leading-edge systems and programming approaches to achieve required levels of performance. The current architectural landscape, however, is particularly challenging, because it is not clear what direction future hardware may follow. The International Exascale Software Project (Dongarra et al., 2011) promises a "roadmap" by 2013. The challenge is starkly presented as one that cannot be met without a concerted effort at exposing concurrency in algorithms and computational infrastructure.

Finding 10.4: Increases in computing performance through the next decade will arrive not in the form of faster chips, but more of them, with considerably more

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[4] http://www.openacc-standard.org/ (accessed October 11, 2012).

complex embodiments of concurrency; the transition to this new hardware and software will likely be highly disruptive.

System Software

System software, such as operating systems, file systems, shells, and so on, will also undergo radical change to cope with the changes in hardware. Input/output (I/O) in particular will be a profound challenge for climate modeling, which is generating data volumes on an exponential growth curve (Overpeck et al., 2011). Furthermore, and potentially more significantly, the highly concurrent machines of this decade have the potential for decreased reliability as the component count increases. Fault-resilient software to account for decreased reliability could reduce the effective computation rate, as many such methods involve redundant computations (Schroeder and Gibson, 2007).

With regards to fault resilience, architectures with extreme levels of concurrency and complexity may not guarantee that a program executes the same way every time. The possibility of *irreproducible computation* presents a challenge to testing, verification, and validation of model results. Chaotic systems with sensitive dependence on initial conditions will wander arbitrarily far outside any tolerance bound, given enough time. The key question in the *climate* context is to see whether trajectories subject to small changes at the hardware bit level stay within the same basin of attraction, or do these small errors actually push the system into a "different climate state." Currently there is no other way to prove that an architectural or software infrastructure change has not pushed the system into a different climate other than computing the climatology of long (usually 100-yr, to take into account slow climate processes) control runs. This requirement is hugely expensive and a significant barrier to testing.

Can the climate modeling community adapt to a world where in silico experimentation is more like in vitro biological experimentation, where reruns of experiments are only statistically the same? Such adaptation would entail profound changes in methodology and be an important research challenge for this decade.

Substantial progress must be made in fault-resilient software. Fault tolerance generally implies redundancy layers, which can also imply a further decrease in achievable execution rate. Currently, the development efforts in high-end computing emphasize "peak flops," and the climate modeling community would benefit from redressing this with increased efforts in fault-tolerant system software and workflows, echoing from previous National Research Council (NRC) reports that endorsed balancing support across the software life cycle. In conclusion, sharp decreases in reliability should be anticipated as the hardware concurrency in machines grows. Investments that emphasize system software and workflow reliability and investments in achieving faster execution rates both need to be balanced.

Adoption of these approaches will involve extraordinary levels of effort by the climate modeling community, who will probably have a minimal influence on the hardware or the software roadmap. Various studies on exascale computing have noted that the computational profile of climate science is unique because of the tightly coupled multiphysics nature of the codes.

SOFTWARE INFRASTRUCTURE FOR MANAGING MODEL HIERARCHIES

The community is best served by adopting a domain-specific technical infrastructure under which its developments can proceed. At the scale of one lab, this has been widely adopted and extremely successful. For example, at most modeling centers, scientists do not directly apply MPI or learn the intricacies of tuning parallel file-system performance, but use a lab-wide common modeling infrastructure for dealing with parallelism, I/O, diagnostics, model coupling, and so on, and for modeling workflow (the process of configuring, running, and analysis of model results). Many things that are done routinely—adding a new model component, adapting to new hardware—could not be done without a growing reliance on shared infrastructure.

It was recognized over a decade ago that such software infrastructure could usefully be developed and shared across the climate modeling community. The most ambitious such project was the Earth System Modeling Framework (ESMF; Hill et al., 2004). It introduced the notion of superstructure, a scaffolding allowing model components to be coupled together following certain rules and conventions to permit easy interchange of components between models (Dickinson et al., 2002). See Box 10.2 for a further description of ESMF and how it has unfolded after a decade of development. ESMF and other examples of common infrastructures, including the Flexible Modeling System (FMS)[5] developed by the Geophysical Fluid Dynamics Laboratory (GFDL), the Model Coupling Toolkit, extensively used in the CESM, and OASIS, a European model coupling project, are the subject of a comparative survey by Valcke et al. (2012).

This committee, which includes several members closely involved in the development of ESMF and other single-institution frameworks, observes that the idea of frameworks and component-based design is no longer novel or controversial. While switching

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[5] http://www.gfdl.noaa.gov/fms (accessed October 11, 2012).

BOX 10.2 THE EARTH SYSTEM MODELING FRAMEWORK (ESMF): CASE STUDY

Following reports on U.S. climate modeling in 2001, federal agencies made substantial investments in software infrastructure and information systems for both modeling and analysis. ESMF is a high-profile activity that was funded in 2001 by the National Aeronautics and Space Administration (NASA), and continues to be developed and maintained under funding by the Department of Defense, NASA, the National Science Foundation (NSF), and NOAA. The first cycle of ESMF was funded as a computational technology activity focused on model coupling in both the weather and climate community. In the second cycle of ESMF, the focus was extended from technology to the formation of a multiagency organization. As discussed in Chapter 2, this focus on process and governance included development of ways to manage sponsor and user expectations, requirements, and delivery.

Building upon earlier work at GFDL and Goddard Space Flight Center (GSFC), ESMF introduced the notion of a *superstructure* (Collins et al., 2008; Hill et al., 2004) providing a common vocabulary for describing model components (e.g., ocean, atmosphere, or data assimilation package), with their own gridding and time-stepping algorithms, and the fields they exchange. The common vocabulary permitted components to be coupled with relatively little knowledge of the internal working of other components, other than those exposed by the interface. This approach has proved very powerful and attractive for communities whose scientific activities depend upon component-level interoperability. In particular within the numerical weather prediction (NWP) community, many participants in the National Multi-Model Ensemble are building the National Unified Operational Prediction Capability,[a] which utilizes ESMF as part of its foundation.

ESMF is also used within some single-institution frameworks, such as the GEOS system from NASA GSFC, and the Coupled Ocean/Atmosphere Prediction System.

NCAR and GFDL have not adopted ESMF as their central framework. GFDL already had internally developed the FMS, from which ESMF borrowed ideas. NCAR was also actively testing another framework alternative, the Model Coupling Toolkit (MCT), while ESMF was under development, and for pragmatic reasons adopted MCT for high-level coupling while using some of the lower-level functionality of ESMF. However, their own frameworks remain architecturally compatible with adoption of ESMF; and in fact ESMF is often the *lingua franca*, or the common language, when their components are widely used in other communities (such as GFDL's Modular Ocean Model).

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[a] http://www.nws.noaa.gov/nuopc/ (accessed October 11, 2012).

between functionally equivalent frameworks has costs, few technical barriers to doing so exist should a compelling need arise.

With ESMF and other infrastructure activities, the climate modeling community is seeing the natural evolution of infrastructure adoption. Individuals, communities, and institutions are seeing advantage. The committee believes that the community is now at the point where the benefits of moving to a common software infrastructure outweigh the costs of moving to it. With the experience, successes, and lessons learned of the past decade, the climate modeling community is positioned to accelerate infrastructure adoption. Cross-laboratory intercomparisons are now routinely conducted and, more importantly, are the way forward. End users require climate model information to be robust and reliable. Common infrastructure improves the ability to enforce scientific methodology (e.g., controlled experimentation, reproducibility, and model verification) across institutions and is one of the primary building blocks of that robustness and reliability.

So far, no one software framework has become a universal standard, because modeling centers that initially invested in one framework have had insufficient incentive to switch to another. Nevertheless, we believe that two critical strategic needs—that the U. S. climate community needs to more effectively collaborate, and that it needs to nimbly adapt to a wave of disruptive new computing technology—position the community for a further unifying step. The vector to parallel disruption led to widespread adoption of framework technologies at the scale of individual institutions. The climate modeling community can now conceive of a framework that could be subscribed to by all major U.S. climate modeling groups, supports a hierarchy of models with component-wise interchangeability, and also supports development of a high-performance implementation that enables climate models of unprecedented resolution and complexity to be efficiently adapted to new architectural platforms. This idea is explored below.

Finding 10.5: Shared software infrastructures present an appealing option for how to face the large uncertainty about the evolution of hardware and programming models over the next two decades.

A NATIONAL SOFTWARE INFRASTRUCTURE FOR CLIMATE MODELING

Very complex models have emergent behavior whose understanding requires being able to reproduce phenomena in simpler models. Chapter 3 makes a strong case for hierarchies of models adapted for different climate problems. From the computational perspective, some model types can be classified by a rough pace of execution needed (i.e., model simulated time per computer clock time) to make efficient scientific progress:

- process study models and weather models (single component or few components; dominated by "fast" physics; 1 year/day),
- comprehensive physical climate models (ocean-atmosphere, land and sea ice,

includes "slow" climate processes important on decadal to centennial climate scales, 10 years/day), and

- Earth system models for carbon-cycle studies; paleoclimate models (most complex physics; dominated by slow processes and millennial-scale variability, 100 years/day).

A single national modeling framework could allow the climate modeling community to configure all of these models from a palette of available components of varying complexity and resolution, as well as supporting high-end modeling. This idea has been proposed in the past: the history of previous efforts is recounted in Chapter 2. The committee believes that current trends in our methodology, both its strengths and weaknesses, point in the direction of a concerted effort to make this a reality, for reasons that are outlined below.

A related methodological advance is the multimodel ensemble and the model intercomparison project, which has become ubiquitous as a method for advancing climate science, including short-term climate forecasting. The community as a whole, under the aegis of the World Meteorological Organization's World Climate Research Programme—through two working groups, the Working Group on Climate Modeling and the Working Group on Numerical Experimentation—comes to consensus on a suite of experiments, which they agree would help advance scientific understanding (more information in Chapter 8). All the major modeling groups agree to a suite of numerical experiments defined for the current-generation Coupled Model Intercomparison Project (CMIP5) as a sound basis for advancing the science of secular climate change, assessing decadal predictability, etc., for participation in defining the experiments and protocols. The research community addressing climate variations on intraseasonal, seasonal, and interannual (ISI) time scales agrees on similar multimodel approaches for seasonal forecasting. A globally coordinated suite of experiments is then run, and results shared for a comparative study of model results.

The model intercomparison projects (MIPs) are sometimes described as "ensembles of opportunity" that do not necessarily sample uncertainty adequately. A second major concern is the *scientific reproducibility* of numerical simulations. Even though different models are ostensibly running the same experiment, there are often systematic differences between them that cannot be traced to any single cause. Masson and Knutti (2011) have shown that the intermodel spread is much larger than differences between individual ensemble members of a single model, even when that ensemble is extremely large, such as in the massive ensembles of QUMP (Collins et al., 2011) and CPDN (Stainforth et al., 2005). To take but one example of why this is so troublesome in the public sphere, consider different studies of Sahel drought made from the

CMIP3 experiments. Two studies, based on the GFDL (Held et al., 2005) and Community Climate System Models (CCSM; Hurrell et al., 2004), have roughly similar skill in reproducing late-20th-century Sahel drought, and propose roughly equivalent explanations of the same, based on Atlantic meridional temperature gradients. Yet the results in the future scenario runs are quite different, producing opposite sign projections of Sahel drought in the 21st century. Hoerling et al. (2006), in their comparative study of the CMIP3 models' Sahel simulations, acknowledged these differences but could not easily point a finger at any feature of the model that could account for the differences: The differences are not easily attributable to any single difference in physics or process between the models, nor can the community easily tell which, if any, of the projections is the more credible. Tebaldi and Knutti (2007) also address this fact, that intermodel spread cannot be explained or even analyzed beyond a point.

This weakness in methodology requires the climate modeling community to address the issue of scientific reproducibility. That one should independently be able to replicate a scientific result is a cornerstone of the scientific method, yet climate modelers do not now have a reliable method for reproducing a result from one model using another. The computational science community has begun to take a serious look at this issue, with a considerable literature on the subject, including a special issue of *Computing in Science and Engineering* (CISE, 2009) devoted to the subject. Peng (2011) summarized the issue as follows:

> Computational science has led to exciting new developments, but the nature of the work has exposed limitations in our ability to evaluate published findings. Reproducibility has the potential to serve as a minimum standard for judging scientific claims when full independent replication of a study is not possible.

Having all of the nation's models buy into a common framework would allow this research to be systematized. Maintaining the ability to run experiments across a hierarchy of models under systematic component-by-component changes could hasten scientific progress significantly.

Research in the science of coupling is needed to make the vision a reality. Existing framework software does not specify how models are coupled. Software standards are one part of the story, but there will remain work to be done to define choices for coupling algorithms, fields to be exchanged, and so on.

An effective common modeling infrastructure would include

- common software standards and interfaces for technical infrastructure (e.g., I/O and parallelism);

- common coupling interfaces across a suite of model components of varying complexity;
- common methods of expressing workflow and provenance of model results;
- common test and validation methods;
- common diagnostics framework; and
- coupled data assimilation and model initialization framework.

ESMF and other frameworks meet many, but not all, of these requirements. Within the infrastructure described above, there is considerable scope for innovation:

- different dynamical cores and discretization methods for global and regional models;
- different vertical coordinates;
- new physics kernels where there is still uncertainty about the physical formulation itself ("structural"); and
- different methods contributed by different groups based on their interests and specializations (e.g., data assimilation).

Finding 10.6: Progress in understanding climate model results requires maintaining a hierarchy of models. There are barriers to understanding differences between model results using different models but the same experimental protocols. Software frameworks could offer an efficient way of systematically conducting experiments across the hierarchy that could enable a better characterization and quantification of uncertainty.

Data-Sharing Issues

The rapidly expanding archives of standardized model outputs from the leading international climate models have heavily contributed to the IPCC assessments. They have also made climate model simulations accessible to a wider community of users as well as researchers. This effort has been led by the DOE-sponsored Program on Climate Model Diagnostics and Intercomparison (PCMDI) at LLNL. While a centralized data archive was initially developed, the volume of model output has grown so much that this internationally-coordinated model data set is now distributed through the Earth System Grid,[6] a linked set of data storage locations. Both the PMDI and Intercomparison and the Earth System Grid are fragile institutions, maintained by a mixture of volunteer effort and a succession of competitive grant proposals, but are a vital backbone for efficiently providing current climate model output to diverse user com-

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[6] http://www.earthsystemgrid.org/ (accessed October 11, 2012).

munities. The data infrastructure benefits from a "network effect" (where value grows exponentially as more nodes are added; see, e.g., Church and Gandal, 1992; Katz and Shapiro, 1985). It involves developing operational infrastructure for petabyte-scale (and soon exabyte-scale; see Overpeck et al., 2011) distributed archives. This infrastructure development has occurred through an international grassroots effort by groups such as the Global Organization of Earth System Science Portals and the Earth Systems Grid Federation.

More generally, needs for data storage, analysis, and distribution have grown significantly and will continue to grow rapidly as models move to finer resolution and more complexity and the needs of an increasing diversity of users become more sophisticated. Furthermore, the scientific research, observational devices, and computational resources are becoming increasingly nonlocal. NCAR has recently built the NCAR-Wyoming Supercomputer Center to house its supercomputer and data repository. NOAA has placed its Gaea supercomputer at ORNL serving research labs across the country. It is increasingly common for scientists at many institutions to modify and enhance models at remote institutions and to analyze results from other models. The need to use large volumes of remotely stored data places extreme strains on systems and requires systematic planning and investment as part of a national climate modeling strategy. This need is similar to that described in Chapter 5 related to the handling of observational data.

This combination of rapidly increasing climate simulation data objects with a more distributed set of supercomputers and data archives requires the climate modeling community to begin to make use of a separate backbone data-intensive cyberinfrastructure, based on dedicated optical lightpaths on fiber optics separate from the Internet, connecting these facilities with each other and with data-intensive end users. These "data freeways" have been developed nationally (ESnet, Internet2, National LambdaRail; see Figure 10.1) and internationally (Global Lambda Integrated Facility) over the past decade outside of the climate community, providing 10-100 gigabit per second (Gbps) clear channels for data movement. Dedicated 10-Gbps optical pathways enable moving a terabyte of data between two sites in 15 minutes, compared to 1-10 days to move a terabyte on the 10-100 Mbps shared Internet. An example of the use of such supernetworks in climate is the recent NOAA 10-Gbps optical network for moving large amounts of data between key computational facilities (including ORNL and GFDL) and end users. The new Advanced Networking Initiative[7] is already developing a prototype scientific network that can operate at 100-Gbps speeds (Balman et al., 2012).

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[7] http://www.es.net/RandD/advanced-networking-initiative/ (accessed October 11, 2012).

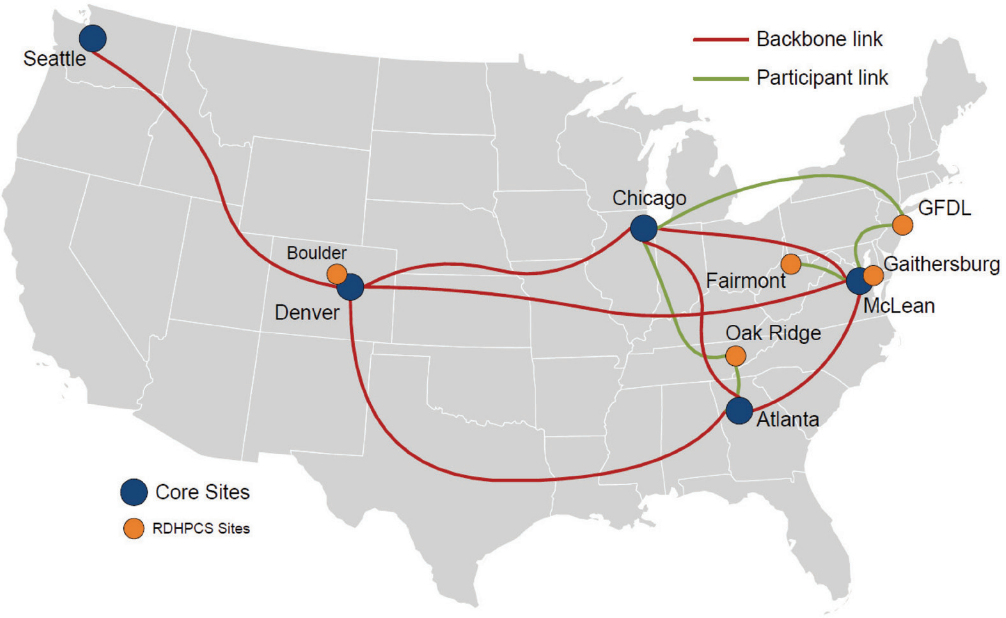

FIGURE 10.1 N-Wave, the NOAA Research Network. A high-performance network dedicated to environmental research and connecting NOAA and the academic and state research network communities. SOURCE: N-Wave website, http://noc.nwave.noaa.gov/.

Finding 10.7: The data-intensive cyberinfrastructure that will be needed to enable the distributed climate community to access the enormous data sets that will be generated from both simulation and observations will require a dedicated data-sharing infrastructure.

THE WAY FORWARD

Climate simulation is difficult because it involves many physical processes interacting over a large range of space and time scales. Past experience shows that increasing the range of scales resolved by the model grid ultimately leads to more accurate models and informs the development of lower-resolution models. Therefore, to advance climate modeling, U.S. climate science will need to make effective use of the best possible computing platform and models. To facilitate the grand challenges of climate modeling in support of U.S. national interests (Chapter 4), increased model resolution and complexity will be required, which in turn will result in the need to exploit enhanced computing power, (i.e., new hardware). Therefore, the committee recommends an expansion of the capabilities within the climate modeling community that includes three main elements: (1) a common software infrastructure shared across all U.S. climate modeling groups; (2) a strategic investment in continuing the ongoing deployment of advanced climate-dedicated supercomputing resources and in research about how to design climate models to exploit new computational capabilities, based on the common infrastructure; and (3) a global data-sharing infrastructure that is operationalized. The data-sharing infrastructure that exists is already vital to the climate modeling enterprise, but it is at risk because of tenuous recognition of its importance in the form of resourcing.

Evolving to a Common Software Infrastructure

The committee believes the time is ripe for a systematic cross-agency investment in a common U.S. software infrastructure designed in close collaboration with the major modeling centers (e.g., CESM, the Goddard Institute for Space Studies, the Global Modeling and Assimilation Office, GFDL, and the National Centers for Environmental Prediction). There is no reason it could not be globally shared, but the committee limits its discussions here to U.S. modeling centers in line with its statement of task (Appendix A). The infrastructure needs to support interoperability of climate system model components and common data-handling standards that facilitate comparisons between component models developed by different modeling groups, and across a hierarchy of component models of different levels of complexity, including regional models. Within this framework, there is still scope to address structural uncertainty (Chapter 6) by allowing competing representations of processes to be systematically compared. The common software infrastructure will follow coding conventions and standards enabling the construction of hierarchies of models of smaller scope to be run on a broad class of computing platforms (see Box 10.3 for further discussion).

While this investment could be justified purely on its potential for allowing more efficient use, comparison, testing, and improvement of U.S. climate models, it is more urgent in light of the upcoming transition to high-end computers that are based on much higher levels of concurrency (Figure 10.2). In particular, it would position the U.S. climate community to make the additional investment to redesign climate models to effectively use new high-end supercomputers, because of the possibility of configuring multiple scientifically credible versions of individual model components to run on such systems without enormous additional effort.

BOX 10.3 SOFTWARE INFRASTRUCTURE ANALOGY TO OPERATING SYSTEM ON A SMARTPHONE

The software infrastructure described in this chapter can be thought of as similar to the operating system on a smartphone. The software infrastructure is designed to run on a specific hardware platform (i.e., the phone), and climate modelers develop model components (i.e., apps) to run in the software development to simulate parts of the climate system like the atmosphere or ocean.

Right now, different modeling centers in the United States have different software infrastructures (operating systems) that run on different pieces of hardware; this would be like the iPhone compared to the Android, for example. This means that climate model components (apps) written for one software infrastructure will not work with another (i.e., iPhone apps will not work directly on an Android).

Ultimately, the vision is that the U.S. modeling community could evolve to use the same common software infrastructure (operating system), so that model components (apps) could be interchanged and tested versus one another directly. This would also mean that when the hardware (phone) advances, the software infrastructure (operating system) can be updated to continue to work with the new hardware without having to completely rewrite the climate model components (apps).

The committee recommends that the best pathway for achieving a common software infrastructure involves a community-based decision process. As discussed in Chapter 2 and Box 10.2 (ESMF), efforts to dictate transformations to specific infrastructures have met with less success than those that have come from the bottom up. This is described further in Chapter 13 in the discussion of the formation of an annual national climate modeling forum. The evolution to a common modeling infrastructure will require ongoing work, and a working group at such a forum could provide a venue for that work.

The evolution to a common software infrastructure will not be without risks and costs. A single infrastructure could inhibit the exploration of alternative approaches to software design and development. Frontier-scale computing is an evolving problem that could be challenging to adapt to a preexisting community framework. Community-based decision processes require nurturing, have inefficiencies, and require compromise. Individual modeling centers may not easily be convinced to migrate from their current infrastructure. However, given a decade of experience, combined with a bottom-up, community design process, the committee believes that the climate modeling is ready to develop a capable and ambitious common software infrastructure whose overall benefits far outweigh the costs.

This evolution can only succeed with adequate sustained resources. It will benefit from the coordinated involvement of the funding agencies to help organize and sup-

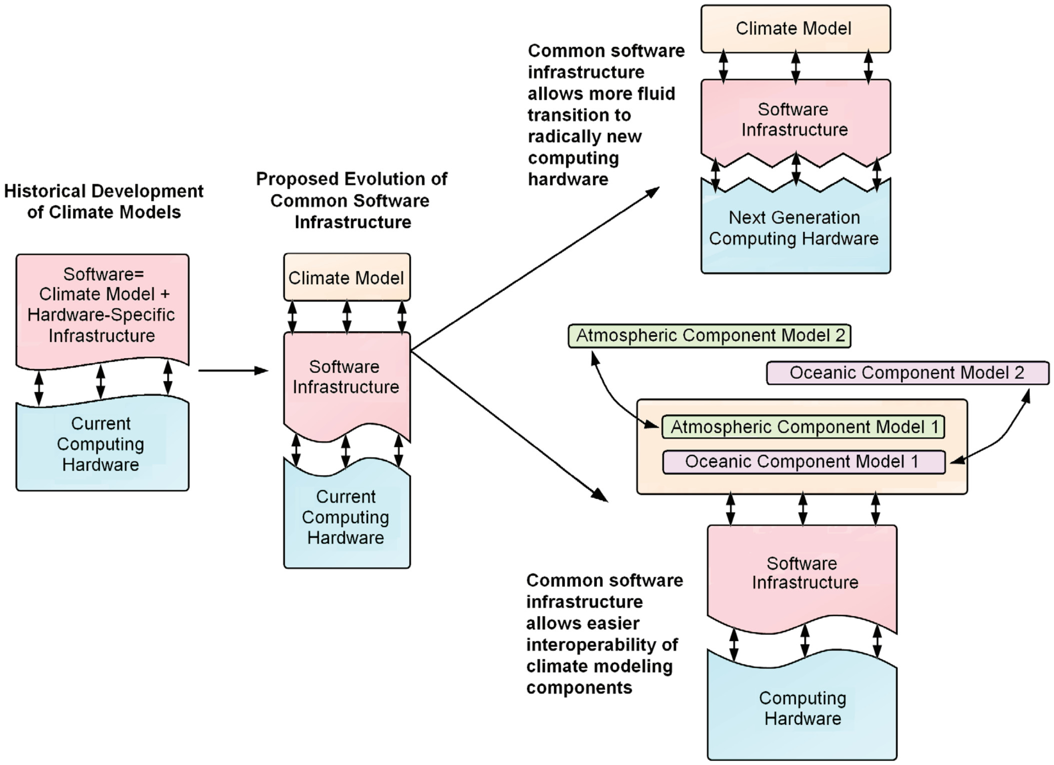

FIGURE 10.2 The development of a common software infrastructure will facilitate the migration of models to the next generation of computing platforms and allow interoperability of model components.

port the development of the new infrastructure and its implementation in the leading U.S. global and regional climate models, as well as its use in model comparisons and national climate model data archival. The U.S. Global Change Research Program (USGCRP) is expected to play an important role in this effort, having stated in its recent strategic plan that "Promoting the development and widespread use of such frameworks is a central task for USGCRP so as to maximize collaboration, co-development of models, and, ultimately, coordinate integrated research efforts" (USGCRP, 2012).

Addressing Climate Model Computing Hardware Requirements

As described earlier in this chapter, the future needs of U.S. climate modeling to provide climate data for decision makers and other users will outstrip its current computing capabilities. Chapter 13 discusses options for how to address these needs in more detail in the context of how they might interact with existing climate modeling centers and regional modeling activities.

Operationalizing the Global Data-Sharing Infrastructure

Two observations can be made about the distributed nature of climate science today. First, the growth rate of climate model data archives is exponential. Without substantial research effort into new methods of storage, data decimation, data semantics, and visualization, all aimed at bringing analysis and computation to the data, rather than trying to download the data and perform analysis locally, it is likely that the data might become frustratingly inaccessible to users. Research efforts under NSF's EarthCube and smaller projects funded by NOAA and DOE/SciDAC attempt to address this, but this is one realm that would benefit from the network effect and consolidation of effort across agencies, and in fact internationally. The challenges posed by a federated global archive demand an equally federated response.

Second, globally coordinated modeling experiments have become central to climate science. Climate science and policy-relevant science and decision making are increasingly dependent on the results of these experiments. The enterprise is critically dependent on a global data infrastructure for disseminating these results. It cannot continue to be developed and run by a dedicated but small cadre of technologists funded by separate, uncoordinated, unstable pools of grant-based resources. European organizations are attempting to do this through enabling an operational European Network for Earth Sciences. (See Chapter 9 for a further discussion of what constitutes "operational" infrastructure.)

The committee believes that climate science will continue to make advances based on globally coordinated modeling experiments based on a small but richly diverse set of models from different research institutions. The results of these experiments will continue to be a treasure trove for climate science, climate impacts science, and services for policy and decision support. The data requirements for modeling data described in this chapter and the observational data described in Chapter 5 both support the need for an enhanced information technology infrastructure for climate data. The committee believes that the existing data infrastructure efforts are too important to be allowed to rely on volunteer efforts and less than stable funding.

Recommendation 10.1: To promote collaboration and adapt to a rapidly evolving computational environment, the U.S. climate modeling community should work together to establish a common software infrastructure designed to facili-

tate componentwise interoperability and data exchange across the full hierarchy of global and regional models and model types in the United States.

Recommendation 10.2: In order to address the climate data needs of decision makers and other users, the United States should invest in more research aimed at improving the performance of climate models on the highly concurrent computer architectures expected in the next 10-20 years, and should sustain the availability of state-of-the-art computing systems for climate modeling.

Recommendation 10.3: The United States should support transformational research to bring analysis to data rather than the other way around in order to make the projected data volumes useful.

Recommendation 10.4: The data-sharing infrastructure for supporting international and national model intercomparisons and other simulations of broad interest—including archiving and distributing model outputs to the research and user communities—is essential for the U.S. climate modeling enterprise and should be supported as an operational backbone for climate research and serving the user community.

CHAPTER ELEVEN

Synergies Between Weather and Climate Modeling

Although weather and climate modeling have common roots in the numerical solution of the governing geophysical fluid dynamics equations of the global atmospheric (initially) and (later) oceanic circulation, the numerical weather prediction (NWP) and climate simulation enterprises have long been entities with different constituencies, distinct detailed technologies, and even specific jargon. Nevertheless, the common origin of these two subdisciplines has been recognized in recent years as fundamental to them both, and efforts to bring them together to address the problem of prediction are now under way (Brunet et al., 2009; Hurrell et al., 2009; Palmer et al., 2008; Shapiro et al., 2010; Shukla et al., 2010; WCRP, 2005). The essence of this "seamless" approach to weather and climate prediction is that they both share common processes and mechanisms, and the interactions across time and space scales are fundamental to the climate system.

Multiple "seamless prediction" strategies are being employed with different aims. They include (i) using suitably initialized IPCC class coupled climate models for hindcasts and predictions on time scales of days to decades; (ii) nesting high-resolution regional models or locally refined grids within global climate models to capture small-scale processes needed to better describe weather events and their statistics; and (iii) using modified versions of operational weather forecasting models for seasonal to decadal prediction. All of these approaches attempt to bridge across the space and time scales of weather and climate.

The ultimate realization of seamless prediction is a single "unified" modeling system designed to work across a broad range of time scales and spatial resolutions, from initialized weather predictions to long-term projections. There are several requirements for a unified weather and climate prediction system:

- data assimilation capability, i.e., to make best use of available observations to generate initial conditions, to facilitate analysis of model parameter sensitivity and uncertainty quantification, and to assess the incremental benefit of new observations;
- unified physical parameterizations and numerical algorithms that can be applied across all scales at which they are needed;

- model forecast skill, evaluated on both weather and intraseasonal to interannual time scales, and model fidelity for long-term climate simulations;
- adequate model development manpower and expertise to simultaneously handle the challenges of both weather and climate applications; and
- computational infrastructure allowing efficient execution and data management for simulations over the needed range of grid spacings and time scales.

Seamless prediction and unified modeling are strategies for better model engineering, aimed at constraining uncertain parameters and taking advantage of the considerable overlap between the internal structure of weather and climate simulation models. Indeed, to the extent such engineering produces more skillful climate models and climate-quality reanalyses, these strategies have clear value to the climate science and applications communities. They may also produce advances that can be transferred between models, including parameterization methodologies that work across a range of scales and new approaches to climate model testing and evaluation.

BENEFITS OF SEAMLESS PREDICTION

The observed climate system contains important features and processes that operate on a wide range of time and space scales, from cloud ice crystals to mesoscale weather systems to basin-scale ocean circulation processes to continental-scale ice sheets. All of these processes contribute to some degree to observed weather and climate phenomena across a range of time scales. Given the complexity of this overall system it has proven useful to construct models that focus on what are deemed the most essential processes for the particular application in mind. For example, weather prediction models used for daily to weekly forecasts focus on high spatial resolution in the atmosphere, and state-of-the-art atmospheric physics, but have less emphasis on a detailed representation of the ocean, because many aspects of ocean changes do not impact the weather on a time scale of a week or two. Similarly, climate models used for projections on decadal to centennial time scales have relatively coarse spatial resolutions for reasons of computational efficiency and thus do not accurately simulate phenomena that may be important on small space and time scales, such as mesoscale convective complexes or tropical cyclones. These choices reflect both limitations on resources, such as computer power, and an attempt to simplify and streamline the problem under consideration.

This approach has its drawbacks, however. Physical and chemical processes in the climate system can have an impact on many time and space scales. For example, small cumulus clouds driven by daytime surface heating can alter afternoon land-surface temperature and help trigger large thunderstorms (weather effects). They also affect large-scale albedo and surface evaporation (climate effects), so they may play a role in the response of the climate system to changing greenhouse gas concentrations and aerosols on decadal and longer time scales. As a second example, it has become common practice within the past decade for weather prediction models used for forecasting tropical cyclones to employ a dynamical or mixed-layer model of the upper ocean (a traditional climate model component). Such examples have led to increasing recognition that because climate and weather share many of the same underlying physical processes, a more unified approach to model development and application could have many advantages.

For climate models, benefits of a more unified approach include the capability for more rigorous testing and improvement of parameterizations of "fast" physical processes that interact with weather. For example, biases in clouds and uncertainties in the response of clouds to changing greenhouse gases and aerosols are major challenges in projecting climate change over the next century. Biases in clouds appear very rapidly in climate simulations, often within the first days or weeks of a simulation. Therefore, it is appealing to test new parameterizations for clouds in a weather context, where relatively short simulations, initialized from the observed state of the climate system, can provide a rapid assessment of the strengths and weaknesses of model parameterizations.

To this end, one can test weather or climate simulation models in hindcast mode against the large data set of observed past weather variations. Such testing can be done using an initialization from another model. In this report, this testing is referred to as "seamless prediction" but not "unified modeling," because it does not necessarily require a data assimilation capability that a unified weather-climate forecast model should have to make real-time forecasts. Over the past decade, this approach has started to gain popularity following the development of software infrastructure such as the Climate Change Science Program-Atmospheric Radiation Measurement Parameterization Testbed (Phillips et al., 2004) to support initialization of the atmospheric component of climate models from gridded reanalyses. For instance, Hannay et al. (2009) and Wyant et al. (2010) used global hindcasts by the National Center for Atmospheric Research (NCAR) and Geophysical Fluid Dynamics Laboratory (GFDL) climate models to evaluate their simulation of subtropical boundary layer clouds in specific regions against satellite and in situ observations. The Year of Tropical Convection Madden-Julian Oscillation (MJO) Task Force[1] is coordinating multiweek global climate-

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[1] http://www.ucar.edu/yotc/mjo.html (accessed October 11, 2012).

model hindcasts of past MJO events. The National Multimodel Ensemble project[2] has generated a series of seasonal-interannual hindcasts (and real-time forecasts) by several U.S. and international global climate models.

The unified modeling approach is much more scientifically and organizationally challenging to implement, but it has considerable additional benefits. For weather prediction models, two potential benefits are reduction of systematic errors due to mean-state drift and more skillful data assimilation. Weather forecast models typically suffer from mean-state drifts as they are run out for periods of a few days or longer and drift toward their biased internal climatology, creating forecast errors. In a weather forecast model also designed and tested as a climate model, minimizing such climatological biases will be a development priority; ultimately this should lead to better medium-range forecasts. Some quantities such as soil moisture affect weather forecasts but are not routinely measured. They therefore are particularly susceptible to large errors due to model drift. Again, model testing in a climate mode should expose such drifts; reducing them can lead to more skillful forecasts and also allow more effective assimilation of observations taken near the land surface, such as near-surface humidity and temperature. A unified model with fewer systematic biases may support more accurate data assimilation and better analyses and reanalyses, which can help in testing of other climate models.

A unified model would foster the development of parameterizations that work well across a range of grid spacings and time scales. Combining weather and climate model resources for development of parameterizations and other modeling infrastructure might ultimately be more efficient and lead to intellectual cross-fertilization between weather and climate model research and development.

Finding 11.1: One useful form of seamless prediction is the testing of climate models in a weather forecast mode. Unified weather-climate modeling has further potential benefits, including improved weather forecasts, data assimilation, and reanalysis, and more efficient use of resources.

SCIENTIFIC CHALLENGES WITH UNIFIED WEATHER-CLIMATE MODELING

This section addresses the scientific and technical challenges for unified modeling, and the management and organizational challenges are discussed later in this chapter.

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[2] http://www.cpc.ncep.noaa.gov/products/NMME/ (accessed October 11, 2012).

Using a model for weather prediction requires a methodology for initialization of the model. For real-time forecasting, this typically involves a data assimilation system, which is a major effort, and requires a substantial infrastructure. Thus, one challenge is to optimize the information gained by using a new model to make short-term predictions, while not being overwhelmed with the necessary infrastructure development associated with data assimilation and model initialization.

For weather prediction, detailed analyses of the observed state of the atmosphere are required, but uncertainties in this initial state grow rapidly over several days. Other components of the climate system are typically fixed as observed. For climate predictions, the initial state of the atmosphere makes less difference, but the initial states of other climate system components are necessary. For predictions of a season to a year or so, the upper ocean state, sea-ice extent, soil moisture, snow cover, and state of surface vegetation over land can all be important. For the decadal prediction problem, a full-depth global ocean initial state could be essential (Meehl et al., 2009; Shukla, 2009; Smith et al., 2007; Trenberth, 2008). Initial conditions for the global ocean could conceivably be provided by existing ocean data assimilation exercises. However, hindcast predictions for the 20th century, which are desirable to test models, are severely hampered by poor salinity reconstructions prior to the early 2000s when Argo floats began to provide much better depictions of temperature and salinity in the upper 2,000 m of the near-global ocean. Challenging research tasks are to develop optimal methods for initializing climate model predictions with the current observational network and identifying an optimal set of ocean observations to use for initializing climate predictions (Hurrell et al., 2009).

The mass, extent, thickness, and state of sea ice and snow cover are key climate variables at high latitudes. The states of soil moisture and surface vegetation are especially important in understanding and predicting warm season precipitation and temperature anomalies along with other aspects of the land surface, but they are difficult to quantify. The errors induced by incorrect initial conditions should become less apparent as the simulations evolve as systematic "boundary" and external influences become more important, but they could still be evident through the course of the simulations (Hurrell et al., 2009). Any information on systematic changes to the atmosphere (especially its composition and influences from volcanic eruptions) as well as external forcings, such as from changes in the sun, are also needed; otherwise these are specified as fixed at climatological average values.

Finding 11.2: Current observations are insufficient for complete initialization of climate models, especially for seasonal to decadal forecasts; poorly observed fields will be subject to more initialization bias and uncertainty.

Climate models have coarser grid resolution compared to NWP models, because they must be run for multiyear simulations. A unified model needs to use parameterizations and a dynamical core that can support this range of resolutions, including across "grey zones" where processes such as atmospheric cumulus convection or oceanic mesoscale eddies are simulated but not well resolved. While the European Centre for Medium-Range Weather Forecasts (ECMWF) and the U.K. Met Office (UKMO) have had some success at this, sophisticated theoretical and physical research is needed to try to develop subgrid parameterizations that seamlessly span the NWP-climate range from 10 to 200 km, especially for deep convection. Significant computing resources to facilitate explicit simulation of smaller-scale processes and their interactions with the larger scale will be needed for this research. Its benefits would spread across climate modeling because different applications already use different grid resolutions (e.g., higher-resolution [~50 km] models are used for the decadal prediction problem [e.g., Meehl et al., 2009] for regional climate modeling, or for 10- to 20-year "time slice" global simulations for looking at probability distributions and extremes of weather variability in future climates). Furthermore, within a decade, climate models will use the grid spacings that NWP models use today, so NWP models are a good testbed for developing future climate models.

Finding 11.3: An important challenge for unified modeling (and climate modeling as a whole) is developing improved parameterizations that can work across a range of scales spanning weather and climate applications.

Challenges with model verification are also formidable. Metrics currently used by the climate modeling community differ widely in variable, time scale, space scale, or functional representation. The same is not true in weather prediction, where some estimates of both prediction limits and the impact of different weather prediction metrics can be determined. The skill of daily weather forecasts can be verified many times, and a quantification of model skill is relatively straightforward. The problem is more difficult for seasonal prediction because a large number of seasons and those forecast states must pass in order to build up forecast verification statistics.

For decadal and longer time scales, the problem of quantifying prediction skill becomes even more difficult, and the metrics will likely involve how the forecasts are used in applications. Even if long-term climate models could be tested with all possible climate metrics proposed in the past decade of journal papers, there is no current method to prioritize or weight their impact in measuring uncertainty in predicting future climate change for temperature, precipitation, soil moisture, and other variables of critical interest to society.

CURRENT EXAMPLES

Several major numerical weather prediction centers have already spawned unified systems also used for climate modeling. These include UKMO/Hadley Centre, ECMWF, and Meteo-France in Europe, as well as the National Centers for Environmental Prediction (NCEP) (Global Forecast System [GFS]/ Coupled Forecast System [CFS]) in the United States. Initial motivations for developing such systems included seasonal-to-interannual forecasting (NCEP and ECMWF) or an external group interested in developing the weather model into a new climate model (EC-Earth). What can be learned from their experiences?

UKMO/Hadley Centre

The most mature unified modeling system is run by UKMO and its climate modeling branch, the Hadley Centre. The Met Office Unified Model, MetUM, was first documented by Cullen (1993) and has been its operational global weather forecast model ever since. It is also the atmospheric component of the HadGEM series of climate models (Collins et al., 2008; Martin et al., 2006). Lastly, regional versions of MetUM are used for high-resolution weather forecasting over the United Kingdom, air-pollution dispersion modeling, and regional climate modeling. Hence, under the unified model umbrella UKMO supports a model hierarchy sharing physical parameterizations, dynamical frameworks, data assimilation, and software infrastructure as appropriate.

Senior et al. (2010) describe the overwhelmingly positive UKMO experience with unified modeling. They note the costs (possible compromises to improved performance on one time scale, additional technical complexity of the modeling and data assimilation system), but they also note "with the MetUM we have encountered relatively few occasions where compromise was required, and more typical is delayed implementation of a change because of lack of performance on a particular timescale." They stress advantages in rigorous model evaluation, use of diverse observations on many time scales, scale-aware parameterization development, common software infrastructure, and cross-fertilization allowing earlier implementation of new physics (e.g., application of chemical models developed for climate to do air quality forecasting embedded within a weather-prediction model). They also report extensive use of MetUM models by outside academic and applications-oriented user groups.

Martin et al. (2010) show examples of how combined analysis of errors at both few-day and climate time scales stimulated improvements in cumulus parameterization that improved tropical precipitation patterns, and improvements in aerosol and land albedo parameterization that improved land-surface temperature predictions on both time scales. They report that UKMO is currently working toward full unification of seasonal/decadal climate prediction, which is currently performed with a slightly different modeling configuration, in this framework.

In the past 5 years, UKMO and ECMWF (discussed below) had the highest 5-day weather forecast skill (measured using a standard midlatitude metric, global root-mean-square error in 500 hPa height) of all modeling centers worldwide (Figure 11.1). Both centers have invested heavily in the climate-model strategy of reduction of systematic biases in their forecasts; this aspect of unified model development has clearly been beneficial to their weather forecasts. Gleckler et al. (2008) found that the overall climate simulation biases (averaged over a variety of well-observed global fields) of HadGEM climate model were among the lowest of the CMIP3 climate models, showing the unified strategy also produce a competitive climate model.

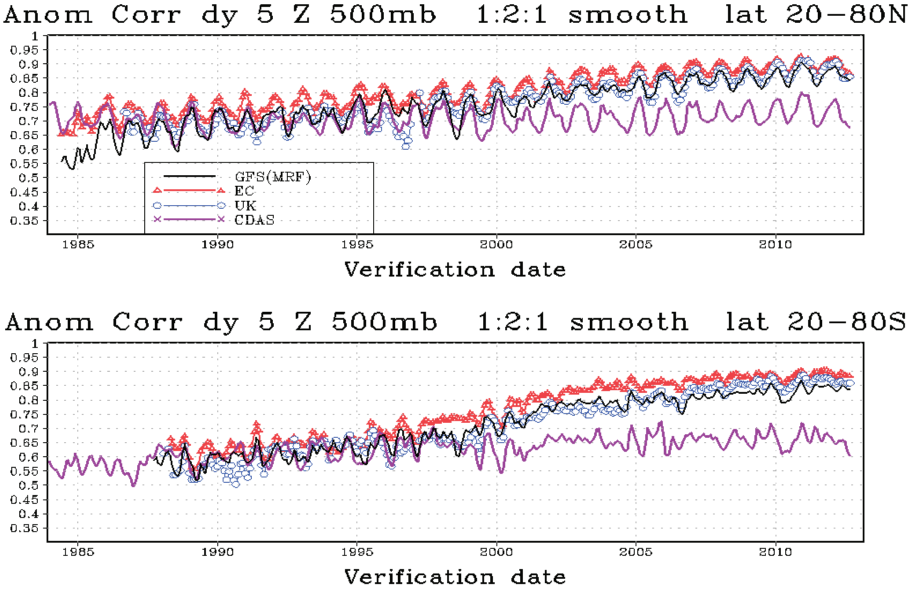

FIGURE 11.1 Time series of monthly mean anomaly correlations for 5-day forecasts of 500-hPa heights for GFS/Medium-range Forecast, ECMWF, UKMO, and CDAS (a frozen NCEP model) since 1984, Northern Hemisphere (top) and Southern Hemisphere (bottom). ECMWF has maintained the highest weather forecast skill of all operational modeling centers. SOURCE: http://www.emc.ncep.noaa.gov/gmb/STATS/html/aczhist.html (accessed October 11, 2012).

ECMWF

In 1975, ECMWF was founded by a European consortium to develop a new medium-range (5-14 days) global weather prediction model, and began operational forecasting in 1979. Since the late 1980s, ECMWF has maintained the highest weather forecast skill of all operational modeling centers (Figure 11.1). In the 1990s, this success led the Max-Plank Institute in Hamburg, Germany, to use a version of the ECMWF model as the basis of a new climate model version, ECHAM4. This was not a true unified model, because a variety of new physical process parameterizations were then added to ECHAM4, and no serious attempt was made to keep ECHAM4 harmonized with further versions of the ECMWF model. However, the ECHAM4 model was among the most skillful of the CMIP3 coupled models at simulating the current climate (Gleckler et al., 2008).

Meanwhile, ECMWF developed its own seasonal-to-interannual forecasting model. In 2005, a new consortium of smaller European climate modeling groups, some university-based, partnered with ECMWF in a project called EC-Earth (Hazeleger et al., 2010), which aims to more fully realize the vision of unified modeling. This project adopted a more intellectually rigorous approach, in which "fast" physics (which respond to atmospheric changes in periods of a few days, such as cloud processes or near-surface soil moisture) are optimized exclusively using weather forecasts (Rodwell and Palmer, 2007). Then long-term climatology and seasonal-to-interannual forecasts are used to optimize "slow" physics such as ocean turbulent mixing or ocean coupling with sea ice that affect the simulation mostly on time scales of months to years, as well as physics that affects both time scales but is most important for climate biases, such as snow density over land. The resulting tuned model slightly improves on the weather forecast skill of the original ECMWF model version and substantially reduces climate biases to a level well below the mean over all CMIP3 coupled models (Hazeleger et al., 2010), showing the value of a seamless approach.

NCEP

In response to a growing scientific consensus on the potential of coupled modeling for El Niño/Southern Oscillation and seasonal forecasting, NCEP implemented the CFS in 2004 (Saha et al., 2006). The atmospheric model was based on a lower-resolution version of their GFS operational weather forecast system, coupled to externally developed ocean and sea-ice models. Version 2 of the CFS, based on a 2007 version of the GFS with a variety of additional modifications made to improve climate biases and the seasonal forecast skill, became operational in 2011. The CFS can be described as a "loosely unified" system, in that neither the coupled model development nor the metrics used to assess it currently feed back into changes in the GFS weather-forecast model. A 30-year coupled reanalysis at 50 km horizontal resolution, CFSR, has been performed using CFSv2 (Saha et al., 2010); this is a major additional contribution to climate data that takes advantage of a coupled climate-capable modeling system with cutting-edge assimilation capabilities, and which should help engage the outside community in the CFS effort.

Finding 11.4: Three lessons stand out from examining existing unified modeling systems:

- **a unified model can be world leading for both weather and climate simulation;**
- **successful climate and weather modeling groups that share a unified or near-unified model require a strong supportive management and adequate dedicated resources that can bridge between the different goals and user needs of weather and climate models; and**
- **unified models are attractive to outside users because of their flexibility and multiscale validation, and help promote interactions between the modeling center and a broad user community whose feedback can improve the model.**

THE WAY FORWARD

Unified Modeling

The committee recommends an accelerated national seamless modeling effort that spans weather to climate time scales. One method to achieve this would be nurturing a U.S. unified weather-climate prediction system capable of state-of-the-art forecasts from days to decades, climate-quality data assimilation, and reanalysis. This prediction system would be a collaboration among operational weather forecast centers, data assimilation centers, climate modeling centers, and the external research community. In particular, it is important to develop it as a partnership between the research and operational communities to best leverage off existing expertise. Versions of this unified model might be deployed as part of an operational prediction system, but it should also be supported for use as a research model.

Ideally, such a model would cross-fertilize parameterization development between the weather and climate communities and naturally lead to parameterization approaches that work well across a range of space and time scales. The committee acknowledges the challenges and risks in such an approach. It requires a clear national-level mandate, strong and skillful leadership, and substantial new resources that recognize that this should be a research effort that can successfully involve a broad scientific community. In particular, these conditions have not been met in the past. No current U.S. modeling center has the resources and capacity to realize this vision on its own. While NCEP's GFS/CFS has taken important steps toward this unified modeling vision, its further development is subject to both operational constraints and resource limitations. Past experience suggests that partnerships between centers can succeed only if the incentives to work together are strong, sustained, and offer clear scientific opportunities that attract talented scientists and software engineers.

A further management challenge is harmonizing model development for weather versus climate applications. For weather applications, it is advantageous to update the modeling system whenever a proposed change has been demonstrated to improve the forecast skill, because the main application is weather forecasts with a shelf life of a few days. For climate applications, the forecast lead time can be years to decades, and the model output may be bias corrected, downscaled, or used as one step in a chain of models. For such applications, users may prefer a modeling system that remains frozen for several years before an improved version is introduced. Thus, there must be scope for separate development of weather and climate branches of the model, then a periodic, possibly challenging, reintegration of model changes into a single trunk model as at UKMO. This latter step is a defining characteristic of unified model development.

The committee recommends that the U.S. Global Change Research Program, together with the major national climate and weather modeling institutions (e.g., NCEP, GFDL, NCAR, and the Global Modeling and Assimilation Office) work toward defining a unified modeling strategy and initial implementation steps (or deciding this is not a good approach). It should take advantage of the common software infrastructure, community-wide code, and data accessibility. Its success could be judged by simultaneous improvement of forecast and climate simulation skill metrics on all time scales.

One possible benefit of unified modeling is more accurate assimilation of a broad range of observations. Hence, such a unified modeling effort could include research and development of state-of-the-art data assimilation methods, with the goal of producing a comprehensive Earth system reanalysis for the past 50 years (or at least for the period 1980 to the present).

Hindcast Testing of U.S. Climate Models

The committee also encourages a nationally coordinated research effort of hindcast testing of all major U.S. climate models (not just the unified model). This is much easier to implement than a unified weather-climate model; each climate model can be run at its preferred grid resolution and need not have a data assimilation capability. The effort could combine several years of hindcasts on weather time scales (up to 15 days) and coupled-model hindcasts on intraseasonal to interannual time scales. Each model could use either externally initialized fields or some form of relaxation or data assimilation. A rigorous and coordinated testing process using a standardized protocol, outputs, and diagnostics would facilitate model intercomparisons and accelerate progress. Tests could include perturbed initial conditions, perturbed-parameter ensemble hindcasting capability, and perhaps ensemble Kalman filter data assimilation to guide the choice of "fast physics" parameters. Results should be made publicly available in a standard web-accessible form. The main goals would be to evaluate and improve model representations of "fast" physical processes that vary strongly on these time scales and to optimize uncertain parameters within these representations.

Recommendation 11.1: To fully exploit a multiscale approach to model advancement, the United States should nurture a unified weather-climate prediction system capable of state-of-the-art forecasts from days to decades, climate-quality data assimilation, and Earth-system reanalysis.

Recommendation 11.2: To reduce sources of uncertainty in climate simulations, the United States should pursue a coordinated research effort to use weather and/or seasonal/interannual hindcast simulations to systematically constrain uncertain parameters and to improve parameterizations in its major climate models.

CHAPTER TWELVE

Interface with User and Educational Communities

While the most prevalent group of users of climate data is the climate science research community itself, this chapter focuses on communities that utilize climate data but are not climate researchers themselves. These communities have an interest in accessing climate data either as an input to their own research, as is the case with the Impacts Adaptation and Vulnerability (IAV) research community, or to inform decision making at some level. These communities have expertise in a nonclimate domain with which climate interacts in some important way. For example, infrastructure decisions such as power plant siting involve literally billions of dollars and are potentially affected by climate in numerous ways including interactions with sea-level rise, cooling system requirements, and regional power demands. Beyond that, the United States, like all nations, has a strategic interest in better understanding potential consequences of climate change as they may affect ourselves and other nations, as well as international lands and seas.

The challenge is to make climate data, models, and numerical simulations available in forms that are useful to the multiple user communities for the next decade and beyond. The following significant user communities are highlighted below: infrastructure decision makers and the insurance sector, national security planners, public policy makers, climate-impacts researchers, and educators. Each of these communities has different needs for data and models and numerical simulations.

CLIMATE DATA USERS

Infrastructure Planning, Energy, and Energy Policy

Infrastructure decision makers need a variety of different forms of information that directly reflect the capital investment decision and its interface with climate. Those who are building harbor infrastructure require a different set of information from those who are designing the cooling systems for power plants. The variety of data needed for these decisions spans a range of temporal and spatial scales. For financial decisions, probabilistic information, or at least a clear representation of attendant uncertainty, is also needed.

Climate model outputs are important inputs to some long-term infrastructure decision making. Some port facilities planning and coastal zones management activities are cognizant of potential climate and sea-level changes. But the use of climate and sea-level information is heterogeneous, and there are major national and private investments being made without regard to the fact that much of their planned usage could occur with a very different climate or sea level.

Climate projections are also important to ongoing decisions regarding energy. For example, winter electric power demand and spring and annual hydropower production in the Pacific Northwest are related to both El Niño and the Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) through variations in winter climate (Voisin et al., 2006). The out-of-phase nature of electricity generation and demand between the Pacific Northwest and California, particularly in spring and summer, provides an opportunity for transfers of hydropower between the two. Forecasts of ENSO and PDO, then, can provide an economic benefit as well as a planning tool.

Insurance and Reinsurance

An important function of the insurance sector is to manage the risk of adverse, weather-related events. The sector insures owners of resources against the effects of events such as floods, hurricanes, and other severe storms. Systematic changes in the frequency and/or intensity of such events are of direct interest to the financial integrity of the sector. Many of the costs of climate change, particularly unanticipated climate change, could be reflected and concentrated in this sector of the economy.

The insurance sector is potentially affected by climate change in its role as a risk manager for economic agents. The sector has been aware that a changing climate could have important effects for years. The consideration is raised in the Intergovernmental Panel on Climate Change's (IPCC's) Second Assessment Report (IPCC, 1995). Insurers and reinsurance companies have taken note of the possible increasing trend in weather-related disasters. Munich Re, a reinsurer based in Germany, has indicated that this trend is associated with climate change and monitors the trend very closely.[1] There is a controversy over whether or not the trend is significant globally; however, there is little dispute that the trend is apparent in data for the United States (Barthel and Neumayer, 2012).

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[1] http://www.munichre.com/en/media_relations/company_news/2010/2010-11-08_company_news.aspx (accessed October 11, 2012).

Assessing the appropriate response to climate change requires assessment of potential impacts across a broad range of potentially insured assets and activities. The challenge to the sector is extremely broad. Many of the sectors that are anticipated to be affected by climate change purchase insurance products. In order to set insurance premiums appropriately, the sector needs to undertake assessments that are much like those of the IPCC, although the sector focuses on near-term rather than long-term climate change impacts. In principle, this means disentangling all of the different forces that affect the value of assets and activities over the period over which insurance applies. The problem of accurately assessing the risk of climate change for all of the insured sectors and assets is truly daunting.

It is not entirely clear to what extent the sector has the resources to accomplish that task, or to what extent the sector undertakes primary research as opposed to drawing on secondary work. Mills (2005) summarized as follows: "Although insurers first expressed concern about climate change more than three decades ago, fewer than one in a hundred appear to have seriously examined the business implications, and fewer still present their analyses in the open literature." What is clear, however, is the fact that better assessment of climate is important to the health and performance of the insurance sector.

National and International Security

Those charged with protecting the national security of the United States must prepare for contingencies that strongly interact with climate. Some aspects of the national security mission are directly affected by climate and sea level, such as port and coastal facilities. Other elements are potentially indirectly affected by climate, such as unrest caused by disruptions in hydrologic and agricultural systems that can produce threats to U.S. interests. In a 2003 Pentagon report (Schwartz and Randall, 2003), the possibility of abrupt climate changes was considered with respect to potential destabilizing effects on the geopolitical environment that might lead to skirmishes, battles, and even war due to resource constraints—food shortages, decreased availability and quality of freshwater in key regions, more frequent floods and droughts, and disrupted access to energy supplies due to extensive extreme weather. Concern also exists for maintaining the integrity of military installations, resources, and training programs within the United States (e.g., the Strategic Environmental Research and Development Program [SERDP][2]).

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[2] http://www.serdp.org/Program-Areas/Resource-Conservation-and-Climate-Change/Climate-Change (accessed October 11, 2012).

In the Quadrennial Defense Review Report (DOD, 2010), a strategic approach to climate and energy is clearly articulated. Climate is clearly seen as contributing to shaping the future security environment, and climate information is being used to produce strategies to cope with climate change both in the domestic and military installations as well as in strategically important locations throughout the world. Outputs from the most recent ensembles of climate change simulations (e.g., CMIP3) have been used. For example, the Oak Ridge National Laboratory (ORNL) recently provided results from the CMIP3 data set to help the Department of Defense (DOD) meet its requirements to assess the implications of climate change for its capabilities. The DOD also maintains a program jointly with the Environmental Protection Agency and the Department of Energy that solicits proposals to provide research on how the military can adapt to climate change (through SERDP); through this program methods and climate products for adaptation purposes are developed.

Public Policy Makers

Public policy faces two challenges: determining interventions to control human actions that could affect climate (e.g., greenhouse gas emissions, land use, and aerosol emissions) and determining an appropriate response to present and potential future climate impacts. These needs require different types of information. In general, public policy makers will have less interest in access to primary data than to expert analysis, assessment, and interpretation. Major public policy decisions, such as the magnitude, pace, and timing of emissions mitigation, are generally made by nations, either individually or in concert. (Decisions about emissions mitigation are also made at state and local levels despite the fact that changes in these parties' emissions may be too small to have a measurable effect on Earth's planetary energy balance.) Emissions mitigation decisions require information about climate change, the ability of public policy decisions to affect climate change, and the relative costs and benefits at the local and global scales from alternative policy interventions. Evidently, the community needs information that has been aggregated, interpreted, and assessed. An authoritative interface between data, models, and users is important.

Those making public policy have a relatively well developed set of resources designed to produce and deliver information. The IPCC was developed by governments to assess what is known, not known, and uncertain with regard to climate change. This organization has produced four full assessments and a wide range of special reports. It is presently in the process of its fifth assessment. In addition, governments have turned to their own scientists to provide tailored assessment products. The National Research Council has played a major role in this regard in the United States. In addition, the

Global Change Research Act of 1990 commissioned a set of assessments of climate impacts, referred to as the National Climate Assessment (NCA), to be completed every 4 years. The NCA has produced two full assessments and a set of synthesis and assessment products. The U.S. Global Change Research Program (USGCRP) is in the process of producing a new product.[3] These assessments in turn rely on climate information products. Both the IPCC and the U.S. government have access to the world's climate scientists and therefore produce authoritative information about climate and climate systems.

In contrast, public policy decisions about how to adapt to climate change are taken by a wider set of actors ranging from international agencies to local communities. These decision makers need information on major climate variables and their projected variability, but unlike the research community, public policy decision makers need information that is actionable. While some decision makers may have sufficient expertise to employ primary data, many will not and will require a professional and trusted interface between data, models, and usable information.

Impacts, Adaptation, and Vulnerability Community

This research community is referred to as the IAV community. The focus of IAV research is understanding the implications for human and natural systems of climate change. The IAV community has highly varied needs for climate data and models. At one end of the spectrum are global ecosystem researchers, who need information on global scales; their spatial and temporal resolution requirements vary from modeling team to modeling team. These modelers can look at both fine scales and long time horizons. At the other extreme are researchers who focus primarily on case studies in which a very specific place, for example, a village, is examined, usually over relatively short (decadal) time horizons, but with extremely fine spatial resolution. This research community can need information about major climate variables, for example, temperature and precipitation, but also about variation in these metrics. In some instances specific metrics, such as the last day of frost or annual number of days above 35°C, are desired. It is important to communicate the uncertainty that attends specific model and ensemble calculations to this user community (Chapter 6).

The highly heterogeneous nature of the IAV research community means that climate information employed by this community is also highly heterogeneous. For some, the Program for Climate Model Diagnosis and Intercomparison and the Coupled Model In-

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[3] http://www.globalchange.gov/what-we-do/assessment (accessed October 11, 2012).

tercomparison Project (CMIP) are central resources. The most recent complete data set from this project, CMIP3, involved 16 international modeling groups from 11 countries, using 23 models and submitting 36 terabytes of model data (Meehl et al., 2007) (see Chapter 8 for more details). For other researchers relatively few climate research data products are used.

Much of the IAV research literature examines the question of how present society would respond to climate change. However, a growing body of research examines impacts and adaptation to climate change as it might be experienced in the future. The development of this literature requires not only climate data and model outputs, but also accompanying socioeconomic and ecosystem information that is consistent with the forcing used to generate prospective climate changes. For the IPCC Fourth Assessment Report, climate models used socioeconomic scenarios taken from the Special Report on Emissions Scenarios, and IAV researchers were able to match these with associated prospective climate calculations. The IAV community found this useful, but it also found that the variety of underlying socioeconomic circumstances covered by these scenarios was not as rich as might be useful. For the IPCC Fifth Assessment, climate ensemble calculations were developed using four Representative Concentration Pathways (RCPs). RCP replications are being produced that will span a broader range of socioeconomic and ecosystem pathways. However, this raises the question of how to pair socioeconomic and ecosystem scenarios that were not actually used as the drivers for climate model experiments. There currently is an effort to generate shared socioeconomic pathways that are associated with the RCPs. This is indeed a complex enterprise, but a critical one for effectively exploring the diversity of possible socioeconomic futures.

Since the information needs regarding future climate are highly diverse within this community, it is difficult to summarize what the needs for improvement will be over the next 10-20 years. Some segments of the community, such as the traditional impacts community may desire high-resolution information on climate change, with robust measures of uncertainty. These needs will be addressed by the types of improvements in modeling, including higher resolution, discussed in Chapter 3. But other segments of the community, such as those more focused on a vulnerability perspective, may need more detailed information on the nature of human and ecosystem vulnerability, and the causes of vulnerability. Generally, more coordination and collaboration between the climate modeling community and the IAV community will help to improve the coproduction of knowledge on future climate.

Educators

The final user category discussed here is educators, who need information about climate that they can understand and in turn communicate to students and the general public. The first step in serving this community is the development of programs to educate the educators. Developing a general level of public understanding of climate and the forces which shape it, as well as the difference between weather and climate, is a long-term enterprise.

The rapid pace of change of climate science presents a particular challenge to the educational community. Textbooks may become outdated as new scientific findings become available. The NRC report *Informing an Effective Response to Climate Change* (NRC, 2010d; Chapter 11) discusses at length the present state of education on climate change, education materials that are available, and the need to link education curricula to scientific advances. The previous NRC committee recommends several priority measures to which this committee also subscribes, including improved "national, state, and local climate education standards, climate curriculum development, teacher professional development, and production of supportive print and web materials." They also recommend a "national strategy and supporting network to coordinate climate change education and communication activities for policy makers and the general public, including the identification of essential informational needs; development of relevant, timely, and effective information products and services; construction and integration of information dissemination and sharing networks; and continuous evaluation and feedback systems to establish which approaches work best in what circumstances" (NRC, 2010d).

As noted above, by the National Academies study *America's Climate Choices* (NRC, 2010a,b,d,e, 2011a) and by the World Meteorological Organization's Global Framework for Climate Services (WMO, 2012), climate data users employ varied data transformed into usable information either directly or by interface organizations.

> Central to the development of user-specific climate information is the recognition that the needs of the user community are diverse and complex. Users of climate information and products can be categorized in many ways: users of global, regional and national products; users in different sectors; users in public policy and planning, and private sector; intermediate users developing products for end users; from well-organized groups to individual users; and from well-informed users to laymen. At the same time it has to be recognized that "users" work on various spatial and temporal scales—from individual farmers, to town planners, to river basin managers, to national

> planners and international development organizations—and have different needs from weeks and seasonal to decadal predictions and long-term projections. They work under various economic and environmental settings and with different financial motives. While there will be some common needs, the general requirements, perspectives and the way to interact with them will differ in each case (WMO, 2012, p. 33).

Finding 12.1: There is a wide variety of needs for climate information across the various user communities, being met with varied success and employing varied providers of climate services.

DELIVERING MORE USABLE INFORMATION TO THE USER COMMUNITY

The committee anticipates that America's national policy makers will continue to have access to the best climate science and climate scientists in the world and that the function of providing information about the state of the science will continue to be performed by America's leading scientists. Organizations such as the National Academy of Sciences will continue to provide the connectivity between evolving climate science and decision makers. National policy makers will also continue to have direct access to the leading climate scientists working at America's universities and climate centers.

Other decision makers do not have access to nor do they need the services of America's leading climate scientists. There is a growing demand for climate products for decision making by user communities other than national decision makers that are provided by others with highly varied skills and backgrounds. The problem faced by many users is not that they want to understand the frontiers of scientific understanding and its broad implications and attendant uncertainties (see Chapter 7), but rather that they need to be able to find and work with someone that has the knowledge of the present state of the science and an ability to access climate data, interpret it in the context of a specific user's need, and to help that user to understand both the implications of those data and attendant uncertainties. The committee notes, for example, that the PACE (Post-docs Applying Climate Expertise) program is a step in the direction of filling this need.[4]

Enhancing the ability of climate data users to access the best available information is an important step in developing a national capability to make well-informed decisions in both the public and private sectors. While there are entities that facilitate the proper use and interpretation of climate model output (e.g., the Task Group on Scenarios for

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[4] http://www.vsp.ucar.edu/pace/ (accessed October 11, 2012).

Climate and Impact Assessment of the IPCC[5]), more detailed attention to groups of users is required. Overpeck et al. (2011) came to essentially the same conclusion. They state that two of the principal challenges facing the climate modeling community are ensuring that "the ever-expanding volumes of data are easily and freely available to enable new scientific research," and "making sure that these data and the results that depend on them are useful to and understandable by a broad interdisciplinary audience."

The committee recognizes that the transformation of climate data from model output to usable knowledge implies transformation and the creation of derivative data products. At each step, climate expertise will be required, including an understanding of what the data imply and the uncertainty associated with them. While the climate data may begin in a climate center's repository, it may well ultimately be transformed into derived data on a university researcher's desk or as actionable information in the private sector.

Finding 12.2: While there is a great deal of climate model output available, there is a growing need for more user-accessible information and tailoring of information to specific user needs.

The translation of climate model output into more helpful products for various user groups is already being performed within many public and private entities. This work involves such skills as understanding the strengths and weaknesses of different climate modeling approaches and model data sets for a specific problem or question, knowledge of different downscaling techniques and their appropriate uses, and the ability to communicate the limitations and uncertainties in climate model projections. Whether as part of a national climate service, or within more local government agencies, private firms, or consulting groups, this work needs to be done by qualified people to ensure that users receive the most accurate and appropriate information. The people currently doing this work come from a diversity of backgrounds such as weather modeling, engineering, statistics and environmental science. Currently, no standards exist for helping potential employers assess whether such people have the necessary skills in the appropriate use of climate model information to ensure that they can provide the most accurate and appropriate information to end users. This suggests an unmet need for training and accreditation programs in this area.

> To develop the human capacity needed in the Framework, a review of the educational qualifications and on-job training requirements for climate specialists would have to be taken up. New skills in developing, producing, accessing, interpreting and analyzing

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[5] http://www.ipcc.ch/activities/activities.shtml#tabs-4 (accessed October 11, 2012).

> global and regional climate products, including downscaled projected climate change scenarios for assessing climate change impacts, would need to be developed at a much larger scale as the climate service provision is made operational in the countries. A number of CLIPS training workshops held across the world have helped to create local experience in climate and climate prediction to a certain degree.[6] These capacities would have to be scaled up and complemented by incorporating foundational elements of climate forecasting and services into the basic curriculum of university programmes around the globe, and particularly in WMO Regional Training Centres (RTCs) (WMO, 2012, pp. 39-40).

As articulated below, the committee foresees a growing need for this activity of "climate interpretation" to continue to grow in the future and envisions a role for trained individuals to act as "climate interpreters" at the interface between climate researchers and climate data user communities. Another approach that is gaining momentum is to invite climate model users to participate in discussions of model development. Such an approach has been initiated at the National Center for Atmospheric Research through the Community Earth System Model Societal Dimensions Working Group[7] and is viewed as an effective method among some climate applications communities (e.g., the Water Utility Climate Alliance[8]). Yet another successful approach has been the Regional Integrated Sciences and Assessments (RISA[9]) effort from the National Oceanic and Atmospheric Administration (NOAA), which started in the mid-1990s to better align climate research with user needs in the United States. Since then many universities and research institutions all over the continental United States, Alaska, and Hawaii have been awarded 5-year RISA awards to conduct research in close collaboration with stakeholders interested in assessing and adapting to climate change-related risks in areas such as fisheries, water, wildfire, agriculture, coastal restoration, and human health. In the United Kingdom, there is the UK Climate Impacts Programme (UKCIP[10]), which coordinates and influences research into adapting to climate change, and provides tools for and shares information with stakeholders.

Finding 12.3: There is further need for climate interpreters to transform climate model output into usable information for a wide variety of decision makers.

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[6] Climate Information and Prediction Services.

[7] http://www.cesm.ucar.edu/working_groups/Societal/ (accessed October 11, 2012).

[8] http://www.wucaonline.org/html/index.html (accessed October 11, 2012).

[9] http://www.climate.noaa.gov/cpo_pa/risa/ (accessed October 11, 2012).

[10] http://www.ukcip.org.uk/ (accessed October 11, 2012).

THE WAY FORWARD

Overpeck et al. (2011) concluded:

> A new paradigm that joins traditional climate research with research on climate adaptation, services, assessment, and applications will require strengthened funding for the development and analysis of climate models, as well as for the broader climate data enterprise. Increased support from the funding agencies is needed to enhance data access, manipulation, and modeling tools; improve climate system understanding; articulate model limitations; and ensure that the observations necessary to underpin it all are made. Otherwise, climate science will suffer, and the climate information needed by society—climate assessment, services, and adaptation capability—will not only fall short of its potential to reduce the vulnerability of human and natural systems to climate variability and change, but will also cause society to miss out on opportunities that will inevitably arise in the face of changing conditions.

The committee recognizes the growing need to improve the quality and usability of climate information available for decision making in the public and private sectors. The importance of good weather information is well established. Climate change raises the prospect for systematic changes in weather events. While precise predictions of changes in weather patterns are not yet available, the research recommended in this report could ensure that, with the passage of time, better information across an ever-wider set of statistics will become available. The heterogeneity of climate statistics coupled with an evolving state of the science argues for the need to develop trained professionals, with the capability to both access state-of-the-art data and model products.

The committee recommends the development of degree or certification programs in climate "interpretation." A climate "interpretation" program would provide a post-graduate training about the workings of climate models, including what goes into a climate model simulation; the strengths and weaknesses of various modeling approaches; regional models and techniques for downscaling; sources of uncertainty in climate simulations; techniques for handling the increasingly large arrays of data coming out of climate simulations; statistical techniques of analysis; and how to obtain data and model outputs. Interpreters would also have the ability to communicate user needs to those generating the climate model information. To keep climate interpreters informed about the evolving state of climate science and climate modeling, there need to be continuing education opportunities for climate interpreters; these could be provided as short courses at major national meetings or a national climate forum (see Chapter 13). The committee also anticipates that the establishment of professional organizations to support these professionals would naturally foster two-way communications between climate scientists, climate translators, and users. The role of interpreter would be similar to that of "information broker" called for by Dilling and Lemos (2011) who would act as an intermediary between users and scientists. The development and training of these intermediaries is viewed as one key innovative mechanism that could foster the types of iterative interactions that would more readily lead to usable climate science.

The committee envisions that such programs would be provided by universities, with certification provided by a national organization that has a broad reach and is independent of any agency or modeling center, such as the American Meteorological Society or the American Geophysical Union. Graduates of such programs would be employed in diverse contexts, in local, state, and federal government; the private sector; boundary organizations within agencies, e.g., RISAs; and nongovernmental organizations. As discussed earlier (Chapter 9), the committee anticipates that the private sector may ultimately provide much of the services that transform data from climate models into useful products for a wide array of decision makers.

The committee expects that such programs would create professionals who could perform tasks that are being done in boundary organizations at the interface between climate science and decision makers. These individuals would have the ability to provide climate information to users in forms that meet specific user needs, and they will also be able to discuss with users their expectations on what data products are possible and meaningful. They would also have the knowledge to communicate user needs to climate modelers and to help climate modelers deliver more useful data products, better reflecting evolving user needs. This could evolve into a system of true coproduction of meaningful usable knowledge on future climate change from both climate scientists' and users' perspectives. As with any professional certification, standards of good practice would be established. Continuing education and recertification programs would ensure that professionals maintained their skills to then current standards.

The organized provision of climate information and "climate services" by the federal government has been discussed and recommended in previous reports as a strategy for making the results from climate modeling more accessible to users (NOAA Science Advisory Board, 2008, 2011; NRC, 2001a, 2009, 2010d). The committee discussed climate services but chose to not add yet further input to this debate. The training of climate interpreters is important, regardless of where in the chain of organizations needing or providing climate information they might sit. It is not envisioned as the sole solution to address all user needs for climate information, but rather a crucial step that benefits any social system for bridging the climate modeling and user communities.

As noted above, the committee does not envision that national policy makers would cease to utilize America's top scientists for guidance in regarding climate science and its implications for America's interests. The committee anticipates that that connection will remain as ever. Similarly, we anticipate that interdisciplinary research will continue to thrive. Joint research projects that foster the development of integrated Earth system models that incorporate the state of the science in multiple disciplines and explore the joint implications for both biogeophysical and human-Earth systems will not be affected. Similarly, direct communications between climate modelers and research users of climate data, such as those in the IAV community, will not be interrupted, although researchers needing access to knowledge about how to access and use existing data products would find this climate translator skill set potentially helpful. Regardless of whether the current communications pathways between national decision makers and collaborative researchers are deemed adequate or not, the growing demand for climate data products would benefit from trained certified professional climate translators who could help establish and maintain two-way communications between climate scientists and data product users.

Recommendation 12.1: To promote the effective application of climate models, the United States should develop climate interpretation certification and continuing education programs to train a cadre of climate interpreters who can facilitate the interpretation of climate model output into usable information for a variety of decision makers and communicate user needs to climate modelers.

CHAPTER THIRTEEN

Strategies for Optimizing U.S. Institutional Arrangements

The current U.S. institutional structure for climate modeling consists of multiple centers that develop and use climate models in largely independent efforts. These institutions coincide primarily with U.S. funding agencies, and this structure has arisen primarily for administrative and historical reasons. Large global climate models are primarily run at larger modeling centers (described below). University-based research helps efforts to better understand processes in the climate system that can advance theoretical understanding of the climate system and lead to improved parameterizations in models, often utilizing models and model output from the large centers. Model development efforts involving both these communities are fostered by activities such as National Science Foundation (NSF)/National Oceanic and Atmospheric Administration (NOAA)-sponsored Climate Process Teams (CPTs). Regional climate modeling is mainly done by small groups at universities and national laboratories.

Climate modeling in the United States has efforts aimed at both global and regional modeling. There is overlap and interaction between the two, but in this report they are discussed separately for ease of presentation.

CURRENT GLOBAL CLIMATE MODELING ACTIVITIES IN THE UNITED STATES

There are several core global climate modeling efforts within the United States, complemented by scientists at a variety of other institutions. For this discussion, a "core modeling effort" is an activity that meets most or all of the following criteria:

- builds complete climate models for use on seasonal to centennial time scales, and includes state-of-the-art representations of the ocean-atmosphere-land-ice system, as well as carbon and biogeochemical cycling;
- develops models with spatial resolution and scientific capabilities that are consistent with state-of-the-art models used internationally; and
- has efforts that are not continually divergent, but that periodically bring together model branches into a central core for ongoing coordinated development.

It is the assessment of this committee that a number of efforts in the United States meet some or all of these criteria. The two core modeling efforts that meet all of the criteria are

- the National Center for Atmospheric Research (NCAR), supported by NSF and the Department of Energy (DOE); and
- the Geophysical Fluid Dynamics Laboratory (GFDL), supported by NOAA.

Additional efforts that meet some of the criteria are

- the Goddard Institute for Space Studies (GISS), supported by NASA, focusing on decadal to centennial climate change;
- the National Centers for Environmental Prediction (NCEP), supported by NOAA, focusing on seasonal prediction; and
- the Goddard Global Modeling and Assimilation Office (GMAO), supported by NASA.

This somewhat distributed system for U.S. model development has evolved over more than three decades with a legacy of funding support among different agencies, as well as differing modeling missions. Early results from the GFDL and GISS models provided much of the basis for the NRC (1979) assessment of the climate change expected from increasing carbon dioxide. NCAR began global modeling activities in the 1960s. Efforts in global modeling were also initiated at a number of universities, such as the University of California, Los Angeles. In part because of the large infrastructure that is required on an ongoing basis, the efforts at comprehensive global climate system modeling in the United States are primarily sustained at large national centers, while drawing upon expertise from universities and other partners. The GFDL and NCAR modeling efforts continue to focus on modeling of climate change and variability on time scales of seasons to centuries, with a strong emphasis on long-term projections. NCAR has partnered with DOE and the university research community to help provide the scientific and computational resources needed to sustain its effort. NASA-GISS, at a much smaller level, has also continued to focus on long-term climate change. All three centers have contributed to the Intergovernmental Panel on Climate Change assessments since they began. GFDL and NCAR were designated as the two primary U.S. climate modeling centers in the 2003 report of the U.S. Climate Change Science Program (CCSP[1]) (CCSP, 2003).

Other major U.S. global modeling activities have focused on other objectives: NCEP on operational weather and climate predictions on time scales from days to seasons, and

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[1] CCSP is now known as the U.S. Global Change Research Program (USGCRP).

NASA's GMAO on the the simulation and global gridded analysis of current climate, in conjunction with the assimilation of satellite and other data.

These centers vary in the size and scope of their activities devoted to modeling (see Chapter 7 for a discussion on the climate modeling workforce). The two largest centers in the United States are NCAR and GFDL. USGCRP (2011) estimates that of the $2.18 billion spent annually by federal agencies on climate research, 11 percent (~$239 million) is allocated for "improving our capability to model and predict future conditions and impacts." That spending supports activities in both global and regional modeling at the large modeling centers, as well as smaller activities in federal laboratories, universities, and private companies.

Finding 13.1: The United States has a distributed system for global climate modeling, with a small number of "core modeling efforts." These efforts have a long history and their structure derives from both modeling functions and agency funding structures. There is a separation of modeling activities across time scales, with operational weather and seasonal prediction centers largely separated from longer-term climate variability and change efforts.

CURRENT REGIONAL MODELING ACTIVITIES IN THE UNITED STATES

Regional climate modeling activities are focused on developing and using climate models with fine spatial resolution to better resolve small-scale climate features over a limited geographic domain. These models can be defined only over this limited domain, with specified boundary conditions at the perimeter of the domain, or they can be global models with varying spatial resolution in which the fine resolution is focused over the region of interest. For the limited domain regional models, boundary conditions can be supplied from a reanalysis or from some other climate model, for example, from a global simulation of future climate change.

Regional modeling activities are also distributed in the United States. Some have primary affiliation in universities, while others have strong affiliations with some of the modeling centers described above. Most of the regional models used are derived from models developed at one of the global modeling centers. For example, a number of regional modeling efforts use the Weather Research and Forecasting (WRF) regional model that is developed through efforts involving NCAR and NOAA. This modeling system is then tailored to specific applications in various institutions according to their scientific foci and goals. WRF supports many different options for physical parameterization, and a centralized effort has not yet evolved to quantitatively evaluate which of these options are most appropriate for a regional climate model. Based on local experience and history, different institutions are making different choices of such options; WRF is a "multiflavored" climate modeling platform. The multiple options available allow and even foster innovation but also make it much more challenging for a user of such regional climate model simulations to be assured of their credibility. MIPs like CORDEX[2] and NARCCAP[3] will be helpful in assessing the credibility of regional climate simulations.

Finding 13.2: The United States has a distributed system for regional climate modeling, hosted both at national laboratories and at universities. The underlying models are used in a variety of applications and have not been as systematically evaluated and intercompared for climate applications as global models.

STRENGTHS AND WEAKNESSES OF CURRENT INSTITUTIONAL ARRANGEMENT

Strengths

The current institutional arrangements have many advantages and have fostered world-class climate modeling activities in the United States. One of the strengths has been the development of a cadre of talented scientists at each institution that contribute to the development and use of state-of-the-art models on a long-term basis. Model development is a long-term enterprise, so a stable team of scientists, supported by stable funding, is needed. Such teams provide important institutional memory. The current system has also effectively entrained talented researchers at institutions outside the primary centers into the model development activities. As mentioned above, activities like the CPTs, which are funded by NSF and NOAA, seek to leverage the talents in both universities and national laboratories to make progress on major uncertainties in climate models.

The existence of multiple climate modeling centers in the United States has led to a healthy diversity of activity and the benefits of competing approaches. For example, focused comparisons of model development activities between NCAR and GFDL have strengthened each modeling effort. However, it could also be argued that such healthy competition could come from a single U.S. modeling effort in competition with international efforts.

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[2] http://wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html (accessed October 11, 2012).

[3] http://www.narccap.ucar.edu/index.html (accessed October 11, 2012).

The current arrangement has produced somewhat stable funding that is concentrated along existing agency lines. Long-lead-time research activities need such stability, although within this arrangement there can be short-term swings in funding that have negative long-term consequences. For example, short-term budget reductions can lead to reductions in the hiring of postdocs or young scientists; these missed opportunities have negative consequences for many years to come.

Finding 13.3: Some positive aspects of the current U.S. institutional arrangement for climate modeling are the general stability of the funding that sustains the various efforts, as well as the diversity of approaches to solve problems and healthy competition that follow from having multiple modeling activities.

Weaknesses

One of the primary weaknesses in U.S. climate modeling is that modeling efforts are subcritical in key areas. Increased model complexity and greater societal expectation and demand for climate information create pressure for expanded climate modeling capacity, while human resources within individual modeling groups have not expanded commensurately (Chapter 7). There are at least two reasons for this:

- funding that, while substantial overall, is inadequate to support the number of major modeling efforts; and
- inadequate career development rewards, especially for young scientists.

Scientific and applications-driven demands for increasing realism and comprehensiveness of climate models also require major modeling groups to seek access to constantly increasing computational capacity, which requires increasingly sophisticated software development to efficiently exploit (Chapter 10). This software development requires additional human resources that core modeling groups struggle to support. These are serious impediments to progress. At the national level, maintaining the current structure of several quasi-independent Earth system modeling efforts cuts into the resources available for each group, pacing progress and creating stress by requiring modeling groups to spread expertise thinly across a broad spectrum of topics.

In the current structure, computational resources for U.S. climate modeling are largely aligned along agency structures. This arrangement has some advantages in terms of stability, with multiple computing platforms providing some level of overall reliability to the availability of U.S. climate computing. Even if one agency's computing platforms were cut, there would remain other platforms available for U.S. climate computing.

However, this fragmentation invites duplication of effort and suboptimal alignment of national climate modeling priorities with computational resources.

An additional weakness of the U.S. institutional structure is that modeling activities for long-term climate change are not well connected with the main U.S. operational center for weather and short-term climate prediction at NOAA's NCEP. In some other countries, such as the United Kingdom, modeling activities for both short-term weather prediction and long-term climate are integrated within a single institution. In this arrangement the models used for weather prediction and climate projections share much of the same software infrastructure and physics, although the models used on the two time scales are not identical. As articulated in Chapter 11, there would be a significant potential for overall advancement in the United States if there were tighter integration between modeling activities across time scales. Two strategies would be (a) enhanced interactions between scientists that are developing and using models for long-term climate change, intraseasonal to decadal climate change, and for weather prediction and (b) development of a single unified modeling system for prediction on all time scales.

Finding 13.4: Some limitations of the current institutional structure are that most U.S. climate modeling centers are individually subcritical with respect to expertise and funding, it is difficult to attract talented young scientists into model development, and the separation of operational and research modeling efforts can be a barrier to advances.

THE WAY FORWARD

A national strategy for advancing U.S. climate modeling should optimize or modify existing structures while adding critical new ingredients, as supported by the lessons learned from previous reports on U.S. climate modeling (Chapter 2). The committee believes it is productive to focus on actions that develop a greater level of unification by combining high-level cross-cutting leadership with science-motivated grassroots efforts. Several key aspects of a national strategy that contributes to this focus are described below. This discussion applies both to core modeling efforts for global climate and to regional climate modeling activities.

Regular National Climate Modeling Forum

In a distributed modeling system, the various model development and applications or user groups need mechanisms to communicate progress, share results, and discuss and plan common strategies for effective collaboration. Modelers can learn about each others' progress at conferences and through scholarly journals, but for a diverse and decentralized community, this can be slow, haphazard, and inefficient. For this purpose, the committee recommends the establishment of an annual "U.S. Climate Modeling Forum," in which scientists engaged in both global and regional climate model development and analysis from across the United States, as well as interested users, would gather to focus on timely and important cross-cutting issues related to U.S. climate modeling. While NCAR hosts an annual Community Earth System Model (CESM) meeting that is widely attended, it is largely focused on the needs of its own global modeling activities and would not be ideal for the broader purposes the committee envisions. The proposed National Climate Modeling Forums would provide regular interactions between scientists from the various U.S. regional and global modeling activities, including operational modeling. The Forum should also include end users of climate model output. The committee recognizes that one meeting may not be able to meet all the goals that are set forth below, and there will need to be experimentation about how to design a Forum that is most effective as a community-building institution for climate modeling and its applications.

The proposed Forum would, at a minimum, provide a periodic synthesis of current U.S. climate modeling capabilities and an opportunity for community discussion of near-term plans. It would also provide a venue for wide-ranging communication across a spectrum of climate model developers and users of climate model information. In the spirit of favoring a science-motivated grassroots approach, the Forum would provide the opportunity for the community to work together in ways that make sense at the scientific level, but which are sometimes difficult to anticipate in detail or to prescribe in advance. The Forum would

- serve as an important mechanism for informing the community of the current and planned activities at core modeling centers and regional modeling efforts;
- provide an important venue for fostering interactions among scientists in the core modeling efforts, regional modeling efforts, and other institutions including universities;
- facilitate a more coordinated approach to global and regional model development and use in the United States; this approach would likely include the design of common experiments using multiple models that seek to improve our understanding and representation of key climate processes, and sharing the results and analyses of such experiments, as well as the formation of joint development teams to focus on addressing limiting biases or shortcomings in the current generation of models in the spirit of the current U.S. CPT approach, funded through multiagency competitively awarded grants;

- provide an important vehicle to enhance and accelerate communication among climate modeling groups at research and operational modeling centers, especially regarding the status and requirements of operational models and potential collaboration;
- offer an opportunity to facilitate the development and implementation of a shared national software infrastructure through sustained, regular interactions between the infrastructure software developers and model developers and users, as well as by providing demonstrations of the benefits of such an approach;
- offer a vital opportunity for end users of climate model information to both learn about the strengths and limitations of models, and to provide input to modelers on the critical needs of end users that could feed back onto the model development and application process; these exchanges could include offering short update courses that would satisfy a continuing education requirement for "climate modeling interpreters;" and
- provide an opportunity for regular broad-based discussion of strategic priorities for the national climate modeling enterprise.

Although current institutions may be subcritical in many areas, frequent interactions addressing the needs of all U.S. models with attractive and varying thematic foci would help to gather a critical mass of scientists across the United States to attack key problems in a coordinated fashion, and tighten the exchanges between global and regional modeling efforts. These interactions would include in-depth communications on activities, progress, and plans of the major research and operational centers and promote the advancement of specific aspects of climate modeling across the United States.

The Forum would be a particularly appropriate venue for discussing and planning more systematic comparisons and evaluations of regional climate models using standardized metrics, and for model development projects (e.g., scale-aware parameterizations) that try to bridge between the scales of regional and global models. It would also be an opportunity to broadly discuss the evaluation and communication of model uncertainty.

Because this activity involves coordination across multiple modeling groups and agencies, it would be most likely to succeed if it were organized through a strong coordinating institution. While other organizations such as the American Meteorological Society, the American Geophysical Union, or the World Climate Research Program could in theory serve this role, the USGCRP might be a natural choice for taking the lead in organizing the Forum and associated activities given its mission to coordinate climate research activities in the United States. The USGCRP has stated in its strategic plan that "the global change research community as a whole would benefit from an increased and more systematic dialogue" and that "USGCRP will play an important role in facilitating this dialogue" (USGCRP, 2012).

Meeting overload is always a concern and that makes it important that the Forum be seen as exciting and attractive. However, it is not expected that every modeler be at the proposed Forum. Instead the emphasis would be on transferring information between modeling communities and interacting with user communities. Representatives of each major modeling group should attend all the meetings, and many more modelers should be encouraged to attend through their interest in discussion of intercomparison projects and various changing themes. One potentially unique attraction of this meeting would be users giving more substantial talks about their experiences and issues with using climate model output and how closely existing simulations meet their needs. This thread could lead to the Forum being a nexus for modelers to interact with the National Climate Assessment, depending on how that evolves.

Common Software Infrastructure

Chapter 10 advocated that a national computing and data infrastructure be a major component of a national strategy for climate modeling; here we discuss some of its institutional benefits and challenges. One of the weaknesses identified in the current U.S. structure is that efforts can be subcritical. The distributed U.S. modeling system has some some tendency for multiple institutions to develop modeling capabilities that partly duplicate efforts at other centers. A common software infrastructure can increase returns from existing structures across the U.S. modeling institutions. One goal of such a structure would be to allow the easy exchange and adoption of modeling components. For example, if certain model components are viewed as "relatively mature," or if there is one facility that is acknowledged as premier in developing some component (e.g., sea ice), those could become the de facto standard in the U.S. modeling community. This designation could effectively liberate resources at the other centers to focus on their strengths and address other critical topics, such as simulation of cloud feedbacks, which might benefit more from a diversity of approaches.

The adoption of common software infrastructures has been advocated previously (e.g., Dickinson et al., 2002), and individual modeling centers have since internally adopted such infrastructures to allow a variety of configurations of their modeling system for different applications (see discussion in Chapter 10, including Box 10.2 on ESMF, an infrastructure that was intended for community use by multiple modeling groups). In the process, much has been learned about how best to do this (see also Chapter 2), and it is now worth investing in the adoption of a common approach across all U.S. modeling centers over the next 5-10 years. The committee anticipates that the proposed annual Forum could play a key role as a venue for working strategic discussions on how to make this happen.

To make a common national software infrastructure a reality, there need to be compelling incentives and benefits for all modeling centers to adopt a common approach, beyond facilitation of collaboration and code exchange. As noted in Chapter 10, the committee believes that cross-laboratory intercomparison experiments are a crucial part of the path forward to advancing U.S. climate models and a common national software infrastructure has the potential to facilitate in-depth comparison between models, including interchanging individual model components. Other compelling reasons for evolution to a common software infrastructure include the move toward fundamentally new computer architectures that will need to be adapted to; another could be enhanced opportunities to exploit high-end computing capabilities facilitated by this approach; and a third could be to facilitate data standards that allow users to easily analyze results from different models with a common set of visualization and analysis tools. Decisive cross-agency endorsement of this approach will be needed to allow the climate modeling and software engineering community to collectively design and test the infrastructure and to provide the resources to transition current major models to it. The adoption of such an infrastructure will facilitate interactions among scientists engaged in the full hierarchy of U.S. modeling efforts, thereby leading to their greater unification and coordination and allowing the climate model enterprise to better serve national needs and advance more efficiently.

It is important that this infrastructure should entrain major regional modeling efforts as well as global climate modeling centers, and be adaptable to both research-oriented and operational modeling, to facilitate cross-fertilization between these model types and their developer and user communities.

Computational Capabilities for Climate Modeling

As described in Chapter 10, in order to meet the climate data and information needs of decision makers and users, U.S. climate models will need substantially increased computing capacity in the coming 10-20 years. This capacity will be distributed over a range of models and applications, ranging from pilot simulations for model development to large ensembles of lower-resolution simulations to extremely long paleoclimate simulations to decadal global and regional simulations at the finest grid resolution feasible. Storage and usability of large model data sets will also be key considerations. As discussed below, the committee recommends a two-pronged approach that involves the continued use and upgrading of dedicated computing resources at the existing modeling centers, complemented by an intensive research program on efficient implementation of high-resolution climate models on architectures requiring extreme concurrency (as also called out in Recommendation 10.2). This section also discusses possible pros and cons of a more radical step—establishment of a new national climate-specific computing facility of higher performance that any current U.S. climate modeling institution can afford to maintain.

Existing climate modeling centers typically use computing resources that are largely dedicated to their institution. These resources are a crucial underpinning of the development and use of climate models, because they provide the required degree of flexibility to support fast-turnaround model testing and innovative and risky model development activities, while providing the computing capabilities for institution or agency specific goals (such as simulations in support of assessments). This approach has proven extremely useful in the past, and this mode of operation and support needs to be maintained. These largely dedicated facilities must be maintained and refreshed on an ongoing basis. They represent a substantial national investment. For instance, the Committee estimates that maintaining a computing system of the class of Gaea (dedicated almost exclusively to GFDL climate modeling), or NCAR's Yellowstone system (for which climate modeling is one major priority), is in excess of $30 million per year, including purchase, maintenance, power, human support, and assuming a 3-year replacement time scale.

However, as noted previously, this arrangement of dedicated climate computing assets does not currently provide the critical mass in computing for breakthrough, innovative modeling activities that require the largest possible computational capabilities. Examples of such activities include ultra-high-resolution climate model simulations for the study of regional climates and extremes, the use of eddy-resolving ocean models to study critical ocean issues such as the oceanic uptake of heat and carbon and their feedback on the climate system, and global cloud-resolving modeling to better understand the interaction of atmospheric convection and climate. The machines associated with individual institutions are well suited for their more targeted goals, but not necessarily for such breakthrough calculations. For climate models such as CESM, the most computationally intensive simulations are being performed on the largest supercomputing systems (e.g., as maintained by DOE) that serve a much broader scientific community than climate modeling. This strategy is attractive because it leverages costly external national resources and allows the climate modeling community to experiment with a wider class of computer architectures than it could internally afford to maintain. However, access to these external systems can be unreliable, and they often have operating protocols that are not suited to the very long simulations often needed for climate models. In addition, the external centers often have very different priorities for allocating resources to particular proposed models and simulations than just their importance for furthering climate science. Despite its obvious drawbacks, this is a "resource of opportunity" that the climate modeling community should continue to exploit for extreme-scale computing challenges.

To effectively use both forthcoming climate-dedicated computers and more experimental systems of opportunity, the climate community needs to aggressively invest in research into how to design models that achieve maximum performance from such systems (HECRTF, 2004). This problem is not unique to climate science, but the complexity of climate model codes exacerbates this issue considerably, as noted in Chapter 7. The design challenge is complicated by the diverse landscape of possible architectures, but the basic issue is architecture independent—achieving much higher concurrency in climate model codes than is now realizable through code refactoring, compiler tools, new algorithms, etc. This investment leverages off the proposed national software infrastructure, which would facilitate the transfer of software tools and methodologies developed using one model across to other climate models, allowing the community as a whole to navigate hardware transitions more nimbly.

Should the United States Invest in a National Climate Computing Facility?

The committee debated whether the current combination of institution-specific computing and use of external computer resources of opportunity was the best national strategy for climate computing. In particular, we envisioned a national facility dedicated to climate supercomputing (which we will refer to as the National Climate Computing Facility or NCCF) to enable Grand Challenge calculations that have the potential to provide breakthrough scientific results through simulations at spatial resolutions and/or with representations of processes not previously possible. An NCCF is not intended as a new U.S. climate modeling center; rather, it is envisioned to be a central cutting-edge climate computational resource for pioneering calculations that benefit the entire U.S. climate modeling community and explore the next generation of climate modeling capabilities. In this section, we list some advantages and disadvantages of this approach.

Achieving a large positive impact on climate modeling would require a substantial additional national investment in climate computing of \$100 million per year or more, in addition to the resources needed to follow the committee's other recommendations on software infrastructure and research into optimization of climate codes for extreme-scale computer architectures. Given the current pressures on human resources for model development, on making model output useful to a broad applications community, and on maintaining an adequate climate observing system, a consensus community-based process would be needed for weighing large additional investments in computing against further investments in these other key links of the climate modeling enterprise.

An NCCF must complement institutionally specific computational resources, not replace them. The NCCF would focus on the execution of cutting-edge models that are primarily developed at existing U.S. centers, but on problems exceeding their internal computational capabilities. Some types of simulations appropriate for an NCCF might include

- the study of regional climate change and extreme weather events, including hurricanes, droughts, and floods, using atmospheric models with resolutions down to a few kilometers or less;
- the study of the effects of small-scale processes in the ocean, including mesoscale eddies, on climate variability and change;
- the study of biogeochemical cycles, including the carbon cycle and atmospheric chemical changes, at very high resolution to better represent ecosystem-scale effects and assess their future response to, and feedback on, climate change;
- the study of projected changes in land-based ice sheets and their interaction with the ocean that will influence future sea-level change; and
- the study of the interactions of ecosystems and climate change at very fine regional scales.

These simulations might involve both global and regional modeling components.

The cost of an NCCF would depend on its scope. To be transformational, it would have to offer a several-fold increase in the size or speed of computations that could be performed on institutional machines, and more useful, reliable, and stable access than is likely to be provided by national computing resources not specific to climate modeling. As discussed in federal plans for high-end computing platforms (HECRTF, 2004) and borne out over the past decade, a single leadership system is expensive, and typically costs in excess of $100 million per year to procure and operate.

Advantages of an NCCF

If the U.S. climate modeling community had stable access to such a hardware platform, it would be easier to customize or codesign software infrastructure to maximize efficiency on that hardware. A single high-end facility would allow higher-resolution simulations to happen sooner, and it might speed up the inclusion of more Earth system components and larger ensembles. A single facility would provide a focal point for advancing the computational performance of U.S. climate models, which would have dividends for both scientific advances and the generation of climate information at the near-local scale that users desire. The dedication of such a facility solely to climate modeling might allow easier access to model output data and the development of data analysis tools for both model developers and model output users. The existence of such a single high-end facility could have significant advantages in economies of scale, such that it could be significantly more cost-effective to procure this additional computing resource through a single site rather than in a distributed fashion.

An NCCF would leverage the investment in software infrastructure that has also been advocated in this report. The infrastructure would facilitate the efficient execution of models on the NCCF that were previously developed on different architectures at the various U.S. centers. Further, the existence of this high-end facility would provide incentive for individual modeling institutions to adopt the same software infrastructure.

Risks of an NCCF

A dedicated leadership-class climate computer facility would entail large additional expense and potentially risky choices about architecture and management. In an environment of constrained budgets, an NCCF would compete with institutional centers for computer resources and personnel, further fragmenting the climate modeling community into subcritical units. It might also be vulnerable to year-to-year budgetary instability.

An NCCF would have to make choices about computer architecture that might place additional risks on the climate modeling community, associated with "pioneering" the use of untested computer architecture, programming environments, and performance optimization. These costs would be decreased by using better-tested architectures, but that might also reduce the potential payoff in transformational capabilities.

The management of an NCCF so as to complement the capabilities of other institutional and external computing resources would be an important challenge. Clear community-governed mechanisms would need to be set up to select the models and problems on which the facility focused. There would need to be close communication and feedback between the computational scientists involved with the operations of the facility and the climate scientists guiding the overall mission. Ultimately, the scientific objectives and imperatives of the overall U.S. climate modeling enterprise would need to drive the operational details of any such facility.

Overall, an NCCF would be most attractive and least risky in an environment of sustained budget growth for climate science and modeling, which would allow it to be pursued in parallel with the other critical investments in climate modeling recommended in this report.

Why Not a Single U.S. Climate Modeling Center?

The approaches outlined throughout this report build on the current distributed system for U.S. climate modeling. They attempt to overcome the obstacles associated with a distributed system through frequent communication at U.S. modeling forums and the adoption of a common software infrastructure to support interlinked model development, execution, and analysis. We discussed a National Climate Computing Facility as a possible way to accelerate research into computational frontiers of climate science. Given this approach, a logical question to ask is: Why not simply move toward a single U.S. modeling center that could achieve these benefits under a "single roof," replacing all the current climate modeling centers?

The committee believes such a move is undesirable at this time for several reasons:

- Current modeling institutions have a variety of missions supporting the needs of their sponsoring agencies, including operational prediction and data assimilation. It would be difficult to carry out those differing missions in a single, monolithic new institution without sacrificing the necessary focus.
- There is a recognized benefit to fostering multiple approaches to address critical topics. The downside of this approach is the potential for duplication of efforts, although the other efforts recommended in this report should reduce such duplication, e.g., the efforts to foster communication and the use of common infrastructure.
- It could be hugely disruptive, at least in the near term. Unless there were an extraordinary and sustained national interagency commitment to the process, the new center would not supplant the current centers, and further dilution of effort and resources might ensue.

The committee believes that a more distributed strategy embraces the philosophy of maintaining scientific diversity where appropriate while maximizing computational resource efficiency. This efficiency comes through the evolution to a common infrastructure, and the existence of a distributed computational capability including both institutionally dedicated resources and the NCCF. The hierarchy of models needed for climate modeling (discussed in Chapter 3) is mirrored by the hierarchy of computational capabilities necessary to take full advantage of those models.

Finding 13.5: The committee believes that the potential benefits of a move to a single U.S. climate modeling center are currently outweighed by the risks.

Although it is difficult to objectively assess how many modeling efforts are now optimal in the United States, it is likely that adoption of the strategies recommended by the committee could make U.S. climate modeling efforts more integrated and transparent. These actions should lead to convergence among some modeling components that are most mature, while maintaining diversity and competitive innovation among those key components that have the greatest scientific uncertainty. With U.S. climate modeling efforts more tightly integrated, different centers may begin to collaborate by specializing on different aspects of the climate modeling problem, acting as a distributed network that ultimately is stronger and more robust than an individual climate modeling center could be.

Recommendation 13.1: To promote communication and collaboration across the climate modeling enterprise, annual U.S. climate modeling forums should be organized to bring together scientists from the global and regional modeling efforts across the United States, scientists from other institutions that are involved in model development and analysis, and model users.

Recommendation 13.2: Model intercomparison activities are key to advancing climate models, and one activity at the climate modeling forum should be discussion and planning of carefully designed suites of simulations to compare the behavior of U.S. climate models with each other and with observational benchmarks. Regional climate models are a particularly pressing focus for this activity. Such simulations could take advantage of a shared software infrastructure to facilitate comparisons, including on a component basis.

Recommendation 13.3: In order to advance climate modeling in the United States in the next 10-20 years, the United States should invest in initiatives that enable the climate modeling community to exploit extreme-scale computing capabilities through the development of new and common software architectures that can be shared across modeling centers and thus spur a national effort to push the computational frontiers of climate science.

CHAPTER FOURTEEN

A National Strategy for Advancing Climate Modeling

Over the next few decades, climate models and observed trends in both greenhouse gas emissions and diverse climate indicators suggest that global warming and its myriad consequences will further unfold and may accelerate. The Arctic Ocean will be a new frontier of shipping and undersea exploration as perennial sea ice disappears. The Greenland and Antarctic ice sheets may respond in surprising ways with surprising speed. Regional droughts in desert margins such as the southwestern United States and the Mediterranean may become more frequent, as may intense flooding events. Large-scale ecosystem changes, associated with pests and disease, may become increasingly hard to ignore, and national and international planning for changes in water resources and agricultural strategy may become essential, challenging the capability of some semi-arid countries to adapt. Pressure for climate engineering "solutions" to delay the consequences of warming will come from diverse quarters. To plan for how to mitigate these changes and to adapt to those that are not forestalled, citizens and policy makers across the United States and around the world will increasingly demand the most accurate global and regional-scale climate projections possible.

Over the next two decades, the U.S. climate modeling enterprise will have to evolve substantially to meet national needs and stay internationally competitive. As described throughout the report, a primary driver for this evolution will be the need to work effectively and increasingly closely with a diverse user community, from design of simulations to choice of outputs, tools for their analysis and distribution, and communicating uncertainty. Another important driver will be the changing design of supercomputers. Over the next decade and beyond, individual computer processors or cores are not expected to speed up. Instead, computers will be developed with 10^7-10^9 cores, requiring a level of coding parallelism far larger than at present. Past experience suggests more computing power will lead to better and more useful climate simulations. However, making high-end climate modeling codes work well in this architecture is one Grand Challenge problem, and managing the vast data sets they produce is a second.

The lessons learned from previous reports on how to improve the U.S. climate modeling enterprise (Chapter 2) emphasize the usefulness of practical recommendations. The large number of specific recommendations that the committee has made throughout this report (Box 14.1) represent stepping stones to a larger strategy, one that emphasizes an evolutionary change in U.S. climate modeling institutions away from developing multiple completely independent models toward a collaborative approach in which different groups pursue different niches or methodologies where scientifically justified. The recommendations in this box are not prioritized or weighted. This chapter attempts to summarize these recommendations into a larger strategy, then gives an outlook of the national capability for climate modeling is 10-20 years if this strategy is followed.

ELEMENTS OF A NATIONAL STRATEGY FOR ADVANCING CLIMATE MODELING

The two principles underlying the committee's vision for U.S. climate modeling a decade hence are that

- U.S. climate modeling groups need to work together more closely, while fully engaging the user, academic, and international communities; and
- taking full advantage of exascale computing will be critical to progress on both longstanding and new climate science frontiers.

As a critical step toward more useful climate models, the committee envisions an evolutionary change in U.S. climate modeling institutions away from developing multiple completely independent models toward a collaborative approach. A collaborative approach does not mean only one center of modeling; rather it means that different groups pursue different niches or methodologies where scientifically justified, but within a single common modeling framework. An overarching thread of the committee's vision is to promote unification of the decentralized U.S. climate modeling enterprise—across modeling efforts, across a hierarchy of model types, across modeling communities focused on different space and time scales, and across model developers and model output users.

The committee recommends a national strategy for advancing the climate modeling enterprise in the next two decades, consisting of four main new components and five supporting elements that, while less novel, are equally important (Figure 14.1). The nation should

1. Evolve to a common national software infrastructure that supports a diverse hierarchy of different models for different purposes, and which supports a vigorous research program aimed at improving the performance of climate models on extreme-scale computing architectures (Recommendations 10.1, 10.2, and 3.2);

2. Convene an annual climate modeling forum that promotes tighter coordination and more consistent evaluation of U.S. regional and global models, and helps knit together model development and user communities (Recommendations 13.1 and 13.2);
3. Nurture a unified weather-climate modeling effort that better exploits the synergies between weather forecasting, data assimilation, and climate modeling (Recommendation 11.1); and
4. Develop training, accreditation, and continuing education for "climate interpreters" who will act as a two-way interface between modeling advances and diverse user needs (Recommendation 12.1).

The nation should increase efforts to

5. Sustain the availability of state-of-the-art computing systems for climate modeling (Recommendation 13.3);
6. Continue to contribute to a strong international climate observing system capable of comprehensively characterizing long-term climate trends and climate variability (Recommendation 5.1);
7. Develop a training and reward system that entices the most talented computer and climate scientists into climate model development (Recommendations 7.1 and 7.2);
8. Enhance the national IT infrastructure that supports climate modeling data sharing and distribution (Recommendations 5.3, 10.3, and 10.4); and
9. Pursue advances in climate science and uncertainty research (Recommendations 4.1, 4.2, 4.3, 4.4, and 6.1).

If adopted, this strategy provides a path for the United States to move forward into the next generation of climate models to provide the best possible climate information for the nation.

VISION FOR U.S. CLIMATE MODEL CAPABILITIES IN 10-20 YEARS

Our national strategy positions the U.S. climate community to fully exploit likely advances in computing, allowing our global climate models to be routinely run at 5-10 km resolution in 10 years and 1-5 km resolution within 20 years. Key processes that are currently parameterized (e.g., ocean eddies and atmospheric cumulus cloud systems, including hurricanes) will be explicitly simulated. Mountain ranges and coastlines will be much better represented. The higher grid resolution will allow improved fidelity of all aspects of climate simulation—clouds, precipitation, upper-ocean structure, extreme weather events, etc.

BOX 14.1 SPECIFIC RECOMMENDATIONS FROM THIS REPORT

Recommendation 3.1: To address the increasing breadth of issues in climate science, the climate modeling community should vigorously pursue a full spectrum of models and evaluation approaches, including further systematic comparisons of the value added by various downscaling approaches as the resolution of climate model increases.

Recommendation 3.2: To support a national linked hierarchy of models, the United States should nurture a common modeling infrastructure and a shared model development process, allowing modeling groups to efficiently share advances while preserving scientific freedom and creativity by fostering model diversity where needed.

Recommendation 4.1: As a general guideline, priority should be given to climate modeling activities that have a strong focus on problems that intersect the space where (i) addressing societal needs requires guidance from climate models and (ii) progress is likely, given adequate resources. This does not preclude climate modeling activity focused on basic research questions or "hard problems," where progress may be difficult (e.g., decadal forecasts) but is intended to allocate efforts strategically.

Recommendation 4.2: Within the realm where progress is likely, the climate modeling community should continue to work intensively on a broad spectrum of climate problems, in particular on longstanding challenges such as climate sensitivity and cloud feedbacks that affect most aspects of climate change (regional hydrologic changes, extremes, sea-level rise, etc.) and require continued or intensified support. Progress can be expected as resolution, physical parameterizations, observational constraints, and modeling strategies improve.

Recommendation 4.3: More effort should be put toward coordinated global and regional climate modeling activities to allow good representation of land-surface hydrology and terrestrial vegetation dynamics and to enable improved modeling of the hydrologic cycle and regional water resources, agriculture, and drought forecasts. This will require better integration of the various national climate modeling activities, including groups that focus on models of surface hydrology and vegetation dynamics. The annual climate modeling forum discussed in Chapter 13 might provide a good vehicle for a working group with this focus.

Recommendation 4.4: At least one national modeling effort in the next decade should aim to simulate historical and future climate change (i.e., the period 1900-2100) at a resolution of less than 5 km, to enable eddy-resolving models of ocean dynamics and more realistic representation of cumulus convection and land-surface exchanges with the atmosphere. Parallel efforts need to aim for century-scale global atmospheric simulations at 1-2 km, to enable cloud-resolving physics. These national efforts would be facilitated by advances in climate model software infrastructure and computing capability discussed in Chapter 10.

Recommendation 5.1: The committee reiterates the statements of previous reports that call on the United States to continue and to augment the support for Earth observations and to address the potential for serious gaps in the space-based observation system. A particular priority should

BOX 14-1 CONTINUED

be maintaining fundamental climate-quality observational data sets that have been gathered for 20 years or longer.

Recommendation 5.2: To better synthesize the diversity of climate-relevant observations, the United States should establish a national Earth system data assimilation effort that builds from existing efforts and merges weather observations, satellite radiances or retrievals for precipitation and various trace constituents, ocean measurements, and land and other observations into the same Earth system model simultaneously.

Recommendation 5.3: Building from existing efforts, the United States should develop a national IT infrastructure for Earth system data, so as to facilitate and accelerate data display, visualization, and analysis.

Recommendation 6.1: Uncertainty is a significant aspect of climate modeling and should be properly addressed by the climate modeling community. To facilitate this, the United States should more vigorously support research on uncertainty, including

- understanding and quantifying uncertainty in the projection of future climate change, including how best to use the current observational record across all time scales;
- incorporating uncertainty characterization and quantification more fully in the climate modeling process;
- communicating uncertainty to both users of climate model output and decision makers; and
- developing deeper understanding on the relationship between uncertainty and decision making so that climate modeling efforts and characterization of uncertainty are better brought in line with the true needs for decision making.

Recommendation 7.1: The United States should attempt to entrain top students into choosing climate model development as a career by providing more graduate and postgraduate training opportunities, enhanced professional recognition and career advancement for participation in climate model development projects, and adequate incentives to attract software engineers who could also choose private-sector careers.

Recommendation 7.2: In order to assess future needs on the climate model development workforce, the United States should obtain quantitative information about the workforce needs and required expertise base to support climate modeling.

Recommendation 8.1: To advance in the next 10-20 years, U.S. climate modeling efforts should continue to strive for a suitable balance among and support for

- the application of current generation models to support climate research activities, as well as national and international projects such as CMIP/IPCC;
- near-term development activities that lead to incremental but meaningful improvements in models and their predictions; and
- the investment of resources to conduct and capitalize on long-lead-time research that

BOX 14-1 CONTINUED

offers the potential for more fundamental and transformational advances in climate modeling.

Recommendation 8.2: The United States should continue to support the participation of U.S. scientists and institutions in international activities, such as model intercomparisons, including support for systems to archive model output, because such activities have proven effective in robustly addressing user needs for climate information and for advancing U.S. climate models.

Recommendation 8.3: To enhance their robustness, national and regional climate change/adaptation assessments should incorporate projections from leading international climate models as well as those developed in the United States.

Recommendation 9.1: To better address user needs for short-range climate predictions, the U.S. and international modeling communities should continue to push toward a stronger operational component for prediction of seasonal climate and regular experimental simulation of climate change and variability on decadal time scales.

Recommendation 10.1: To promote collaboration and adapt to a rapidly evolving computational environment, the U.S. climate modeling community should work together to establish a common software infrastructure designed to facilitate componentwise interoperability and data exchange across the full hierarchy of global and regional models and model types in the United States.

Recommendation 10.2: In order to address the climate data needs of decision makers and other users, the United States should invest in more research aimed at improving the performance of climate models on the highly concurrent computer architectures expected in the next 10-20 years, and should sustain the availability of state-of-the-art computing systems for climate modeling.

Recommendation 10.3: The United States should support transformational research to bring analysis to data rather than the other way around in order to make the projected data volumes useful.

Recommendation 10.4: The data-sharing infrastructure for supporting international and national model intercomparisons and other simulations of broad interest—including archiving and distributing model outputs to the research and user communities—is essential for the U.S.

BOX 14-1 CONTINUED

climate modeling enterprise and should be supported as an operational backbone for climate research and serving the user community.

Recommendation 11.1: To fully exploit a multiscale approach to model advancement, the United States should nurture a unified weather-climate prediction system capable of state-of-the-art forecasts from days to decades, climate-quality data assimilation, and Earth system reanalysis.

Recommendation 11.2: To reduce sources of uncertainty in climate simulations, the United States should pursue a coordinated research effort to use weather and/or seasonal/interannual hindcast simulations to systematically constrain uncertain parameters and to improve parameterizations in its major climate models.

Recommendation 12.1: To promote the effective application of climate models, the United States should develop climate interpretation certification and continuing education programs to train a cadre of climate interpreters who can facilitate the interpretation of climate model output into usable information for a variety of decision makers and communicate user needs to climate modelers.

Recommendation 13.1: To promote communication and collaboration across the climate modeling enterprise, annual U.S. climate modeling forums should be organized to bring together scientists from the global and regional modeling efforts across the United States, scientists from other institutions that are involved in model development and analysis, and model users.

Recommendation 13.2: Model intercomparison activities are key to advancing climate models and one activity at the climate modeling forum should be discussion and planning of carefully designed suites of simulations to compare the behavior of U.S. climate models with each other and with observational benchmarks. Regional climate models are a particularly pressing focus for this activity. Such simulations could take advantage of a shared software infrastructure to facilitate comparisons, including on a component basis.

Recommendation 13.3: In order to advance climate modeling in the United States in the next 10-20 years, the United States should invest in initiatives that enable the climate modeling community to exploit extreme-scale computing capabilities through the development of new and common software architectures that can be shared across modeling centers and thus spur a national effort to push the computational frontiers of climate science.

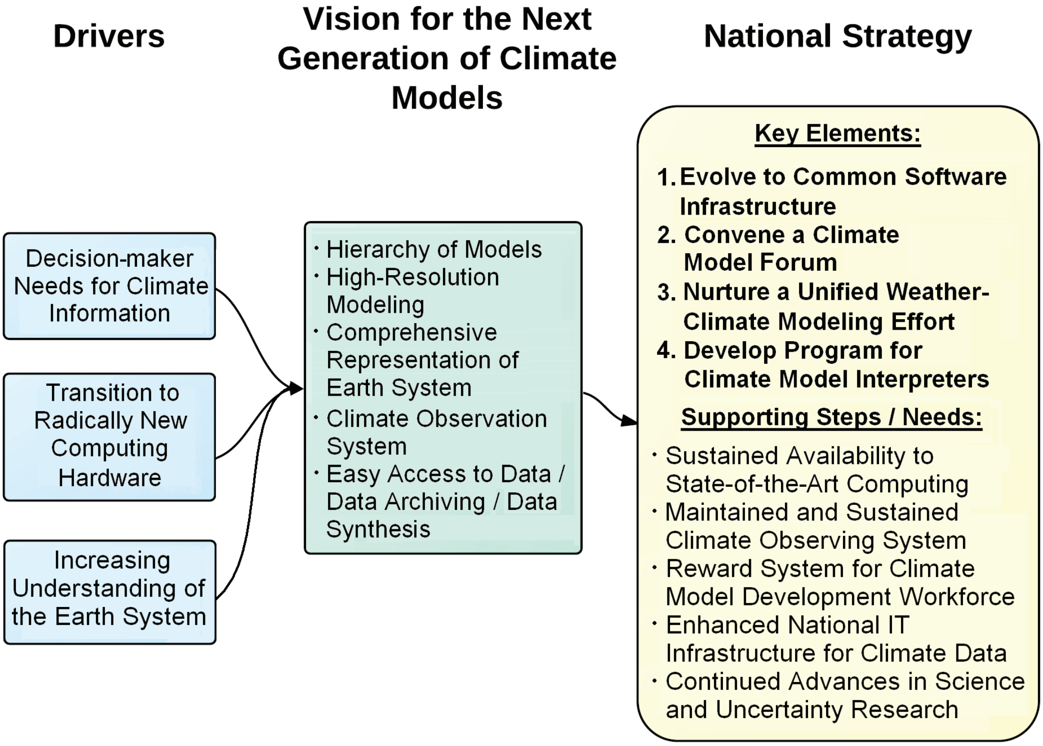

FIGURE 14.1 Driven by the growing need for climate information, the committee envisions a new generation of climate models that can address a wide spectrum of climate information needs. To achieve this vision and in preparation for the coming transition to radically new computing hardware, the committee recommends a national strategy consisting of four key unifying elements and several other recommendations.

In 10-20 years, our global climate models will simulate more ramifications of climate change and variability, such as much more sophisticated modeling of ice sheets and ice margins, and biological responses to climate change in land and ocean. Models of human-climate interaction will be much more sophisticated, better tested, and widely used. A well-documented, nationally organized hierarchy of models will be used for research ranging across many space and time scales and turn our diversity of modeling efforts into a more powerful strength. Different modeling groups around the country will specialize in different aspects of the hierarchy or in taking diverse approaches to modeling issues with large scientific uncertainty while sharing both data output standards and, where appropriate, model components. In this collaborative paradigm, model improvements will rapidly propagate across and between U.S. modeling communities.

The grid of some global climate models will nearly reach the local scales at which many users need climate information; interpolation or other simple statistical methods will suffice for many such needs. Climate interpreters using advanced software tools will quickly access and analyze the large, comprehensive, but readily available model data sets to generate needed local-scale information and digest it for end users. Regional climate modeling will still have a place in allowing interactive simulation of additional processes not included in the global model because they require even finer spatial resolution (e.g., ice-sheet calving, estuarine ecosystems) or because they do not feed back substantially on climate (e.g., projection of coastal ecosystems or the climatically viable range of an endangered species or pest).

The United States will have an organized process for climate model users and stakeholders to help design new climate model simulations and suggest new directions in climate modeling, centered on a U.S. climate modeling forum. It will also continue to be a strong supporter of a broad-based international effort in climate modeling and the sustained observations that are required both to document climate change and skillfully add new processes into the models.

In the United States, research and operational weather, regional climate, and global climate modeling will be done within a common software infrastructure with a set of dynamical cores and physical parameterizations that work across a broad range of scales. Within a decade, the international climate modeling community will understand whether useful prediction of "decadal" climate variability on time scales of 2-10 years is scientifically viable; if it is, the United States will be a major player in the context of an international collaborative effort.

Climate projection uncertainty will remain a big issue. The most important driver of local climate change is global climate change. Uncertainty in projecting local climate change and variability cannot be greatly reduced without reducing uncertainty about the overall rate of global-mean temperature increase. Faster global temperature increase would cause sea ice and ice sheets to melt faster and sea level to rise more and would amplify regional and local precipitation trends due to the changing global hydrologic cycle. Projecting global climate change on multidecadal and longer time scales convolves uncertainties in climate sensitivity and in emissions. The past four decades of climate modeling suggest that both of these uncertainties will remain substantial even 20 years hence. There is hope that climate sensitivity may become somewhat better constrained in the next decade or two by the continuing observational record (if the global climate-observing system is adequately maintained and advanced), if not by reduced modeling uncertainty. Uncertainty in projection of regional precipitation trends will also remain substantial; we envision gradual progress over the next decade or two as the diverse sources of this uncertainty are all incrementally reduced through model improvements and a longer, higher-quality observational record. A 50 percent reduction in model-related uncertainty in climate sensitivity or precipitation response to a given greenhouse gas change over the next 10-20 years would be an optimistic hope.

Climate is complex, multiscale, and multifaceted. Even with the strategic plan we envision, overall improvements in climate models will likely be gradual, not revolutionary. Nevertheless, they can have huge economic value to the nation, because climate change affects everyone and should be a factor in a myriad of planning decisions around the country.

FINAL COMMENTS

Climate models are among the most sophisticated simulation tools developed by mankind, and the "what-if" questions we are asking of them involve a mind-boggling number of connected systems. As the scope of climate models has expanded, so has the need to validate and improve them. Enormous progress has been made in the past several decades in improving the utility and robustness of climate models, but more is needed to meet the growing needs of decision makers who are increasingly relying on the information from climate models.

The committee believes that the best path forward is a strategy centered around the integration of the decentralized U.S. climate modeling enterprise—across modeling efforts, across a hierarchy of model types, across modeling communities focused on different space and time scales, and between model developers and model output users. A diversity of approaches is necessary for progress in many areas of climate modeling and vital for addressing the breadth of users needs. If adopted, this strategy of increased unification amidst diversity will allow the United States to more effectively and efficiently utilize that diversity to meet the climate information needs of the nation in the coming decades and beyond.

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Appendixes

APPENDIX A

Statement of Task

Climate models are the foundation for understanding and projecting climate and climate-related changes and are thus critical tools for supporting climate-related decision making. This study will develop a strategy for improving the nation's capability to accurately simulate climate and related Earth system changes on decadal to centennial time scales. The committee's report is envisioned as a high-level analysis, providing a strategic framework to guide progress in the nation's climate modeling enterprise over the next 10-20 years. Specifically, the committee will

1. Engage key stakeholders in a discussion of the status and future of climate modeling in the United States over the next decade and beyond, with an emphasis on decade to century time scales and local to global resolution. This discussion should include both the modeling and user communities, broadly defined, and should focus on the strengths and challenges of current modeling approaches, including their usefulness to decision making, the observations and research activities needed to support model development and validation, and potential new directions in all of these spheres.
2. Describe the existing landscape of domestic and international climate modeling efforts, including approaches being used in research and operational settings, new approaches being planned or discussed, and the relative strengths and challenges of the various approaches, with an emphasis on models with decade to century time scales and local to global resolution.
3. Discuss, in broad terms, the observational, basic and applied research, infrastructure, and other requirements of current and possible future climate modeling efforts, and develop a strategic approach for identifying the priority observations, research, and decision-support activities that would lead to the greatest improvements in our understanding and ability to monitor, model, and respond to climate change on local to global space scales and decade to century time scales.
4. Provide conclusions and/or recommendations for developing a comprehensive and integrated national strategy for climate modeling over the next decade (i.e., 2011-2020) and beyond. This advice should include discussion of different modeling approaches (including the relationship between decadal to centennial-scale modeling with modeling activities at other time scales); priority observations, research activities, and infrastructure for supporting model

development; and how all of these efforts can be made most useful for decision making in this decade and beyond.

Examples of the types of strategic questions to be addressed include: What is the appropriate balance between improving resolution and adding complexity as computing power improves? What are the advantages and disadvantages of different approaches to projecting regional climate change (e.g., embedded regional models, statistical downscaling, etc.)? What are the benefits and tradeoffs associated with multimodel versus unified modeling frameworks? What opportunities might exist to develop better interfaces and integration between Earth system models and models of human systems? What observations and process studies are needed to initialize climate predictions on both regional and global scales, advance our understanding of relevant physical processes and mechanisms, and validate model results? What critical infrastructure constraints, including high-performance computing and personnel issues, currently limit model development and use? What steps can be taken to improve the communication of climate model results (e.g., presentation of uncertainties) and ensure that the climate modeling enterprise remains relevant to decision making? What modeling approaches and activities are likely to provide the most value for the investments required?

APPENDIX B

Community Input

In addition to reviewing relevant literature and using its expert judgment to write this report, the committee was responsible for providing opportunities for input from a full range of relevant stakeholders. This was facilitated through five open session meetings held in various cities around the United States (Washington, DC; Seattle, Washington; Irvine, California; and Boulder, Colorado), a series of interviews, and a climate modeling questionnaire. The open session meetings included one community workshop held in April 2011 in Boulder, Colorado, and involved a wide range of stakeholders from labs, agencies, academic institutions, international organizations, and the broad user community. All workshop participants were also asked to answer a three-question questionnaire to share their thoughts about the current climate modeling landscape and ideas for a future strategy. The following individuals participated in at least one of the committee's open session meetings and provided valuable input:

D. James Baker, William J. Clinton Foundation
Anjuli Bamzai, NSF
Pete Beckman, ANL
David Behar, San Francisco Public Utilities Commission
Cecilia Bitz, University of Washington
Andy Brown, UK Met Office
Frank Bryan, NCAR
Bill Collins, University of California, Berkeley
David Considine, NASA
Ted Cope, NGA
David Dewitt, Columbia University
Scott Doney, Woods Hole Oceanographic Institution
Steve Easterbrook, University of Toronto
Dave Easterling, NOAA
Paul Edwards, University of Michigan
Jack Fellows, NCAR
Baruch Fischhoff, Carnegie Mellon University
Joe Friday, University of Oklahoma (Professor Emeritus)
Gregg Garfin, University of Arizona
Gary Geernaert, DOE
Peter Gent, NCAR

Jin Huang, NOAA
Kathy Jacobs, OSTP
Laurna Kaatz, Denver Water
Jill Karsten, NSF
Jeremy Kepner, Massachusetts Institute of Technology
Jeff Kiehl, NCAR
Tim Killeen, NSF
Ben Kirtman, University of Miami
Chet Koblinsky, NOAA
Arun Kumar, NOAA
Bryan Lawrence, British Atmospheric Data Centre
Stu Levenbach, OMB
S.J. Lin, NOAA
Rich Loft, NCAR
Steve Lord, NOAA
Johannes Loschnigg, OSTP
Jim McWilliams, University of California, Los Angeles
Jerry Meehl, NCAR
Phil Mote, Oregon State University
Tim Palmer, European Centre for Medium-Range Weather Forecasts
Bill Putman, NASA
Erik Pytlak, Bonneville Power Administration
V. Ramaswamy, GFDL
David Randall, Colorado State University
Michele Rienecker, NASA
Todd Ringler, LANL
Rick Rosen, NOAA
Jagadish Shukla, George Mason University
Graeme Stephens, Colorado State University
Karl Taylor, Lawrence Livermore National Lab
Claudia Tebaldi, Climate Central
Rear Admiral David Titley, Navy
Kevin Trenberth, NCAR
Louis Uccellini, National Centers for Environmental Prediction
Andrew Weaver, University of Victoria
Mike Wehner, Lawrence Berkeley National Laboratory

As described in Chapter 2, there have been a number of previous reports from the National Research Council and other organizations that have recommended activities to improve climate modeling in the United States. To inform the committee on ideas of what impacted the effectiveness of these previous reports, interviews were conducted with 11 individuals (listed below) who either held positions where they could use report recommendations to bolster policy decisions, or were in positions directly impacted by actions taken as a result of the report findings. These interviews were conducted by three researchers who have experience with climate-related research and have conducted interviews previously, but who had no affiliation with the current or previous reports. The interviewees were asked about their experiences and opinions on previous NRC reports, about their thoughts on important aspects of a national strategy for advancing climate modeling, and about their opinions on previous community efforts related to software infrastructure. No individual comments are attributed to the interviewees, but rather the information from these interviews was used to draw out general lessons, which are described in Chapter 2.

Interviewees
David Bader, Lawrence Livermore National Laboratory
D. James Baker, William J. Clinton Foundation
Rosina Bierbaum, University of Michigan
Guy Brasseur, Climate Service Center (Germany)
Paul Edwards, University of Michigan
David Evans, Noblis
Robert Ferraro, NASA
James Fischer, NASA
Timothy Killeen, National Science Foundation
David Randall, Colorado State University
Mariana Vertenstein, NCAR

Interviewers
Dr. Steve Easterbrook, University of Toronto
Dr. Christine Kirchhoff, University of Michigan
Dr. Jessica O'Reilly, St. John's University

APPENDIX C

Biographical Sketches of Committee Members

Dr. Chris Bretherton (Chair), University of Washington

Chris Bretherton is currently a professor in the University of Washington Departments of Atmospheric Science and Applied Mathematics. His research focuses on the interactions of atmospheric turbulence and convection, clouds and climate, and includes observational analyses, cloud-scale modeling, and climate model development. He teaches classes on weather, atmospheric turbulence and cumulus convection, tropical meteorology, geophysical fluid dynamics, and numerical and analytical methods for solving ordinary and partial differential equations. Dr. Bretherton is a lead author of the Intergovernmental Panel on Climate Change Fifth Assessment Report, leader of the CGILS international cloud feedbacks model intercomparison project, and a former director of the University of Washington Program on Climate Change. His research group developed the parameterizations of shallow cumulus convection used in the newest versions of two leading U.S. climate models, the National Center for Atmospheric Research Community Atmosphere Model, version 5 (CAM5), and the Geophysical Fluid Dynamics Laboratory (GFDL) Atmosphere Model, version 3 (AM3), as well as the turbulence parameterization used in CAM5, and is currently working with the National Centers for Environmental Prediction to improve the representation of boundary-layer clouds in the U.S. operational global weather and seasonal climate forecast models.

Dr. Venkatramani Balaji, Princeton University

V. Balaji heads the Modeling Systems Group serving developers of Earth system models at GFDL and Princeton University. With a background in physics and climate science, he has become an expert in the area of parallel computing and scientific infrastructure, providing high-level programming interfaces for expressing parallelism in scientific algorithms. He has pioneered the use of frameworks (such as the Flexible Modeling System [FMS], as well as community standards such as Earth System Modeling Framework [ESMF] and PRISM) allowing the construction of climate models out of independently developed components sharing a technical architecture; and of curators (FMS Runtime Environment, FRE) for the execution of complex workflows to manage the complete climate modeling process. The Earth System Curator (U.S.) and Metafor (EU) projects, in which he plays a key role, have developed the use of a common information model, which allows the execution of complex scientific queries on model data archives. V. Balaji plays advisory roles on National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), and Department of Energy (DOE) review panels, including the recent series of exascale workshops. He is a sought-after speaker and lecturer and is committed to provide training in the use of climate models in developing nations, leading workshops to advanced students and researchers in South Africa and India.

Dr. Thomas L. Delworth, Geophysical Fluid Dynamics Laboratory

Thomas L. Delworth is a research scientist and Group Leader in the Climate Change, Variability and Prediction Group at NOAA's GFDL. He is also a lecturer at Princeton University in the Atmospheric and Oceanic Sciences Program. Dr. Delworth has played a key role in the development of several generations of climate models at GFDL. His research largely focuses on decadal to centennial climate variability and change through the synthesis of climate models and observational data. On these time scales the behavior of the climate system is a mixture of natural variability and the response of the climate system to changing radiative forcing induced by changing greenhouse gases and aerosols. Understanding the natural variability of the climate system on decadal scales is critical to our ability to detect climate change, and to understand the processes responsible for observed change from the global to the regional scale.

Dr. Robert E. Dickinson, The University of Texas at Austin

Robert E. Dickinson joined the Department of Geological Sciences in August of 2008. For the previous 9 years, he was professor of atmospheric sciences and held the Georgia Power/Georgia Research Alliance Chair at the Georgia Institute of Technology, the 9 years before that he was professor of atmospheric sciences and Regents Professor at the University of Arizona, and for the previous 22 years he was a Senior Scientist at the National Center for Atmospheric Research. He was elected to the National Academy of Sciences in 1988 and to the National Academy of Engineering in 2002, and was elected a foreign member of the Chinese Academy of Sciences in 2006. His research interests are in climate modeling, climate variability and change, aerosols, the hydrologic cycle and droughts, land-surface processes, the terrestrial carbon cycle, and the application of remote sensing data to modeling of land-surface processes.

Dr. James A. Edmonds, Joint Global Change Research Institute

Jae Edmonds is a Chief Scientist and Laboratory Fellow at the Pacific Northwest National Laboratory's Joint Global Change Research Institute, a collaboration with the University of Maryland at College Park. His research in the areas of long-term, global, energy, technology, economy, and climate change spans three decades, producing several books, numerous scientific papers, and countless presentations. He is one of the pioneers in the field of integrated assessment modeling of climate change. His principal research focus is the role of energy technology in addressing climate change. He is the Chief Scientist for the Integrated Assessment Research Program in the Office of Science at the U.S. Department of Energy. He has been an active participant in all of the major assessments of the Intergovernmental Panel on Climate Change.

Dr. James S. Famiglietti, University of California, Irvine

James S. Famiglietti holds a joint faculty appointment in Earth System Science and in Civil and Environmental Engineering at the University of California, Irvine (UCI), where he is the founding director of the system-wide UC Center for Hydrologic Modeling. He holds a B.S. in geology from Tufts University, an M.S. in hydrology from the University of Arizona, and an M.A. and a Ph.D. in civil engineering and operations research from Princeton University. He completed his postdoctoral studies in hydrology and climate system modeling at Princeton and at the National Center for Atmospheric Research. Before joining the faculty at UCI in 2001, Dr. Famiglietti was an assistant and associate professor in the Department of Geological Sciences at the University of Texas at Austin, and was the Associate Director of the UT Environmental Science Institute. He is the past Chair of the Board of the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI), and past Editor in Chief of *Geophysical Research Letters*. His research concerns the role of hydrology in the coupled Earth system. Areas of activity include the continued development of the hydrologic components of climate models; climate system modeling for studies of land-ocean-atmosphere-human interaction; and remote sensing of the terrestrial and global water cycles, including groundwater depletion and freshwater availability. Dr. Famiglietti is currently leading the Community Hydrologic Modeling Platform (CHyMP) effort to accelerate the development of hydrologic models for use in addressing national and international priorities related to water, food, economic, climate, and national security.

Dr. Inez Y. Fung, University of California, Berkeley

Inez Fung is a professor in the Department of Earth and Planetary Science and the Department of Environmental Science, Policy and Management at the University of California, Berkeley. She has been studying climate change for the past 20 years. She is a principal architect of large-scale mathematical modeling approaches and numerical models to represent the geographic and temporal variations of sources and sinks of CO_2, dust, and other trace substances around the globe. Dr. Fung's work in carbon-climate modeling concludes that the diminishing capacities of the land and oceans to store carbon act to accelerate global warming. She has initiated a new project to assimilate raw meteorological data and satellite CO_2 observations into a climate model to produce the best estimation of the four-dimensional distribution of CO_2 in the atmosphere. Dr. Fung received her S.B. in applied mathematics and her Sc.D. in meteorology from the Massachusetts Institute of Technology. She joined the Berkeley faculty in 1998 as the first Richard and Rhoda Goldman Distinguished Professor in the Physical Sciences and the founding Director of the Berkeley Atmospheric Sciences Center.

Dr. James J. Hack, Oak Ridge National Laboratory

James J. Hack directs the National Center for Computational Sciences (NCCS), a leadership computing facility at Oak Ridge National Laboratory supporting transformational science. He identifies major high-performance computing needs from scientific and hardware perspectives and puts forth strategies to meet those needs as machines evolve to the petascale, able to carry out a quadrillion calculations per second. An atmospheric scientist, Dr. Hack also leads ORNL's Climate Change Initiative. Dr. Hack became a research staff member at the IBM Thomas J. Watson Research Center, where he worked on the design and evaluation of high-performance computing architectures. In 1984 he moved to the National Center for Atmospheric Research, a National Science Foundation-sponsored center, where his roles included Senior Scientist, head of the Climate Modeling Section, and Deputy Director of the Climate and Global Dynamics Division. He was one of the principal developers of the climate model that ran on NCCS supercomputers to provide more than one-third of the simulation data jointly contributed by the Department of Energy and the National Science Foundation to the most recent assessment report of the United Nations' Intergovernmental Panel on Climate Change, the group that shared the 2007 Nobel Peace Prize with Al Gore.

Dr. James W. Hurrell, National Center for Atmospheric Research

James (Jim) W. Hurrell is the Director of the Earth System Laboratory at the National Center for Atmospheric Research (NCAR). NCAR is a federally funded research and development center that works with partners at universities and researchers to explore and understand the atmosphere and its interactions with the sun, the oceans, the biosphere, and human society. Dr. Hurrell joined NCAR after earning his doctorate in atmospheric science from Purdue University. His research has centered on empirical and modeling studies and diagnostic analyses to better understand climate, climate variability, and climate change. He has been involved in assessment activities of the Intergovernmental Panel on Climate Change and the U.S. Global Change Research Program. Dr. Hurrell has been extensively involved in the World Climate Research Programme (WCRP) on Climate Variability and Predictability (CLIVAR), including roles as cochair of the Scientific Steering Group (SSG) of both U.S. and international CLIVAR and membership on several other CLIVAR panels. His former roles at NCAR include service as Director of the Climate and Global Dynamics Division and Chief Scientist of the Community Earth System Model (CESM). He has given testimony on climate change issues for congressional subcommittees and has received numerous prestigious honors and awards in his field of atmospheric science.

Dr. Daniel J. Jacob, Harvard University

Daniel J. Jacob is a professor of atmospheric chemistry and environmental engineering at Harvard University. The goal of his research is to understand the chemical composition of the atmosphere, its perturbation by human activity, and the implications for climate change and life on Earth. His approaches include global modeling of atmospheric chemistry and climate, aircraft measurement campaigns, satellite data retrievals, and analyses of atmospheric observations.

Dr. James L. Kinter III, Center for Ocean-Land-Atmosphere Studies

James (Jim) L. Kinter is Director of the Center for Ocean-Land-Atmosphere Studies (COLA), where he manages all aspects of basic and applied climate research conducted by the Center. Dr. Kinter's research includes studies of climate predictability on seasonal and longer time scales. Of particular interest in his research are prospects for prediction of El Niño and the extratropical response to tropical sea-surface temperature anomalies using high-resolution coupled general circulation models of Earth's atmosphere, oceans, and land surface. Dr. Kinter is also an associate professor in the

Climate Dynamics Ph.D. Program and the Atmospheric, Oceanic and Earth Sciences department at George Mason University, where he has responsibilities for curriculum development and teaching undergraduate and graduate courses on climate change, as well as advising Ph.D. students. After earning his doctorate in geophysical fluid dynamics at Princeton University in 1984, Dr. Kinter served as a National Research Council Associate at NASA Goddard Space Flight Center, and as a faculty member of the University of Maryland prior to joining COLA. Dr. Kinter has served on many national review panels for both scientific research programs and supercomputing programs for computational climate modeling.

Dr. L. Ruby Leung, Pacific Northwest National Laboratory

L. Ruby Leung is a Laboratory Fellow at the Pacific Northwest National Laboratory. Her research focuses on understanding and modeling regional climate including the role of land-atmosphere interactions, orographic processes, and aerosol effects on water-cycle variability and extremes. She has led important efforts in defining research priorities and needs in regional climate modeling and coordinated community efforts to develop capability in community mesoscale models to simulate regional climate. Currently she is leading a team project to apply a hierarchical evaluation framework to evaluate different approaches to modeling climate at the regional scale.

Dr. Shawn Marshall, University of Calgary

Shawn Marshall joined University of Calgary’s Department of Geography in January 2000, following Ph.D. and postdoctoral research at the University of British Columbia (UBC). He is a glaciologist and climatologist with research programs that focus on glacier and ice-sheet dynamics, ice-climate interactions, and paleoclimatology. He is active in ice-sheet model development and in efforts to couple ice sheet and climate models, and also works extensively as a “user” of climate model output to drive scenarios for cryosphere response to climate change. He has served as Director of the Arctic Institute of North America, as Chair of the American Geophysical Union Cryospheric Sciences group, and on the Science Steering Committees of the Canadian Arctic research agency (Polar Continental Shelf Project) and the NCAR Community Earth System Model enterprise.

Dr. Wieslaw Maslowski, U.S. Naval Postgraduate School

Wieslaw Maslowski is a research professor of oceanography at the Naval Postgraduate School in Monterey, California. Dr. Maslowski's research interests include polar oceanography and sea ice; regional ocean, sea-ice, and climate modeling and prediction; mesoscale processes in the ocean and sea ice and their interaction with and impact on general ocean circulation, climate change, and climate variability; ocean-ice sheet and air-sea-ice interactions and feedbacks. He is currently leading a DOE-supported research program to develop a Regional Arctic System Model (RASM). Dr. Maslowski earned his Ph.D. from the University of Alaska in 1994.

Dr. Linda O. Mearns, National Center for Atmospheric Research

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