U.S. DEPARTMENT OF ENERGY | Office of Science

SCIENCE CHALLENGES AND FUTURE DIRECTIONS:

Climate Change Integrated Assessment Research

Report from the U.S. Department of Energy
Office of Science
Office of Biological and Environmental Research
Workshop on Integrated Assessment, November 2008

JUNE 2009

COVER: Climate change impacts have been linked to ecological and agricultural shifts, public health and economic consequences, energy security, and even national security. The field of climate research known as **integrated assessment** combines human systems such as energy, the economy, and land management with knowledge drawn from other fields such as atmospheric science and hydrology. The result: new insights for decision makers who must meet energy demands, manage natural resources, and set policy.

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PREFACE

This report represents the discussions and findings of a major workshop conducted in Arlington, Virginia, in November 2008, to identify the future research needs in the field of climate change integrated assessment (IA). This report and the November workshop represent the synthesis of supporting, focused workshops; meetings; white papers; and other venues for critical thinking that were sponsored over the past two years by the Department of Energy's (DOE's) Office of Biological and Environmental Research, Integrated Assessment Research Program. The result is no less than a blueprint of ideas that could transform IA.

The effort reflects the contributions of many people involved in DOE's IA Research Program, the broader IA research community, and scientists and managers in other disciplines, programs, and agencies. It is the culmination of a process of scientific consultation, interagency coordination, and judgments by the scientists about the greatest challenges facing the IA research and modeling communities and how those challenges might be faced.

The challenges are both varied and important. The interaction of human decisions and the evolution of the entire Earth system—decisions about mitigating greenhouse gas emissions, about coping with changes that cannot be avoided, and about the potential influence of investments in science and technologies—has risen to the forefront of climate science. This is the intellectual territory that IA models were originally designed to explore, and now it is the territory of more than academic interest.

Today's decisions will matter greatly to the future course of the environment and human well being. Our hope is that by addressing the challenges outlined in this report, the IA research community can play an increasingly important role in understanding their scientific foundations.

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Acronyms and Abbreviations

CCS	carbon dioxide capture and storage
CCSP	Climate Change Science Program
CFCs	chlorofluorocarbons
CH_4	methane
CO_2	carbon dioxide
DOE	U.S. Department of Energy
ESM	Earth system model
GCM	general circulation model
GHG	greenhouse gas
HFCs	hydrofluorocarbons
IA	integrated assessment
IAM	integrated assessment model
IAV	impacts, adaptation, and vulnerability
IGBP	International Geosphere-Biosphere Program
IGSM	integrated global system model
IPCC	Intergovernmental Panel on Climate Change
MERGE	Model for Evaluating Regional and Global Effects
N_2O	nitrous oxide
NH_4	ammonium
PFCs	perfluorocarbons
PNNL	Pacific Northwest National Laboratory
ppm	parts per million
ppmv	parts per million by volume
RCP	representative concentration pathway
R&D	research and development
SAP	Synthesis and Assessment Product
SAR	Second Assessment Report
SLS	short-lived species

1.0

Executive Summary

Water is the currency of life. A future with climate change means fundamental changes in precipitation patterns throughout the world, from flooding to droughts. Understanding these vulnerabilities for agriculture, human health and settlements, economies, and even energy will provide crucial insights for adaptation.

1.0 Executive Summary

The United States and other nations must face the daunting challenge of managing the risks of climate change, from limiting its progression to minimizing the damage of unavoidable effects. Environmental consequences of climate change are unfolding in real time, they are documented, and they illustrate the importance of a new era of science, which treats the Earth system and human systems as a single, closed system, to identify vulnerabilities to climate change and opportunities for coping with them. Through science, public authorities and private citizens can understand the risks of climate impacts and the potential consequences of strategies and options to address them that span sectors such as energy and infrastructure, natural resources and the environment, economics, and indeed, national security. A growing national priority is understanding the vulnerabilities to, and associated risks of climate change, including extreme weather and flooding that could threaten our coastal communities; changes in precipitation that can threaten the livelihoods and economies of entire regions; and heat waves and other events that can disrupt the nation's power supplies, transportation, and critical infrastructure or pose considerable health risks in urban areas. A quantitative understanding of the highly complex systems interactions at play, the emergent properties of these complex systems, and how the nation's scientific and engineering enterprise (our capacity for innovation) can provide needed options are significant scientific challenges.

1.1 Integrated Assessment and Emerging Challenges

Integrated assessment (IA) research provides a useful foundation for this new generation of science. Integrated assessment models (IAMs) are the central tools of the field that have delivered tremendous value to date, but evolving climate issues present new, substantial challenges and demands. Previous modeling emphases and supporting research have focused on understanding human influences on climate and options for mitigation of climate change. For nearly two decades, the IA community through the use of IAMs has provided:

- Globally consistent projections of greenhouse gas (GHG) emissions, driven mostly by energy use and consumption, and their potential energy, economic, and ecological consequences
- Emissions and land-use scenarios for use in studies applying atmosphere-ocean general circulation models (GCMs)
- Investigation of pathways of emissions consistent with particular goals for limiting climate change
- Analysis of alternative forms of international cooperation in emissions mitigation
- Analysis of the ways various economic and technology choices could affect emissions levels
- Consequences of climate mitigation measures under various scenarios
- Study of feedbacks between human activities (e.g., urban air pollution and its control) and the climate system.

The emerging decision environment now demands expanded tools that integrate all of these historical considerations with explorations of intersections with climate impacts and adaptation. Such integration would reveal feedbacks to climate forcing and insights into the multiple stressors that decision makers must confront. More specifically, some of the challenging questions include the following:

- How will human settlements change, how many people will live where, and what energy and other resources will they need that will influence and be influenced by climate change?
- How will climate change affect water resources, and what are the implications for energy and other infrastructure, competing water demands, land use, and adaptation strategies?

- How will regional decision makers respond to multiple climate-induced stressors, accompanying vulnerabilities, and tradeoffs between mitigation and adaptation?
- What promises do science and technology hold for transformational solutions to both mitigation and adaptation?
- What are the costs and averted risks arising from climate decisions—for implementing mitigation actions and for preventing damages to human and natural systems?

The climate research community is looking to IAMs to help fill this void and to provide the common framework for exploring both the costs and benefits of actions, the interactive consequences of actions, and a combined risk perspective for mitigation and adaptation decisions. There is wide research community agreement, as reflected in this report, providing the needed blueprint for a targeted expansion of nascent efforts that have demonstrated the viability of this approach.

Research in climate change modeling is represented by three characteristically different but increasingly interacting scientific communities that seek both to advance understanding in their domains and to represent it in appropriate models.

1. Climate (or Earth system) modelers focus on the consequences of anthropogenic and other changes to the composition of Earth's atmosphere, oceans, ice, and lands. Their global and regional models represent natural systems interactions and circulations affecting the climate system.
2. Impacts, adaptation, and vulnerability (IAV) modelers study the consequences of changes to Earth's climate for humans and nature. They depend on climate modelers to project climate change under various scenarios. Usually these IAV models are sector-specific, focusing on topics such as energy, forestry, transportation, agriculture, health, and more.
3. IA modelers study the broad range of human activities and the intersection of human and natural systems.

Figure 1.1 shows the interactions and dependencies among these three communities. These communities are and will be co-joined as part of a network of systems, and, importantly, IA models draw from and support the two other climate research and modeling communities.

Importantly, the IAM community will be critically dependent in the coming years on research progress and the development of component sector-specific models in areas such as energy, forestry, agriculture, health, and more. Although the core research for most of these sectoral models is not developed within the IAM community itself, a high priority is to bring the IAV elements into integrated assessments, providing insights into averted risks and damages to human and natural systems as well as insights into issues and economics associated with mitigation. The IAM community must seek to expand and strengthen collaborations that will deliver these needed component models and knowledge perspectives; this approach follows strategies for IA that have been successful in other parts of the world. Finally, beyond this modeling research, underlying process research is needed to move climate research forward. Resolving critical uncertainties in the role of clouds and aerosols, carbon cycle, and ice sheet dynamics all will have important implications for climate change modeling.

Climate models depend on IAMs to provide projections (internally consistent scenarios) for different development pathways that form the basis for climate model runs. IAMs project land use, geographically specified anthropogenic emissions of GHGs and short-lived species (SLS), and other needed parameters that provide input for climate models, informing not just atmospheric emissions but fundamental, human-induced changes to the carbon, nitrogen, and water cycles. In turn, more detailed climate models

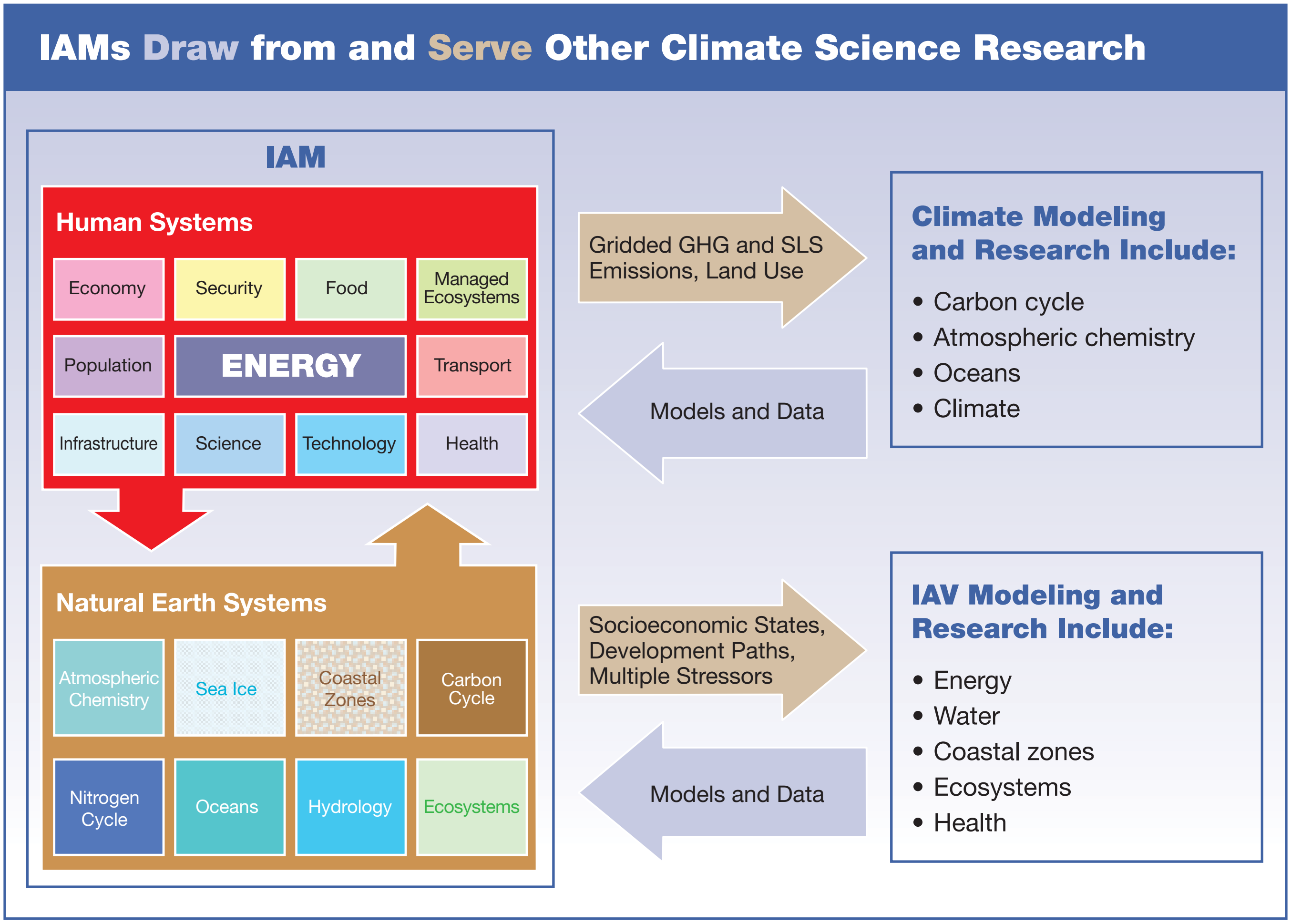


Fig. 1.1. Integrated Assessment Models (IAMs) Draw from and Serve Other Climate Science Research. IAMs include representations of climate, using models and data generated by the climate modeling and research community, and Earth systems, using models and data generated by the impacts, adaptation, and vulnerability (IAV) modeling and research community. In turn, IAMs provide to the climate modeling community emissions scenarios of greenhouse gases (GHGs) and short-lived species (SLS) and land-use projections. IAMs provide to the IAV modeling community projections of socioeconomic states, general development pathways, and the multiple stressors of climate change.

help to develop the computationally simplified Earth system models (ESMs) of intermediate complexity typically used in IAMs.

Changing patterns of human systems and adaptations, coupled with climate changes such as shifts in precipitation patterns, illustrate the dynamic, complex modeling challenges that lie ahead. For example, IAMs include representations of the energy system, the economy, land use, land management, and more. IAMs combine those representations within a single modeling framework to explore complex, nonlinear, and highly interactive systems relationships and interdependencies. IAV models will become increasingly dependent on these IAM constructs, since few sectoral impacts are truly independent of other sectoral impacts and adaptations. For example, understanding climate change impacts on biofuels and agriculture will not be independent of the climate change impacts on other sectors that may demand water or land resources.

Understanding and capitalizing on these growing relationships—such as the current joint IAM-ESM-IAV modeling paradigm for the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report—

are crucial for achieving the breadth and depth of recommendations in this report and for shaping the future context that will define the field of IA.

1.2 Findings

Table 1.1 summarizes, topically, the main research challenges identified and discussed in greater detail within this report. Organized around six major themes, corresponding to six major subsections within Chapter 3 of this report–the technical chapter–this list illustrates the scope and depth of the research challenges for IA.

Understanding and representing the systems interactions that give rise to mitigation and adaptation options are clearly a challenge. Within this space, modeling the energy-water-land connections, including interdependencies and vulnerabilities, is critically important. More explicit representation of water and future water demand in IAMs is a major goal, as are more tightly linked representations of terrestrial systems, including the terrestrial carbon and nitrogen cycles. Perhaps one of the greatest challenges remains: how to improve the representation of technologies themselves in IAMs, or more specifically, the potential transformations that might be possible through scientific discovery and innovation. Many previous results from IAMs illustrate the critical dependency on technological solutions for mitigation of climate change. It is anticipated that many adaptations will benefit from similar science-driven technological innovations.

Clearly, if there is one "grand challenge" for the IA community, it is representing IAV within IAMs. The overarching analytic framework exists but many questions remain. There is, as yet, no consensus on how to treat adaptation decisions within an IAM framework. And how should models address tipping points–that is, non-linear responses of various human and natural systems? In addition, some important impacts are not adequately represented by economic metrics, although some risk-based metrics might work. Ultimately, researchers will need to devote considerable effort to deciding how to translate social determinants of vulnerability into numerical representations for modeling.

Decisions about climate change decisions are increasingly focused on regional implications and near-term consequences. This is because the next few decades will determine what paths might be achievable through the end of the century, and because some climate impacts will be inevitable in the near term. In addition, decision makers want to know the potential consequences of climate change and policy for the regions where they live and for which they are responsible. Such concerns mean IAMs must develop strategies for improving their regional, near-term representation, a significant modeling challenge that has many associated issues.

Quantifying risks and uncertainties in IA projections is important because decision makers need greater insights of the implications of their decisions for energy, economics, climate impacts, and adaptations. Seminal work performed by the IAM modeling research teams discussed later in this report speaks to the opportunities presented by this capability. However, significant scientific challenges must be overcome, including our understanding of risk propagation within and across modeling components and across the models from the three major modeling communities–IAM, ESM, and IAV. It will be important to better characterize different types of risk. Ultimately, the IAMs must undergo more sophisticated testing and diagnostics to resolve various issues and improve our understanding of how different representations of human and Earth systems affect model uncertainties.

The interdependencies between the climate, IAV, and IA modeling communities have been previously described. As uses and users of IAMs expand, interactions between these three communities will increase and the need for more agile, interoperable

Table 1.1: Scientific Challenges to be Addressed by IA

Mitigation, Transformational Science and Technology, and Complex Interactions

- Linkages and dynamics of combined mitigation and adaptation
- Natural resources and other issues at larger scales (e.g., the energy-water-land interface)
- Nonidealized human behavior
- Regional capacities, governance, and institutional and human behaviors
- Improved resolution for near- to mid-term strategic, technology-based architectures
- Understanding and modeling of the translation of scientific discovery into technology and systems innovation
- Development of technology and systems scenarios around fundamental change in energy systems
- Temporal dimensions and deep uncertainty of transformational technologies and systems
- Use of IAMs to develop insights into interactions among different components of the human-climate system

Impacts, Adaptation, and Vulnerability (IAV)

- Incorporation of separately developed impact domain models
- Incorporation of IAV knowledge that is not fully represented in IAV models
- Alternative metrics
- Improved understanding of multiple interacting stresses
- Regional and local heterogeneity and data
- Tipping points and nonlinear dynamics
- Adaptations, vulnerabilities, and significant knowledge gaps

Spatial and Temporal Resolution

- Process scaling and nonlinearities
- Interfaces among physical, economic, and IAV model components
- Data matching (to scales)
- Scale and model uncertainties

Risk, Uncertainty, and Diagnostic Methods

- Modeling of risk and quantification of different kinds of uncertainty relating to data, parameters, and model structure
- Interpretation of and communication of risk and uncertainty
- Propagation of uncertainty across model components
- Validation: confronting models with data and observations
- Model intercomparisons

Interoperable and Accessible Modeling Frameworks and Collaborations

- Interoperable input and output detail, timesteps, and scales
- Interdisciplinary modeling environments
- Agile modeling frameworks for approaching questions of different user communities
- Community modeling approaches
- Multiple models for scientific learning
- Enabling computation and networks (high-performance computing)

Data Development and Accessibility

- Observations: harmonizing regional data, dealing with sparse datasets, and incorporating and querying very large datasets
- Data quality and verification
- Data management, distribution, and access
- Supporting cyber-infrastructure

models and modeling components will expand as well. Improving accessibility to the models is a high priority, not just for users, but for accelerating development of the models themselves. A critical finding of this workshop is the need to explore and accelerate the development of at least one community-based, open-source model for IAM. A corresponding finding is that multiple IAMs are needed as part of the foundational research and development for this field. Each will have unique strengths and weaknesses, and the science is advanced as quickly by what we learn from the differences in the models as what we learn from the similarities in model results.

Finally, significant challenges remain for IA in handling data requirements, data quality, data management, and accessibility. Developing and maintaining the necessary science cyber-infrastructure–the supporting computational capabilities, data handling and storage, networking, and other supporting infrastructure–is a critical challenge for the field. Related challenges are linked to appropriate visualization and data output/display capabilities and methodologies that can help facilitate understanding and analysis across complex, multi-dimensional decision space. In general, segments of the IA community have been limited by access to the necessary cyber-infrastructure; this has significant implications for the field and for progress on virtually every element mentioned above. Recent progress has been made and some doors opened to resolve these issues. Simple things such as access to archived results from model runs themselves would greatly facilitate progress within the IAM community and in IAM collaborative research spanning communities. Achieving the goal of providing open and easy access to data requires both technical capacity and institutional changes within the IAM community to ensure success.

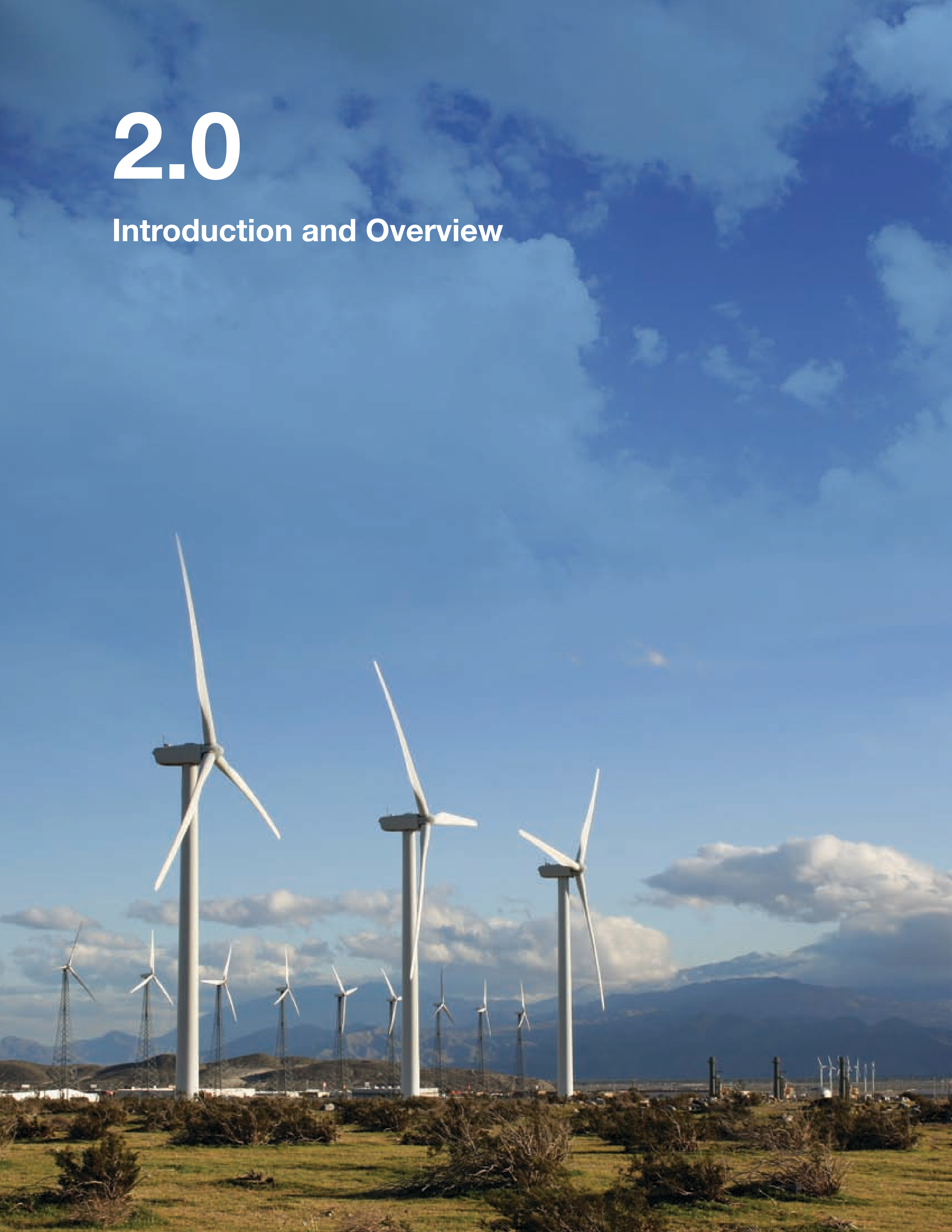
1.3 Integrated Assessment: The Next Generation

Today's decision-making has expanded beyond the causes of climate change to responding to its consequences. This shift is creating new demand to transform IA from its roots in strategic decisions about energy and economics to a more comprehensive view of regional, shorter-term decisions about mitigation and adaptation. Progress on the research challenges, enumerated in this report and summarized in Table 1.1, will open the door to the next level of insights that decision makers need to manage climate risks in our energy-driven society.

Although IAMs have proven useful in the decision-making and scientific communities, this report envisions a future in which this usefulness continues to grow. A more sophisticated generation of IAMs–drawing on new collaborations with climate modelers, experts on technological innovation and diffusion, and experts in IAV–will provide important new insights to those who are wrestling with simultaneous mitigation and adaptation decisions. More sophisticated merging of IAMs with other climate research models will yield new scientific insights into the magnitude and dynamics of human decisions on both the Earth system and on other human systems.

2.0

Introduction and Overview



Renewable energy resources, such as wind power, hold significant potential to change the way we produce energy, eliminating or greatly reducing greenhouse gas emissions. Renewable energy brings questions about energy storage, siting, deployment scale, distribution, and costs. Virtually all energy options also will be affected by climate change, including wind and precipitation patterns; changes in clouds, dust, and aerosols; and even micro-climates. Integrated assessment models that can explore these interactions will make important contributions to decision-making about the energy systems of the future.

2.0 Introduction and Overview

2.1 Background and Motivation

Along with other nations, the United States faces a daunting set of challenges in managing the risks of global climate change and limiting the damage of climate effects that likely cannot be prevented. In 2007, the IPCC's Working Groups I and II documented scientific evidence that shows the climate is changing, largely because of human action, and that without emissions mitigation, the social and environmental risks in coming decades are very great. The challenges presented encompass environmental quality, sustainable development, and the state and condition of both natural resources and human infrastructure (CCSP SAP 4.7 2008). Furthermore, environmental consequences of climate change already are beginning to be documented (CCSP SAP 4.3 2008a, b), making issues of vulnerability to such change and identification of opportunities for adapting to it ever more pressing. As a result, public authorities and private citizens face complex decisions that need to be supported by science-based understanding of the threat and consequences of various measures to deal with global climate change. There is thus a great and growing need for analysis that encompasses the various interacting components of the choices faced.

Confronted with these challenges, both scientific and policy communities need analytical tools to evaluate the interaction between human decision-making and changes in the physical Earth system. How, for example, might changes in carbon pricing affect GHG emissions? Would those changes also affect the amounts and distribution of land use? Are there constraints that the changing climate system itself puts on human decisions and thus on the fluxes of energy, water, and GHGs among the atmosphere, oceans, and Earth's surface?

The process for studying the human-climate system—which involves climate and ecological science, social science, and decision support—is known as integrated assessment, or IA. The foundation of IA is embodied in various implementations of computer-based models—called integrated assessment models, or IAMs—that integrate components of the human-climate system. Much of the work in IA originated in energy and economic studies. However, in the past two decades, this community's research has expanded to include analyses of how energy production and use, land use, and associated technology developments affect GHG emissions, and studies of resulting climate change and its social and environmental effects. IAM applications differ in form, but all apply reduced-form representations of the climate system or an Earth model of intermediate complexity. Depending on the application, IAMs include one or multiple combinations of the components illustrated in Fig. 2.1. These studies have contributed to our understanding of the issues surrounding climate change in many ways, including:

- Provision of globally consistent emissions projections of major GHGs and chemically active short-lived species (SLS) and analysis of their likely consequences
- Provision of emissions and land-use scenarios for use in studies applying atmosphere-ocean CGMs
- Investigation of emissions pathways consistent with particular goals for limiting anthropogenic radiative forcing or global temperature change
- Analysis of alternative forms of international cooperation in emissions mitigation
- Analysis of how different economic choices and technology developments influence emissions pathways
- Assessment of the economic and emissions consequences of mitigation measures
- Study of two-way feedbacks between human activities (e.g., urban air pollution and its control) and the climate system.

IA Modeling

IAMs focus on the connection between human systems research and energy.

- IAMs provide natural science researchers with information about human systems, such as GHG emissions, land use, and land cover.

IAMs **integrate** natural and human system climate science.

- IAMs provide insights that would be otherwise unavailable from disciplinary research.
- IAMs capture interactions between complex and highly nonlinear systems.

IAMs provide important, science-based decision support tools.

- IAMs support national, international, regional, and private-sector decisions.

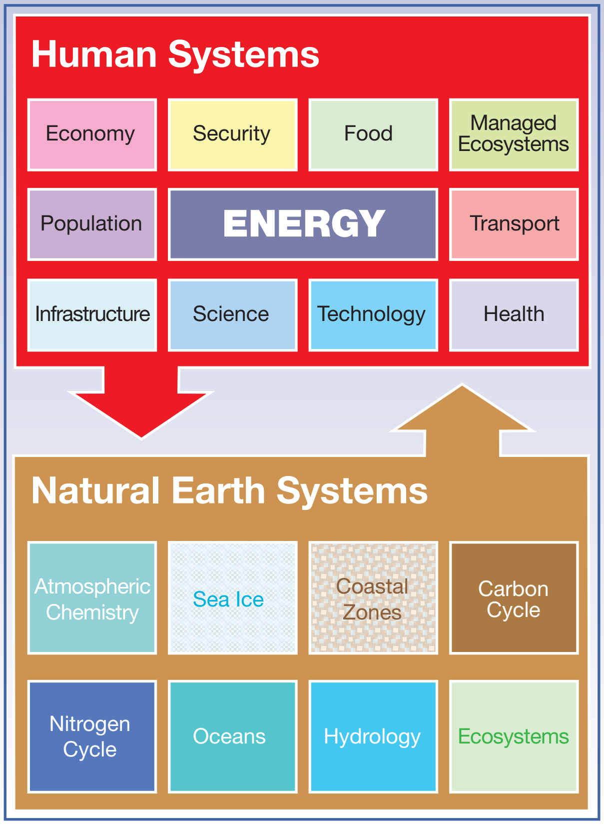


Fig. 2.1. IA Modeling. The focus of IAMs is on the interactions among human and Earth systems. Energy is the predominant human system represented in IAMs, but many systems—from the economy to managed ecosystems—are included. Earth systems that affect and are affected by humans encompass the atmosphere, oceans, fresh water, the carbon and nitrogen cycles, and ecosystems. Modeling the interactions among these systems yields insights that do not usually arise from disciplinary studies.

IA research continues in several U.S. universities, U.S. Department of Energy (DOE) laboratories and agencies, and foreign institutions. IA groups in the United States frequently are asked to respond to inquiries from federal, state, and local government agencies; congressional staff; the IPCC and other international organizations; nongovernmental groups; the media; and the public in more detail (Fig. 2.2).

As useful as IA efforts have been, the evolving climate issue is presenting new demands that require substantial extensions and deepening of IA research if societal needs are to be met satisfactorily. Current research focuses on the global and national levels, but decision makers increasingly need additional research at regional and local levels. "What if" projections over a century are common, but such projections *and* quantitative predictions over years and decades are now required. Scientific inquiry has done much, but now inquiry must be coupled with policy-making, planning, and decision support. The focus on mitigation studies has shifted to encompass both mitigation and IAV. Finally, climate understanding as a goal must yield to climate *and* combined insights on energy, environment, and economic security. Subsequent sections of this report present several of the most important of these research and information needs.

Users of IA Models and Research

- Office of Management and Budget, Office of Science and Technology Policy, and the Council of Economic Advisers
- U.S. Congress
- U.S. Climate Change Technology Program
- U.S. Global Change Research Program and climate researchers worldwide
- Federal and state agencies
- Universities and nongovernmental organizations
- National Intelligence Council
- International governments
- State and local resource managers and planners
- Private industry planners

Fig. 2.2. Users of IA Models and Research

2.2 Current and Emerging Challenges for Decision Makers

Since roughly the mid-19th century, a combination of fossil fuel combustion and the transformation of forests to agricultural lands has raised the concentration of carbon dioxide (CO_2) in the atmosphere from approximately 280–285 parts per million (ppm) to its current level of nearly 390 ppm (IPCC and the International Geosphere-Biosphere Program [IGBP]). Over that century-and-a-half, about half the extra carbon in the atmosphere has come from land-use conversion, the other half from fossil fuel combustion. But since the end of World War II, the human contribution of carbon to the atmosphere has been substantially different, with the larger contribution coming from fossil fuel combustion. In fact, over the past several decades, land-use change has accounted for about 15 to 20 percent of atmospheric composition changes, while fossil fuel contributions have ranged from 80 to 85 percent and grow each year. Other GHGs [e.g., methane (CH_4), nitrous oxide ($N_2$0), and chlorofluorocarbons (CFCs)] have followed patterns similar to the increases in CO_2 derived from fossil fuels, with some differences due to their lifetimes in the atmosphere and the contributions of different source terms and different sink terms (IPCC and IGBP).

Clearly, the long-term fluxes of GHGs to the atmosphere have been, for more than a century, the consequence of human decisions. Over the past several decades, the most important of these decisions have been those concerning energy production and use. The rise in atmospheric CO_2 undoubtedly has been driven by global increases in the demand for energy and energy services and by the choice to supply those services largely through the use of fossil fuels.

Because of the importance of energy for economic growth and development, there has long been an active energy research community dedicated to understanding how changes in energy production, technologies, and use might interact with national and global economies. During the past two decades, this community's research has expanded to include understanding how changes in energy production, end use, technologies, and land use might interact with economic decision making to affect GHG emissions. Such research is the genesis of IAMs.

As our understanding has grown regarding emissions, energy technologies, and the regional economics of the global energy system, the questions asked about emissions mitigation have evolved. In response to progressively more stringent atmospheric concentration targets, these questions increasingly are related to costs and timing over the next several decades. Questions also have involved trying to understand the consequences of various nations or global regions pursuing different strategies for reducing emissions and then attempting, under these scenarios, to understand the overall consequences for costs and timing of emissions reductions to meet atmospheric targets. Such questions have prompted the use of IAMs to understand how particular suites of technologies for energy production or end-use efficiency affect the overall costs or distribution of costs to achieve particular concentration targets.

Thus IAMs have been developed to do more than simply investigate energy choices. Because they simulate shifts in agricultural productivity and land-use changes and include representations of the carbon cycle and generally relatively simple representations of physical and biological climate systems, IAMs also can be used to investigate how human decisions on energy interact with these other components of the Earth system. Even with simple or medium-complexity representations of other Earth system components, IAMs can be—and already have been—used to understand, for example, how differences in climate sensitivity affect realized climate change under various emissions scenarios and how different development pathways influence the balance between energy and land-use emissions.

Finally, because IAMs generally are computationally less intensive than the very complex GCMs or more recent ESMs, they easily can be used to understand the likelihood of different climate outcomes, given particular emissions scenarios or different parameterizations of physical processes. These types of studies have taken two forms: they have either explored the value of improved knowledge in science (e.g., the carbon cycle or cloud research), or they have explored the likelihood of different climate outcomes under different emissions scenarios by calculating the probability distribution functions of those outcomes and exploring their implications for decision making (e.g., the likelihood of exceeding a two-degree average temperature rise under different emissions scenarios given different physical parameterizations of the climate system).

As understanding and quantification of climate impacts on agriculture, water, natural resources, transportation, energy, and other sectors have grown (National Assessment Synthesis Team 2000; CCSP SAP 4.3 2008 a,b; CCSP SAP 4.5 2008; CCSP SAP 4.7 2008; IPCC WG I 2007, WG II 2007), concern over the effects of climate change has stimulated interest in how people could adapt to those changes, either reactively or prospectively. More fundamentally, research on the underlying vulnerability of natural resources and human societies is beginning to help us understand the factors that determine how sensitive societies and their resources are to various stresses, whether driven by climate alone or climate change in combination with other factors. The 21st century faces sweeping questions that challenge current knowledge and require integrated answers.

Because IAMs are structured to investigate the interaction of human decisions and environmental processes, they are an effective framework for understanding the broad dimensions of IAV. In the past, outputs from IAM simulations of changes in climate have been used to drive various impact models to understand the potential for changes in forests, agriculture, and water resources (National Assessment Synthesis Team 2000), but these studies typically did not include explicit descriptions of adaptation strategies. Similarly, indicator-based studies of national vulnerability to climate change have been done with IAM outputs (Yohe et al. 2007), but such studies also are not full dynamic simulations of changes in vulnerability. Like the energy-related and GHG emissions studies cited above, research using IAM outputs to assess impacts and vulnerabilities has focused primarily on either CO_2-doubling model experiments or national-level consequences, by sector, from gradual increases of CO_2 over long periods of time.

2.3 Integrated Assessment Research and Modeling

Within the various climate change research communities, IA is the home of human system research. From its beginnings in the 1970s, IA research has focused on the role of humans in shaping the global Earth system. The original themes of IA research were energy and CO_2 emissions from fossil fuels; the original use was to provide estimates of potential future human CO_2 emissions for analysis by the carbon cycle community. IA continues to provide scientific services to other climate change research communities, but the breadth and scope of IA research have expanded dramatically.

Models have played an extremely important role in the development of the field of IA for climate change. They have been the vehicles researchers have used to systematically build, maintain, and integrate knowledge from a diverse set of science-based sources to support both science and decision making. For example, IA models capture knowledge derived from scientific research in human and natural Earth systems, analyzing the interactions between these systems to obtain integrated insights that would not be available otherwise from traditional, disciplinary research. IA undertakes human-system climate research that integrates key anthropogenic processes, such as energy, technology, the economy, agriculture and land use, to help understand human climate change mitigation, impacts, and adaptation. The resulting knowledge and tools are used by the scientific community to further scientific understanding and by decision makers in both the public and private sectors.

2.4 Integrated Assessment Modeling Research Teams

IA modeling takes place around the world. IA research teams established in the United States and abroad bring together scientists with diverse backgrounds and expertise to facilitate the development of IAMs that capture specialized knowledge derived from a variety of climate change sciences (see Fig. 2.3). Major world IA research teams include two supported by DOE's Office of Science: The Massachusetts Institute of Technology's (MIT's) Joint Program on the Science and Policy of Global Change builds and maintains the Integrated Global System Model (IGSM), and the Joint Global Change Research Institute, a partnership of Pacific Northwest National Laboratory (PNNL) and the University of Maryland at College Park, builds and maintains the MiniCAM modeling system. Other research teams include the IMAGE modeling team centered in the Netherlands, the MESSAGE modeling team at the International Institute for Applied Systems Analysis, and the Asia integrated modeling team located at Japan's National Institute for Environmental Studies. Another important U.S. modeling team exists at the Electric Power Research Institute, which builds and maintains the MERGE IAM. The Regional [Dynamic] Integrated Model of the Economy-Dynamic Integrated Model of the Economy models developed at Yale University by William Nordhaus are mathematically simpler IAMs designed to rapidly explore the qualitative character of many climate concerns, including policy issues focused on balancing the benefits of climate mitigation against cost.

2.5 Applications and Uses of Integrated Assessment Models

A major function of IA research is providing other climate scientists with scenarios of potential future emissions of GHGs and SLS. IA analyses of emissions pathways for various climate stabilization scenarios that optimize economics and incorporate technological innovation have become the standard for framing climate projections (see Figs. 2.4 and 2.5). The single most important anthropogenic GHG emission is CO_2, and the largest source of CO_2 emissions is fossil fuel use. CO_2 is well mixed in the atmosphere because of its long residence time, which dictates that limiting the concentration of atmospheric CO_2 to any specific value requires limiting cumulative net emissions from all sources anywhere on Earth.

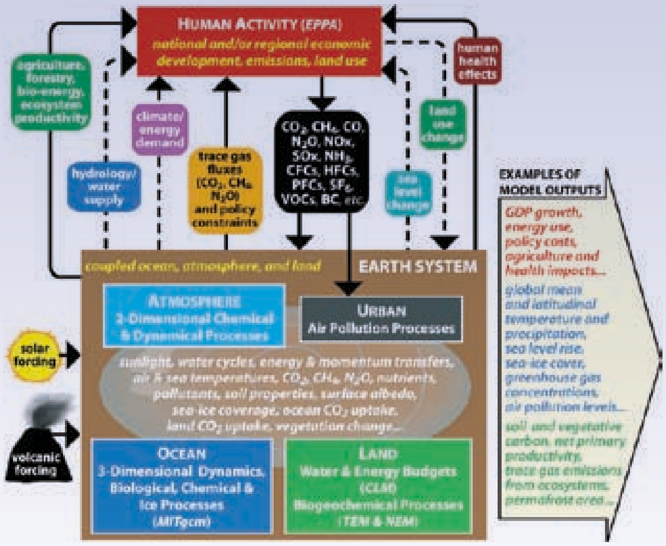
As part of its expanded services to various climate research communities, IAMs routinely produce analyses that involve many forms of emissions. Information demands are expanding, as reflected in the specifica-

Leading IAMs and Research Teams

Two of the DOE-sponsored research teams

Massachusetts Institute of Technology
Joint Program on the Science and
Policy of Global Change

GLOBAL CHANGE
SCIENCE POLICY
MIT



Joint Global Change
Research Institute

Pacific Northwest
NATIONAL LABORATORY

UNIVERSITY OF
MARYLAND

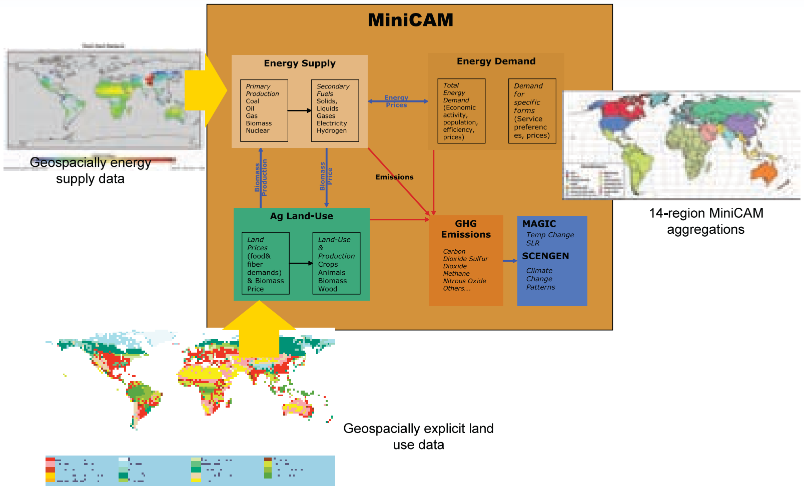
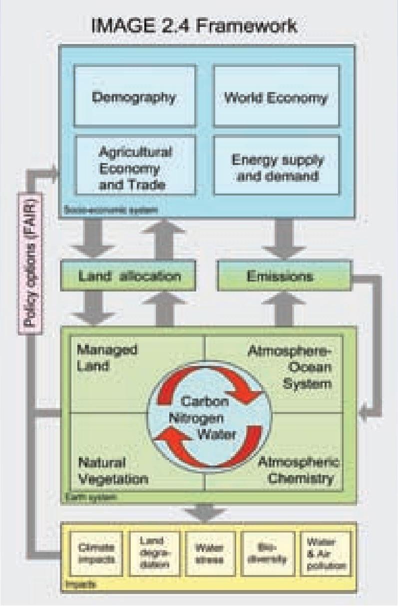
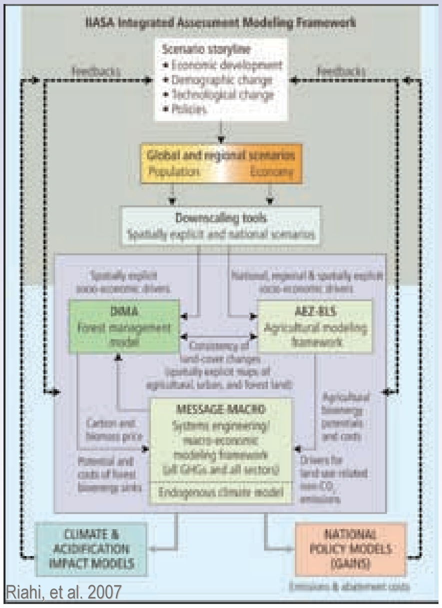


Fig. 2.3. Leading IAMs and Research Teams. The six IAMs and research teams identified here have provided other scientific communities and policy makers with relevant and timely model results and analyses as the world considers appropriate actions in response to climate change. Many smaller teams exist, but this list includes the larger ones from around the world. (Figure continues on next page.)

IMAGE
Netherlands Environmental
Assessment Agency
The Netherlands

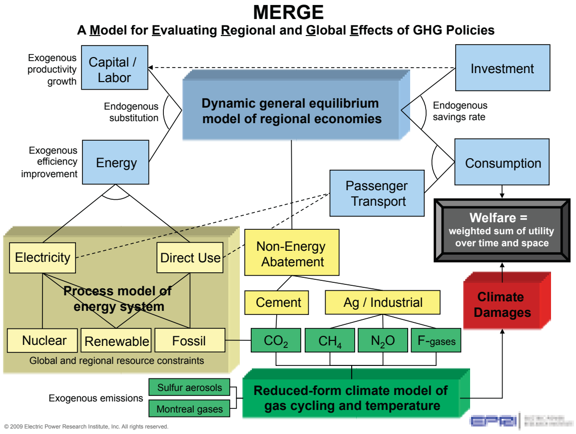


MESSAGE
International Institute for
Applied Systems Analysis
Austria



Riahi, et al. 2007

MERGE
Electric Power
Research Institute
United States



AIM
National Institute for
Environmental Studies
Japan

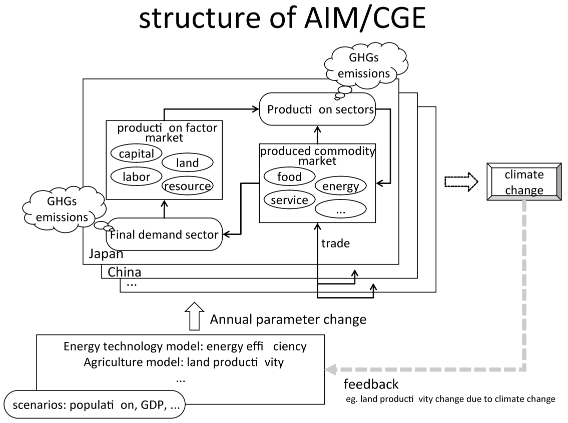


Fig. 2.3. Leading IAMs and Research Teams. The six IAMs and research teams identified here have provided other scientific communities and policy makers with relevant and timely model results and analyses as the world considers appropriate actions in response to climate change. Many smaller teams exist, but this list includes the larger ones from around the world. (Figure continued from previous page.)

IA is an Integral Part of the Science for the IPCC

Fifth Assessment Report Representative Concentration Pathways (RCPs)

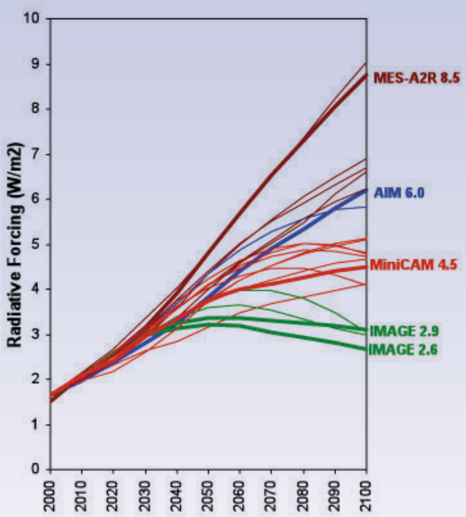
RCPs
Selection,
Extension to 2300,
Downscaling

8.5 W/m²

6 W/m²

4.5 W/m²

<3 W/m²



RCP 8.5
>8.5 W/m² in 2100, rising

RCP 6
~6 W/m² at stabilization after 2100,
stabilization without exceeding target

RCP 4.5
~4.5 W/m² at stabilization after 2100,
stabilization without exceeding target

RCP 3-PD
<3 W/m² in 2100,
peak and decline stabilization

Climate Modeling Community
Develops RCP-based
Ensemble Runs

Fig. 2.4. IA is an Integral Part of the Science for the IPCC. The IAM community produced four RCPs, or scenarios, for use by climate modelers and researchers in the IAV communities. The four scenarios of anthropogenic climate forcing were chosen from published, peer-reviewed literature. The highest scenario exhibits radiative forcing of 8.5 W/m² in 2100, with radiative forcing continuing to rise thereafter; the lowest is 2.6 W/m² in 2100 and continues falling. The other two scenarios exhibit radiative forcing of 6.0 W/m² and 4.5 W/m², respectively, in 2100 and are stable thereafter.

tions from the ESM community in the next round for the IPCC's Fifth Assessment Report. The evolution of climate models from coarse-scale atmospheric process models to those that link atmosphere, oceans, and terrestrial systems at fine resolution (½° x ½°) now means that IAMs must deliver to climate modelers fine-scale geospatial information on land use and land cover in addition to fine-resolution emissions patterns for GHGs and SLS.

Because IAMs simultaneously provide descriptions of both human and physical and biological climate systems, they are highly sought after tools for decision support. Detailed process models can take months to run a single scenario and thus are not particularly tractable tools for exploring multiple decision options. Today, IAMs are used by decision makers in both the public and private sectors to develop strategic responses to the challenges of anthropogenic climate change. This comes at the cost of reduced detail and accuracy in modeling of the individual processes but provides greater perspective into the interactions of the many parts of the complex system. In addition, because IAMs can provide specific information on the roles of particular energy technologies, they can be used to investigate the portfolio of technologies that might prove effective in mitigation decisions. The U.S. Climate Change Technology Program, for example, uses MiniCAM to provide information to help inform U.S. public-sector investments in technology research and development.

As decision making shifts to a more integrated understanding of responses to climate change and

IA Provides the Inputs to ESMs for the IPCC Fifth Assessment Report

Summary of IAM Outputs to ESMs

Variable	Units	Spatial scale	
GHGs		**Concentrations**	**Emissions**
CO_2 (fossil fuel, industrial, land-use change)	ppm and Pg/yr	Global average	Sum
CH_4	ppb and Tg/yr	Global average	< 1° x < 1°
N_2O	ppb and Tg/yr	Global average	< 1° x < 1°
HFCs	ppb and Tg/yr	Global average	Sum
PFCs	ppb and Tg/yr	Global average	Sum
CFCs	ppb and Tg/yr	Global average	Sum
SF_6	ppb and Tg/yr	Global average	Sum
Aerosols			
Sulfur (SO_2)	Tg/yr	Generated by ESM	< 1° x < 1°
Black Carbon	Tg/yr	Generated by ESM	< 1° x < 1°
Organic Carbon	Tg/yr	Generated by ESM	< 1° x < 1°
Chemically active gases			
CO	Tg/yr	Generated by ESM	< 1° x < 1°
NO_x	Tg/yr	Generated by ESM	< 1° x < 1°
VOCs	Tg/yr	Generated by ESM	< 1° x < 1°
NH_4	Tg/yr	Generated by ESM	< 1° x < 1°
Land use and land cover			
CO_2 flux (land-use change)	Tg/yr	n/a	< 1° x < 1°
Land-use and land cover	Fraction of types	< 1° x < 1°	

Fig. 2.5. IA Provides the Inputs to ESMs for the IPCC Fifth Assessment Report. The four RCPs involving GHGs, aerosols, chemically active gases, and land use and land cover have greater detail than any previous set of scenarios provided to the climate modeling and the IAV research communities. The list of GHGs and SLS is more inclusive than in previous scenarios of climate forcing, and data on emissions, land use, and land cover are provided with ½° x ½° spatial resolution. Source: Moss et al. 2008.

its ramifications for human activities and actions, IAMs are being pressed to address a broader array of climate issues, including climate impacts and adaptation options undertaken in concert with emissions mitigation.

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3.0

Challenges and Future Directions

The research needs and future directions for integrated assessment address six major scientific topical areas: 1) mitigation, transformational science and technology, and complex interactions, 2) impacts, adaptations, and vulnerabilities; 3) spatial and temporal resolution; 4) risk, uncertainty, and diagnostic methods; 5) interoperable and accessible modeling frameworks; and 6) data development and accessibility.

3.0 Challenges and Future Directions

Each of the following sections of the report examines a particular challenge for the future of IA research and modeling. Following are the major challenges discussed:

- Linking and integrating mitigation, transformational science, and complex interactions
- Incorporating IAV
- Improving spatial and temporal resolution
- Developing better methods for representing risk and uncertainty, and improving diagnostic methods
- Building interoperable and accessible modeling frameworks and collaborations
- Expanding data development and accessibility activities.

Topics have arisen not only from the workshop itself, but also from collaborations in the research community and from previous workshops sponsored by the Energy Modeling Forum and DOE (see Fig. 3.1). Each section briefly identifies the current status of the theme and the major scientific challenges to be addressed. A brief examination of interdependencies follows to indicate areas in which the IA research community is dependent on progress in other scientific fields. Each section ends with a short discussion of the potential impacts if the research is implemented successfully (i.e., What difference would be made in our understanding of climate change and our responses to it?).

Context and Community Input for this Report

- November 2008 synthesizing workshop: Science Challenges and Future Directions for Climate Change IA Research
- Biological and Environmental Research Advisory Committee review of the IA Research Program – 2007
- 2007 and 2008 annual workshops on IA, Snowmass, Colorado
- Joint Global Change Research Institute and Oak Ridge National Laboratory 2007 Interagency Summer Workshop Series – Impacts, Adaptation, and Frontiers in Science
- Biological and Environmental Research's Climate and Environmental Sciences Division strategic plan for climate change research
- U.S. Climate Change Science Program Interagency Working Group on Human Contributions and Response and Decision Support
- IA Research Program co-sponsored 2008 workshop (and related workshop) on uncertainty methods – Argonne National Laboratory and University of Chicago

Fig. 3.1 Context and Community Input for this Report. This figure lists the major venues for discussions and determinations of the broad climate change research community as well as of the IA research teams to articulate the challenges addressed in this report and develop approaches for meeting them.

3.1 Mitigation, Transformational Science, and Complex Interactions

Research-driven advances in photovoltaic cells and new forms of energy storage could revolutionize energy production and electrification of the U.S. economy, exhibiting a unique "signature" for water, land, and the carbon and nitrogen cycles. Improving the ability to explore the transformational role of science and technology is crucial for IAs and insights into future energy development pathways.

Key Research Questions

- How do climate change impacts on human and natural systems affect subsequent climate forcing? What effects will adaptations have?
- How will decision makers and planners respond to multiple, simultaneous stresses, such as the economic and institutional stresses of mitigation and various adaptation actions?
- How do large human and natural systems, such as land-water-energy systems, interact at coarse and fine scales? What are the effects on the carbon, nitrogen, and water cycles, for example, for biofuels? What are the effects of water-cycle and human decisions about water use on microclimates in various regions?
- How do we understand and factor into decision processes and models the transformational innovations and shifts in science and technology that could revolutionize our energy future and bring new solutions to climate change and adaptation to climate change?
- What insights can we develop regarding the potential role of institutional, governance, and human behaviors that will affect the pace and extent of mitigation and adaptation actions?
- What are the capacities of different regions to respond to change, given unique economic, natural resource, and other capacities for change?
- At the most fundamental level, what are the costs and benefits (avoided damages) and associated probabilities of various mitigation strategies?

3.1.1 Current Status

The primary focus of the IA community has been on modeling and research covering a wide variety of mitigation options. These options range from associating adjustments in energy and agricultural systems with long-term climate goals to understanding the roles of various technologies such as carbon dioxide capture and storage (CCS), energy end-use technologies, nuclear power, and renewable energy. Historically, these options have been explored in models using idealized decision rules about carbon pricing and simultaneous action among all parties and regions. However, recent research has begun to explore issues associated with less-than-optimal policies. IAMs were the basis for scenarios included in the IPCC's Special Report on Emissions Scenarios and the U.S. Climate Change Science Program's (CCSP's) product 2.1a. The Climate Change Technology Program uses IAMs as the basis for exploring technology portfolios.

Technology is the foundation of actions to reduce emissions and adapt to a changing climate. Over the past two decades, IA research has informed a wide range of technology-related issues. This research has investigated the value and implications of various technological improvements, particularly in the energy sector, and clearly has articulated the importance of technological advances in reducing the costs of addressing climate change, thus increasing the social and political viability of deep emissions reductions. Research also has demonstrated the technological mixes that might emerge under different mitigation approaches, degrees of emissions reduction, and technological options. IA studies have highlighted the role of technological advancements, such as improvements in agricultural productivity, that might not otherwise have been considered to be directly associated with climate mitigation. Exploring technology and transformational changes, particularly in the energy and agricultural systems, will remain a key focus of IA research. A critical role for IA research is to understand how cutting-edge science can have transformational effects on the nation's technological portfolio and thus its options for mitigating and adapting to climate change.

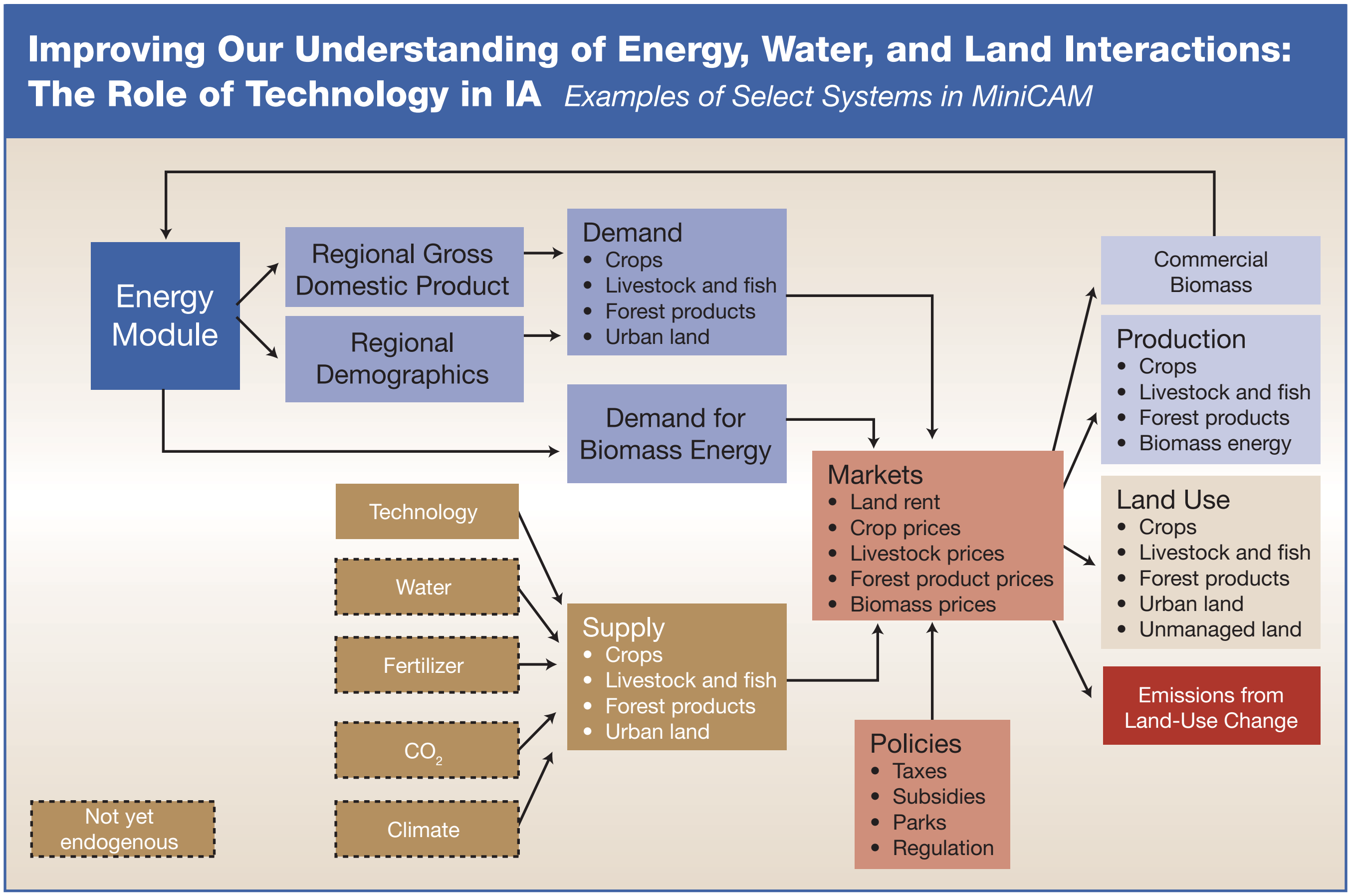
3.1.2 Major Scientific Challenges

The major scientific challenges detailed below reflect the complexity of the IA modeling task of combining information about human decision making on energy systems with information on the physical and biological climate system and the climate consequences of energy decisions. Concerns about how to represent the links between the generalized topics of mitigation and adaptation, as well as those how about technologies themselves are represented in IAMs, clearly are among the most important challenges the IA modeling and research communities face. Beyond IAMs, the field of IA will benefit from examination and possible development of complementary models and tools. Full or partial general equilibrium models are expected to remain the workhorse of IA. However, additional insights are possible and likely through development of additional tools, including but not limited to systems dynamics models and/or frameworks organized more centrally around risk and/or human behaviors.

Linkages and Dynamics of Combined Mitigation and Adaptation. Mitigation actions will interact with both a changed climate and with options for adaptation. Understanding mitigation within a framework that includes these linkages will be necessary if IAMs are to fully articulate the available decision space and the consequences of particular actions (see Fig. 3.2 for an illustration of current linkages in one IAM, the MiniCAM). For example, existing research from IAMs demonstrates that carbon sinks associated with forests and other natural ecosystems are a function of regional ground-level ozone concentrations, which themselves are a function of decisions made in the energy and transportation sectors. Other recent research shows that continuing the historical increases in agricultural productivity is extremely important as a carbon management strategy but only if prices are associated with terrestrial carbon as well as with fossil fuel and industrial sources of GHG emissions. In addition, the agricultural and biological productivity of ecosystems will vary, of course, with climate change. These are classic problems of identifying and evaluating feedbacks in dynamic systems as represented in numerical models and are only two of many possible examples of the interaction between mitigation decisions and impacts and adaptation. Such feedbacks are important to understand as society moves toward making a series of complex decisions on these issues.

Modeling Natural Resources and Other Issues at Scale. IAMs face significant challenges in representing the interaction of natural resources and their management with decisions made about the energy system. Foremost among these challenges will be more sophisticated and more tightly linked representations of terrestrial systems, including the terrestrial carbon and nitrogen cycles. Equally important are more complete representations of land uses by type and their linkages to food, forest products, and bioenergy demands (see Fig. 3.2). Collaboration will be required with land-use modelers to achieve these goals.

Water poses another significant challenge. From a mitigation perspective, advancements are needed in IA modeling of water availability for energy technologies (e.g., water for cooling and biofuels). Currently, even the models that have some way to simulate precipitation and runoff lack adequate representations of water demand and management. This challenge is linked tightly to that of increasing the regional specificity of IAMs, as water demand and management are inherently regional and even local problems. However,



Improving Our Understanding of Energy, Water, and Land Interactions: The Role of Technology in IA *Examples of Select Systems in MiniCAM*

Fig. 3.2. Improving Our Understanding of Energy, Water, and Land Interactions: The Role of Technology in IA. The MiniCAM modeling system is built and maintained by the Joint Global Change Research Institute, a partnership of PNNL and the University of Maryland at College Park.

because water is an important resource for mitigation strategies—including those related to agriculture and land use—explicitly incorporating water demand, use, and management into IAMs is a high priority.

This nexus of interactions among energy, water, and land systems is but one example of the more general issue concerning the fact that climate impacts and decisions about managing natural resources ripple through these systems in unexpected ways. For example, global deforestation has had and will have a profound impact on the overall global carbon cycle and thus on carbon emissions budgets for human activities (see Fig. 3.3). Models are uniquely positioned to investigate such interactions precisely because they treat management and adaptation decisions about these resources and about energy explicitly.

Nonidealized Human Behavior. To stabilize GHG concentrations, GHG emissions ultimately must be reduced toward zero, requiring concerted actions by all nations. To date, IA research on mitigation largely has focused on global approaches in which every nation participates in emissions reductions immediately and does so in such a way as to undertake reductions where they are cheapest. Although such scenarios have proven valuable in providing general insights into the characteristics of mitigation, they do not give decision makers insight into more realistic policy regimes, particularly over the next several decades. For example, if large developing countries such as China and India stay out of international stabilization agreements for an extended period, the costs of mitigation rise substantially for the participants in the agreements. Perhaps more surprisingly, meeting aggressive stabilization targets by the end of

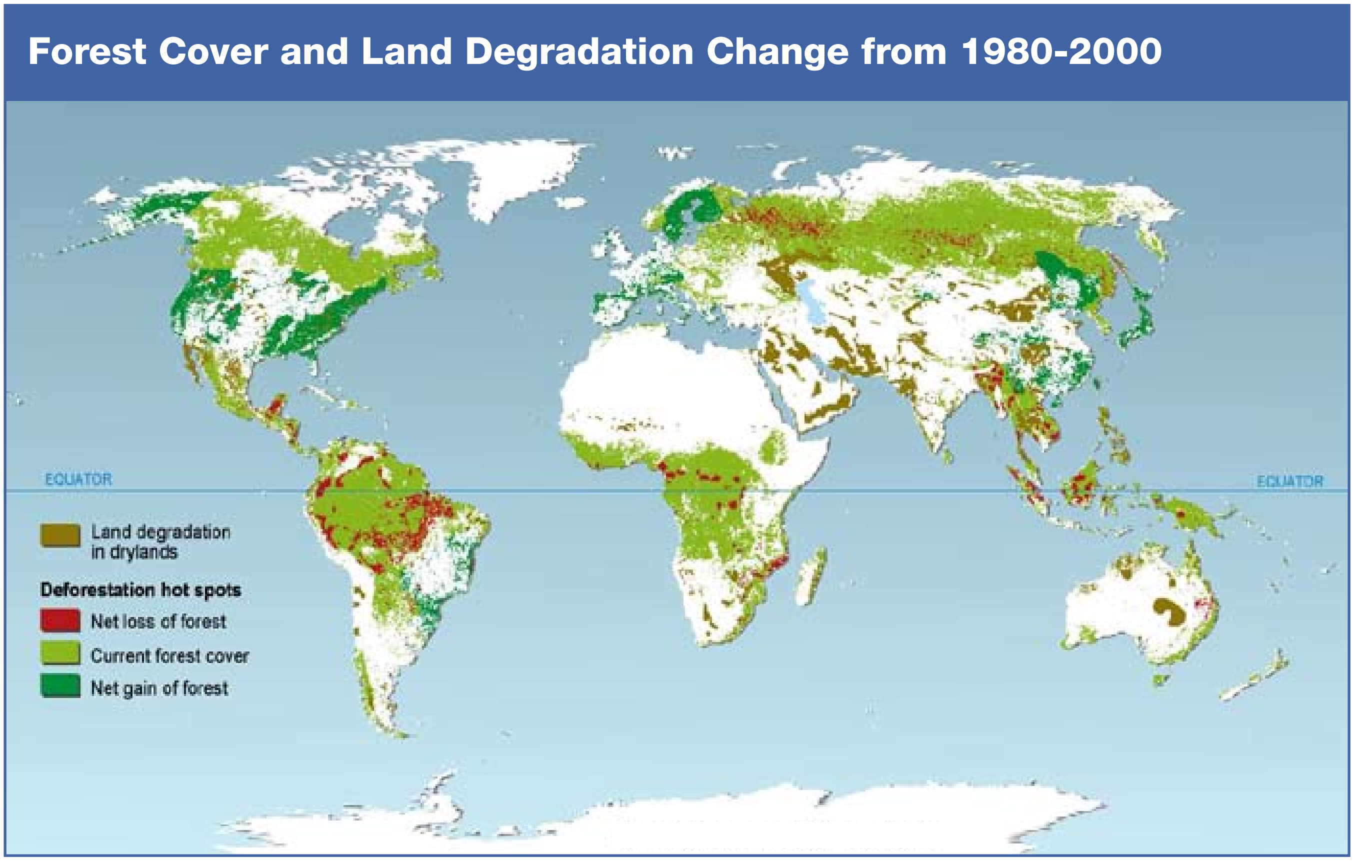

Forest Cover and Land Degradation Change from 1980-2000

Fig. 3.3. Forest Cover and Land Degradation from 1980-2000. Understanding past deforestation, as shown in the figure, speaks to the challenge of projecting future deforestation, a critical dimension of climate change and a focus of integrated assessment. Source: Millennium Ecosystem Assessment 2006.

the century may not be possible in such situations. But this result is as dependent on how well the IAMs represent the carbon cycle as it is on how well they represent the economics of the energy system and available technologies.

IA research should explore the possibilities for near-term policy regimes and endeavor to enhance IAM capabilities to include policy structures having differentiated burdens across countries and both market and nonmarket approaches to mitigation. Current IAMs already are poised to explore many such scenarios for differing regional allocations of emissions reduction responsibilities. Research needs in this area largely center on an enhanced understanding of the possible policy structures that might evolve. However, many architectures can be difficult to represent in current IAMs, particularly those that are regulatory (e.g., standards for fuel economy and appliance efficiency) rather than market-based (e.g., cap and trade). In many cases, model developments may be needed to create or enhance these capabilities.

In addition, IAMs must reconcile many decisions, particularly about adapting to climate impacts or about meeting other needs for ecological services that are not necessarily made in the context of efficient pricing in economic markets. Such decisions may be made to minimize the risk of undesirable outcomes or for regulatory or other reasons. Finally, the phenomenon of path dependency of scenarios should be explored (i.e., the degree to which early decisions about technologies or policies can limit later choices). Such investigations would be extremely useful, although they will raise challenges for how the IA community will then represent the uncertainties that accompany them.

Regional Capacities, Governance, and Institutional and Human Behaviors. Mitigation ultimately will be undertaken by national and regional entities, and the details or constraints of particular regions will determine which opportunities can be realized. Relevant regional characteristics include institutional structures, resource bases, population growth rates, economic development rates, and associated demands for energy and agricultural goods. Although it is well understood that addressing climate change will require that future technology systems be different than those of today, major questions remain about the timing and pathway toward possible futures and the manner in which actions today might influence the pace of change. For example, the rate of uptake of new technology may vary between developed and developing countries, yet the latter increasingly will bear the burden of emissions reduction responsibilities over time as their energy usage and potential associated emissions continue to grow. Understanding technology uptake in developing regions and the actions that might influence this uptake is thus needed to inform choices about these actions today. Finally, there is a great need for understanding both the constraints and opportunities that different governance regimes and regional capacities may bring to bear on how technologies and other decisions are implemented. This is an area in which substantial, fundamental social science research, performed outside the IAM community, may be required before a consensus can be reached on how, or whether, to represent these concerns in numerical models. Should this research bear fruit, the IAM community will then need to explore ways of drawing from this and converting it to usable forms for IA.

Improved Resolution for Near- to Mid-term Strategic, Technology-Based Architectures. The IA research community must continue to enhance representations of regional characteristics that would influence regional mitigation options. This requirement does not necessarily imply more detailed regional representations in all cases. Often, it might involve simply a greater vetting of the structure and behavior of regional analyses with experts, especially those in-country. Greater detail should be applied as necessary to capture particularly salient characteristics currently lacking in aggregate representations. To accomplish this task, two needs must be met.

First, IA research needs to capture greater regional representation within large countries or economies, particularly for the United States and other major Organisation for Economic Cooperation and Development economies. Achieving this is critical because there are important possible regional limitations in the ability to deploy potential mitigation technologies due to, for example, differences in water supply, solar and wind resources, the installed base of current technologies, and geological sequestration reservoirs. There also is considerable interest in understanding how these opportunities and constraints may influence the deployment of mitigation technologies.

The second major need is to greatly improve our current understanding of the situation in developing countries. This is important because most of the growth in energy demand over the next several decades to a century will, in fact, take place in the developing world as a result of rapid population and economic growth as well as the energy intensity of economies. The IA community needs to understand how energy and land-use technologies and practices will develop in these regions. For example, could these areas mirror the development of the United States and Western Europe, or could they quickly take up modern technologies? The implications are significant for GHG emissions and the likelihood of reaching particular concentration or climate targets.

Understanding and Modeling the Translation of Scientific Discovery into Technology and Systems Innovation. The future character of energy and other climate-related systems such as agriculture will depend on the rate and direction of technological change (i.e., improvements to existing technologies and development of entirely new technologies). The future of technology is uncertain, yet the relevance of IA research depends on incorporating representations of future technological improvements that are both reasonable and that capture the range of possibilities.

The processes of technological change are enormously complex and not amenable to full incorporation into IAMs. Nevertheless, the relationship between mitigation and adaptation actions and technological change may prove important to decision makers. IAM developers therefore should continue to explore stylized representations of technological change in their models, not so much for predictive power, but to understand the possible implications of various forces such as basic and applied R&D, technological spillovers from other industries, and learning-by-doing.

Developing Technology and Systems Scenarios around Fundamental Change in Energy Systems. IA research increasingly must explore the details of energy systems dramatically different from those of today. For example, energy systems with large deployments of wind and solar power will face grid integration issues, and understanding these systems will require clearer insights into the interactions among electricity storage technologies, electricity grids, transmission capacity expansions, and demand-side management options. In addition, assessing the national and regional character of bioenergy demand and production will require a greater understanding of the regional distribution of bioenergy cropping regions, transportation costs and options, and demand centers for the use of bioenergy crops (see Fig. 3.4). Hydrogen will be a viable energy carrier only if an infrastructure can be constructed to produce and distribute it. Enabling coal-based technologies through CO_2 capture and storage depends on the spatial relationships between possible emission sources, such as power plants, and the reservoirs for large-scale CO_2 injection (see Fig. 3.5 for comparative costs of policies with and without CO_2 sequestration in fossil fuel and biomass power plants). Increased deployment of nuclear power will require more detailed understanding of waste and nuclear security concerns. Although not all of these issues can be incorporated at a structural level in IAMs, side research with focused models may provide a clearer

Exploring a Broad Range of Potential Technologies, Including those that Affect Land Use and Energy

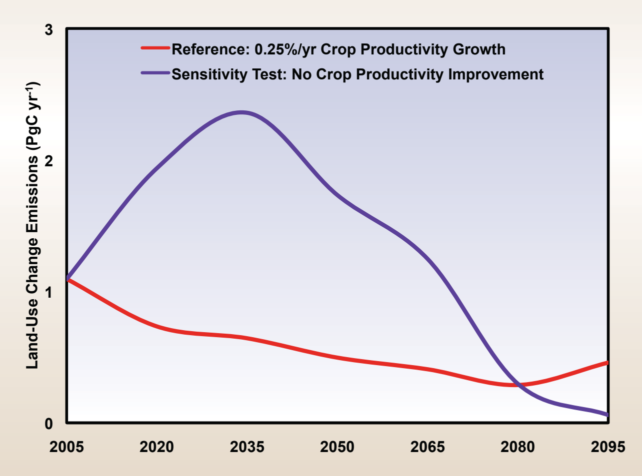


Fig. 3.4. Exploring a Broad Range of Potential Technologies, Including those that Affect Land Use and Energy. This figure shows why improving agricultural production is crucial to mitigation efforts. If crop productivity does not improve, emissions increase in the short and medium terms because more land is dedicated to food production, leaving less land for forest and biofuels crops, two important mitigation strategies. Source: Wise et al. 2009.

understanding of the related dynamics that could be incorporated into IAMS in reduced form.

Temporal Dimensions and Deep Uncertainty on Transformational Technologies and Systems. The representation of mitigation options in IAMs is based on assumptions about technologies that will be available in the near and long term. Indeed, assumptions about technology evolution largely determine mitigation costs and near-term actions needed to meet any long-term climate goal (see Fig. 3.6). New technologies such as cellulosic ethanol methods, high-capacity and high-efficiency batteries, and a new generation of solar photovoltaic cells could strongly influence the costs and character of mitigation options. Currently, the IA community has no mechanism to clearly articulate possible technological options of the future and the likelihood of these options coming to fruition. Furthermore, a key component of decision making today is associated with investment in R&D to reduce the costs of existing mitigation options and create a new generation of options. Such decision making would be aided greatly by a better understanding of the linkages between investment in the fundamental R&D necessary to create new technology portfolios and of how those technologies might evolve and be adopted over time.

Exploring Systems Interactions at Scale, Such as the Value of Combined Technologies, Leads to New Insights and Options

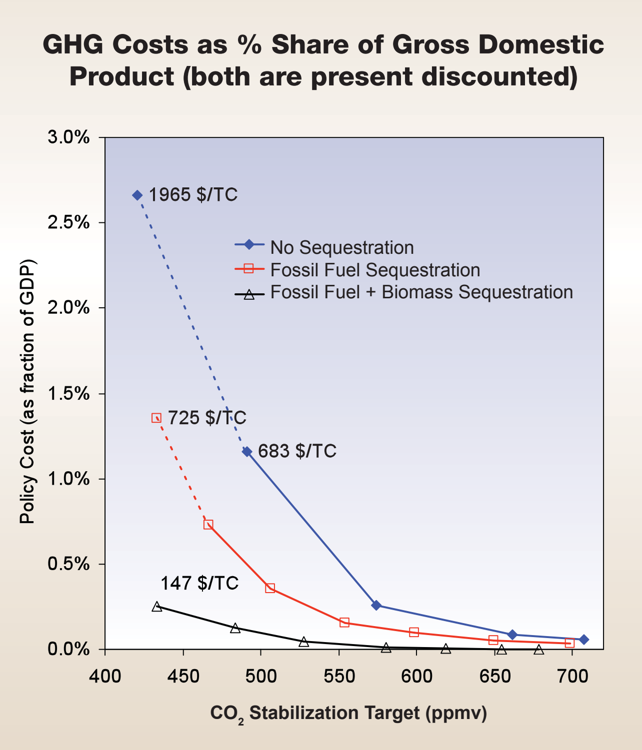


Fig. 3.5. Exploring Systems Interactions at Scale, Such as the Value of Combined Technologies, Leads to New Insights and Options. Technology is paramount in estimating the costs of climate change mitigation. For example, combining bioenergy with CO_2 capture and storage appears particularly powerful in reducing the costs of achieving very low CO_2 concentrations, as the black line in this figure shows.

Improving Insights into the Role of Technology and Economics for Stabilization

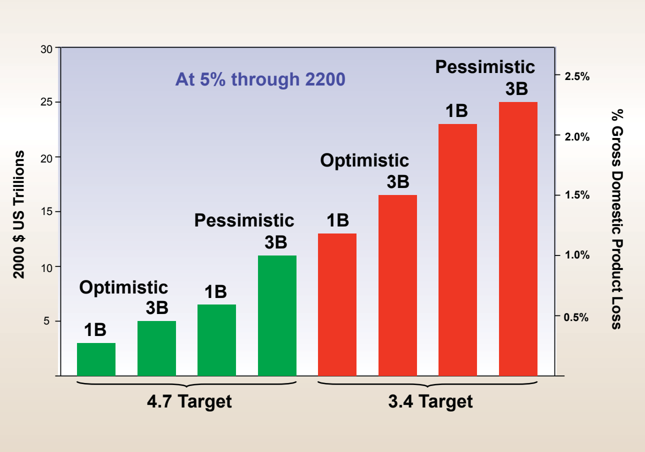


Fig. 3.6. Improving Insights into the Role of Technology and Economics for Stabilization. This figure, from analyses conducted using the MERGE model, shows the costs of mitigation for meeting different long-term climate goals with different assumptions about technology evolution and the degree of international participation in climate mitigation (first-best and third-best options). In this way, IA modeling provides insights into the consequences of approaches to climate mitigation and technology evolution. It demonstrates that improved technologies can have strong consequences for the economic costs of meeting climate goals. Source: Richels et al. 2007.

Using IAMs to Develop Insights into Interactions Among Different Components of the Human-Climate System. Human decisions are the major factors affecting many aspects of the coupled human-Earth system on time scales of a few years to a decade. This linkage has been established frequently in scientific literature during the past decade in issues ranging from the increase in hypoxic areas in coastal regions to the rise in atmospheric CO_2 and subsequent changes in the climate to the doubling of biologically available nitrogen through fertilizer production and fossil fuel combustion. IAMs are uniquely situated to analyze the interactions of human decision making with other components of the Earth system, whether biogeochemical or climatic, and with different components of uncontrollable natural variability.

3.1.3 Interdependencies and Critical Connections

Progress on the major challenges and research tasks for mitigation involves several areas in which the IAM community already has well-established research traditions, especially in modeling how technologies enter the economy and diffuse according to well-understood principles. However, in other areas, progress within the IA community depends on progress being made in those other areas in the representation of technology insertion.

First, the IA community would benefit from continued improvements in information provided by engineers and analysts on the cost and performance of energy technologies. No IA group is large enough to do such work on its own. Moreover, involving experts on the technologies in question will enhance the utility of IAM results. For example, IAMs will not model the U.S. electricity grid to the level captured by models focused specifically on the grid. IA research therefore must continue to support the development and use of such domain-specific models and the linkage of their results and insights to the IA community.

Secondly, the IAV community and the decision makers with whom they traditionally work need to make progress on understanding the interplay among land uses; the demand, availability, and management of water; and feedbacks with the physical and biological climate system (see Fig.3.7). Ensuring that the IAM community reasonably represents this knowledge base is a challenge all modelers face. However, the IAM community cannot, in any sense, replace or duplicate the expertise needed to build the underlying knowledge base.

Finally, the IAM community needs experts on development paths in different parts of the world to focus on how energy options might change, what the actual opportunities are, and how the interplay between energy supply and demand might differ in those regions. Again, no individual IAM group can or should recreate this knowledge base, but they need to incor-

Developing Improved Understanding of the Linkages Between Land Use and the Earth System

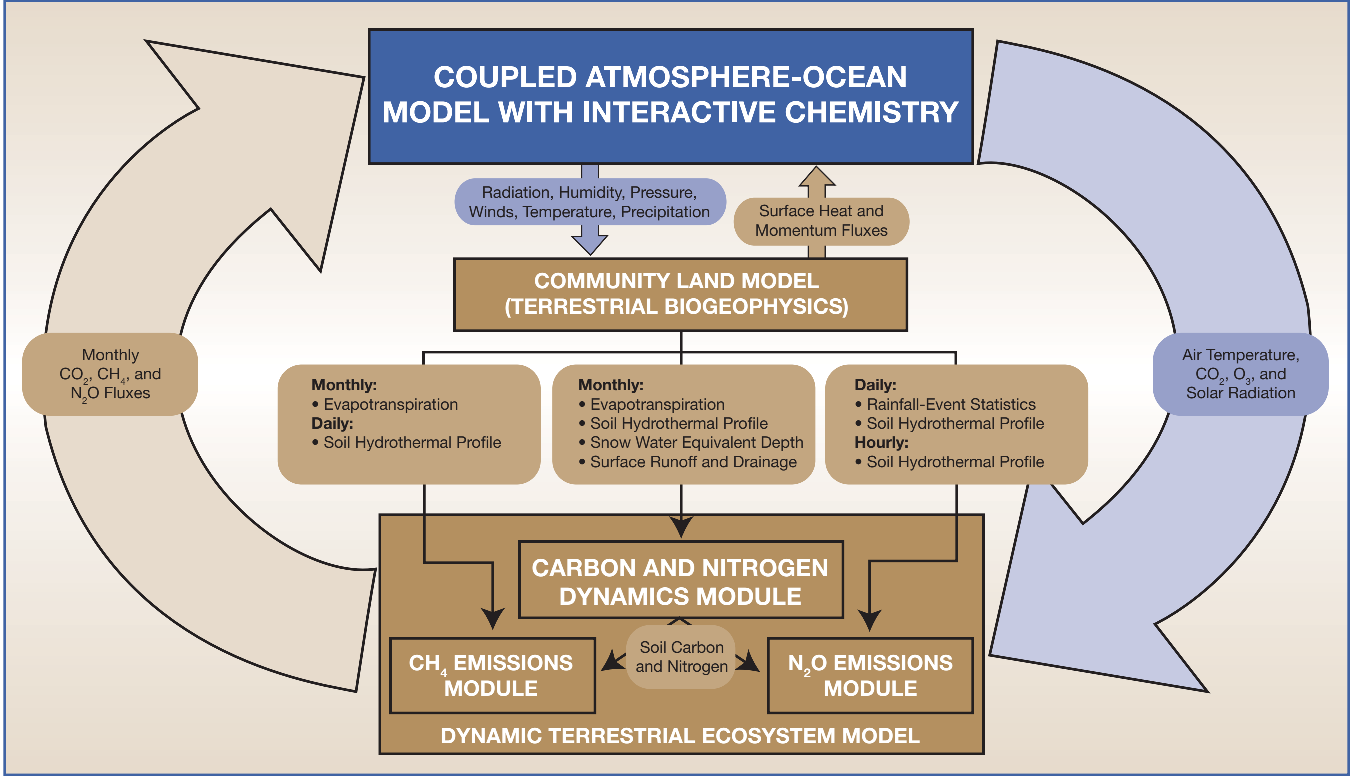


Fig. 3.7. Developing Improved Understanding of the Linkages Between Land Use and the Earth System. This figure shows the interactions and feedbacks between the atmosphere-ocean system and terrestrial biosphere, as represented in the Massachusetts Institute of Technology's (MIT's) IGSM. The atmospheric model provides climate variables to the community land model, adapted from a version developed by the National Center for Atmospheric Research, that feeds heat and moisture fluxes back to the atmosphere. A terrestrial ecosystem model receives data on soil conditions and other factors from the community land model and atmospheric submodels and computes CO_2 fluxes and the natural emissions of two non-CO_2 GHGs: CH_4 and N_2O. Fluxes of those gases then are fed back to the coupled atmosphere-ocean model. These interactions are computed on different time steps depending on the nature of the terrestrial processes.

porate progress other research communities continue to make. Of particular interest are issues associated with both the uptake of end-use technologies in places where a range of market failures is known to exist and the uptake of new technologies in developing regions that are increasingly responsible for the bulk of global GHG emissions.

3.1.4 Implications of Improvements

The ultimate impact of making significant progress on the identified research tasks and challenges requires a far more sophisticated understanding of the actual technologies that might be available for mitigating GHG emissions and an equally sophisticated understanding of the potential environmental and economic constraints that might influence the spread of those technologies. One benefit would be decision makers' ability to examine, for the first time, the consequences of international architectures in which all nations do not act uniformly. This, in turn, would lead to an understanding of the implications of such scenarios for the chances of meeting particular concentration or climate targets.

Precisely anticipating exactly how decision makers might use such an analytical capability is impossible. However, the insights generated by enhancements of

IA research and modeling in these areas undoubtedly would increase their utility to decision makers as they transition from formulating broad, general strategies to asking more specific questions about the timing and character of mitigation implementation.

IAMs already are used in part to examine the possible consequences of investments in different technology portfolios. For example, they are useful for understanding which investments potentially could result in large differences in mitigating GHG emissions. Such analyses, while valuable, could be enhanced considerably if IAMs not only had better representations of the technologies themselves, but were better able to analyze the complexities of the energy systems in which they were embedded and the actual dynamics of how those technologies might be introduced and spread. In addition, if IAMs were to begin successfully incorporating adaptation strategies and technologies into their frameworks similarly to how they now incorporate energy technologies, they could serve in principle the same sort of function for thinking about infusions of the combination of mitigation and adaptation technological responses. This could be a potentially valuable contribution to decisions about which R&D investments might have large consequences for responding to climate change.

One of the most profound scientific challenges facing IAMs and their underlying research is the need to strengthen the treatment of IAVs related to climate change. For both climate change science and policy, the “so what?” of climate change is increasingly salient, and better representations of IAVs and their interplay with energy and GHG mitigation issues is a high priority for research.

3.2 Impacts, Adaptation, and Vulnerability

Energy systems, agriculture, human health, coastal systems, and infrastructure would be affected dramatically by droughts, heat waves, intense storms, rising sea levels, and temperature shifts that climate change could bring. IAMs must improve representations of these combined, interactive effects under various mitigation and adaptation scenarios.

Key Research Questions

- What process knowledge must be incorporated into IAMs to reflect sectoral impacts and adaptations? Based on the field of IAV, a critical source of knowledge for IAMs, what are the significant knowledge gaps?
- What mechanisms can be used to capture impact and adaptation information that is not amenable to modeling, economic, or risk estimation? What alternative metrics exist?
- What interactions occur between sectors, and how can these be represented and modeled?
- What are the spatial and temporal dimensions of impacts and adaptations that will define appropriate scales by sectors?
- How do we reflect the nonlinearities of impacts, realizing that many human and natural systems exhibit thresholds for tolerance?

3.2.1 Current Status

Climate change impacts have been the major focus of IPCC's Working Group II and an entire series of the Climate Change Science Program (CCSP) Synthesis and Assessment Products (SAPs). There is a growing body of knowledge about some impacts, particularly for ecosystem processes, agriculture, and natural resources. Climate-driven impacts to forests, agriculture, drylands, water resources, coastal areas, biodiversity, and human health and settlements already are being observed (CCSP SAP 4.3 2008a, b and IPCC WG II 2007) and are expected to grow during the next several decades. However, investments in research on climate change impacts and adaptation have accounted for only a small fraction of total climate change science funding, and the resulting knowledge often is limited and incomplete (National Research Council 2007).

Knowledge gaps are particularly acute for understanding adaptation strategies. Besides several studies on the prospective costs of hardening coastlines against sea-level rise (CCSP SAP 4.1 2009), there has been little focused research on the potential availability, costs, and effectiveness of a suite of adaptation strategies to prepare for and react to changes in climate. Similarly, not much work has been done on prospective adaptation (i.e., investments or changes in management practices that would enable society to avoid adverse impacts rather than simply cope with them). Vulnerability is the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate variability and change (IPCC WG II 2007). Vulnerability to climate change is described as a function of the character, magnitude, and rate of climate variation to which a system is exposed; its sensitivity to that exposure; and its ability to avoid, prepare for, and effectively respond. Both the National Research Council (2009) and the IPCC's Working Group II have identified this topic as a critical research area.

With respect to impacts and adaptation, several IAM groups have a history of exploring impacts in agriculture and ecosystems. Indices of country-level vulnerability to climate change have been developed and used to investigate the potential interaction of impacts, vulnerabilities, and different magnitudes of climate change (Brenkert and Malone 2005; Malone and Brenkert 2009; Yohe et al. 2007; Yohe et al. 2006a, b). In addition, IAMs are beginning to investigate the linkages among impact domains and mitigation questions (Wise et al. 2009), but this area is in its infancy. No IAM group has done significant modeling of adaptation strategies as a focused area of research.

Scientific research into vulnerability and adaptation needs to incorporate climate information at a local scale and develop noneconomic measures of ecological effects useful to the lay public. Vulnerability to climate change comes at very different scales, from threats to survival of a whole country or society (e.g., drought, migration, and conflict) to social and environmental damage at a local scale (e.g., local coastal damage and loss of species habitat). Diverse groups of analysts—referred to as the IAV community—work on these issues more or less individually, often with poor connections to analysis of the driving factors within climate and economic systems. Isolated analyses can lead to mistakes because many of these effects are interdependent, and adaptation measures can interact positively or negatively with mitigation actions (e.g., large-scale wind or solar installations may change both land use and local climate, influencing species habitat). An example of the need for integrated analysis is the building of sea walls in anticipation of greater storm risk, which will cause, in some cases, the loss of wetlands trapped behind the sea-wall barrier.

3.2.2 Major Scientific Challenges

Incorporating Separately Developed Impact Sector-Specific Models. There is a long tradition of using models to investigate many climate impacts, particularly in the ecosystem, agricultural, water resource, and coastal impacts communities (National Assessment Synthesis Team 2000, CCSP SAP 4.1 2009; CCSP SAP 4.3 2008a, b; CCSP SAP 4.5 2008; Ebi et al. 2008; IPCC WG II 2007). In the health impact domain, a special issue of the journal *Climatic Change* was devoted to incorporating health into IA modeling and the Massachusetts Institute of Technology (MIT) is working on incorporating air pollution and heat impacts. Such efforts primarily have been based within their individual disciplines and have offered insights into both the sensitivity of those impact sectors to climate change and, when coupled with observations, a measure of the expected magnitude of impacts. However, because these impact models have originated in separate disciplines, few studies have examined the interactions among impact sectors (e.g., the interaction of changes in water supply with either ecosystem or agricultural productivity). In principle, IAMs should be able to incorporate insights from such separately developed models and then investigate the interactions among sectors. In practice, there is some effort in the IA research community to integrate independently developed impact models, either through model coupling or by incorporating the critical elements of the independent models. From an impacts perspective, IAMs have not yet fully incorporated water resources and the hydrologic cycle, so the study of interactions among impact domains amenable to modeling needs more attention.

Incorporating IAV Knowledge that Does Not Originate in Models. Considerable knowledge about IAV has been captured in numerical models. However, a growing body of knowledge about observed and potential impacts and about adaptation strategies does not originate within a modeling tradition and thus is more difficult to incorporate into IA models. For example, although both direct and indirect health impacts from climate change have been documented (IPCC WG II 2007; Ebi et al. 2008) and probably can be expected to increase as the climate continues to change, this knowledge has not been captured yet within IA models; neither have the costs and effectiveness of adaptation strategies. Projections of vulnerability indices have been derived from IA model calculations (Malone and Brenkert 2008; Ibarrarán et al. 2008), but these typically have been used to characterize broad categories at a country level. In addition, the aggregation within IAMs sums over disparate and sometimes unacceptable risks. Pursuing integrated systems analyses of such impacts and adaptation domains as well as a concerted effort to consider how they might be incorporated into modeling frameworks would be highly worthwhile.

Alternative Metrics of Impacts, Adaptation, and Vulnerability. IA models are designed to address tradeoffs and interactions among different sectors based on economic values. However, particularly for IAV, while market economics are clearly important, they are by no means a complete description of how and why different sectors and resources have social value. Other metrics may be equally or even more important than prices and market value. For example, the entire concept of ecosystem services (Janetos et al. 2005) has arisen within the ecological community precisely because ecosystems provide many services (e.g., regulating water flow and quantity and maintaining soil fertility and biological diversity) that are not priced and thus do not enter markets directly. Nonmarket valuation techniques are well known in economics literature, but IAMs that have specific representations of impact domains automatically maintain information about ecosystems, sectors, or regions in their natural, noneconomic forms. So, for example, while IAMs naturally calculate the economic returns from forestry, their ability to track carbon flows also means they calculate land-use change and, in most cases, actual carbon storage in forests, a key ecosystem service. Although IAMs can do this for some impact domains, they clearly cannot do so for all for reasons identified above. Selecting appropriate metrics for adaptation and vulnerability issues is in its infancy compared with identifying metrics for physical or natural resource impacts. Research clearly is required to first develop appropriate metrics for adaptation and vulnerability studies and then determine how such metrics might be best incorporated or derived from IAM modeling frameworks.

Understanding Multiple Interacting Stresses. For human and human-managed systems, impacts and adaptation are driven by forces other than climate alone, including demographic, technological, institutional, and economic changes in a globalized world. However, scenarios of these other drivers and associated variables generally are unavailable over time scales equivalent to those of climate change scenarios. For example, changes in transformational technologies in energy sources and adaptation options, such as affordable desalination, could alter current assessments of impacts and adaptation prospects. Even unmanaged natural resources respond to multiple driving forces—including changes in the climate system itself, resource exploitation, and nitrogen deposition—and these are not necessarily captured in IAMs. Thus, multiple challenges present themselves. First, IAMs need to develop the ability to capture the range of multiple interacting stresses both for unmanaged and managed ecosystems and for human systems. In addition, IAMs and their associated research community need to develop new scenarios of nonphysical drivers of economics, demographics, and technologies. Such scenarios should be developed jointly with IAV researchers to ensure their interests and needs are met, as they likely will differ in both scale and the particular variables tracked.

Regional and Local Heterogeneity and Data. The natural scale for investigating many climate-related impacts and adaptation is intrinsically regional or local. This raises significant challenges for IAMs because most have been designed to study large regions or the globe rather than smaller regions or localities. However, the pressure for IAMs to be more regionally specific is not limited to IAV topics, as outlined above. So while incorporating regional-scale IAV knowledge and relationships will be a challenge for IA research, this task has common elements with other parts of the IA research agenda. An additional challenge, however, is that data on IAV are more heterogeneous than many of the data IAMs are designed to encompass. This diverse information ranges from physical and economic impacts to characteristics of governance to human capital and demographics. IA researchers will need to work with IAV experts to determine how best to represent such a wide range of information and knowledge in model frameworks.

Tipping Points and Nonlinear Dynamics. Many ecosystems and natural resources clearly do not respond to climate change in a slow, continuous, and linear fashion. They often respond discontinuously and nonlinearly and in ways difficult to predict or simulate numerically. There are numerous well-studied examples of nonlinear ecosystem responses, but predicting such responses is difficult. Nevertheless, responding to extreme events, tipping points, and threshold dynamics in ecosystems is extremely important to decision making about impacts and thus is an issue that demands attention in IA modeling research (see Fig. 3.8). The need to understand tipping points, thresholds, and nonlinear dynamics in impacts and adaptation research also has implications for how IAMs pass information back and forth with their atmospheric and climate components.

Adaptations, Vulnerabilities, and Significant Knowledge Gaps. Adapting to the consequences of a changing climate is one part of an overall response to climate change as an issue. Adaptation as a policy response has gained substantial attention recently for reasons similar to those surrounding climate impacts. One such reason is that adaptive responses already are occurring to impacts clearly related to variability

Improving Models for Assessing New Impacts: Ocean Acidification

$$\mathrm{CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow HCO_3^- + H^+ \Leftrightarrow CO_3^{2-} + 2H^+}$$

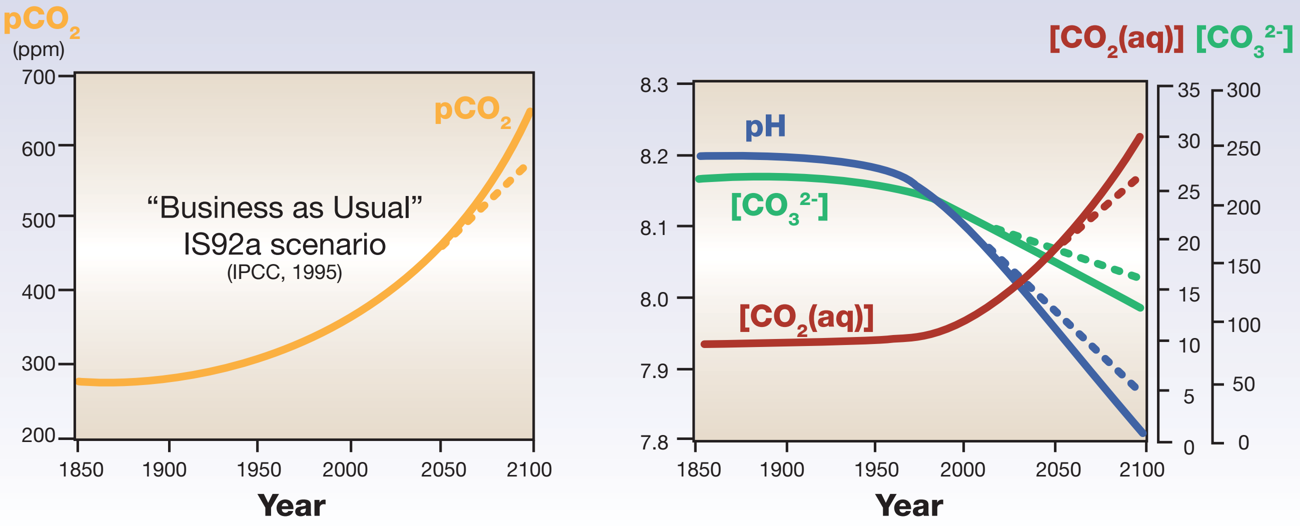


Figure 3.8. Improving Models for Assessing New Impacts: Ocean Acidification. IA models can improve our ability to understand how physical and biological systems respond to different GHG concentration scenarios. Important for IA is understanding the implications of a range of affected human and natural systems, including but not limited to ecosystem services.

and change in the physical and biological climate system. Such impacts in domains like natural resources and human health are prompting responses to these impacts from different countries and societies. Secondly, researchers are learning more about the overall capacity for adaptation, both in terms of the effectiveness of response strategies and the determinants for how much adaptation is possible in different societies. The research community is starting to discover the limitations of current knowledge about determinants of adaptive capacity, especially as studies begin to document actual impacts of similar types of effects (e.g., heat waves) in different circumstances and societies (e.g., the United States and Western Europe). Thirdly, diverse stakeholders increasingly are demanding the development of adaptation options as preparatory measures to provide amelioration of costs or harm that otherwise would occur. Within the United States, a recent report from the U.S. Government Accountability Office highlighted the need for such information to develop adaptation responses for U.S. land and natural resource management agencies (GAO 2007). Similar demands for information and guidance are arising from urban infrastructure managers, water managers, state and local officials, and the private sector. However, significant weaknesses in the IAV knowledge base are a lack of information on the cost and effectiveness of adaptation strategies and a lack of consistent metrics to evaluate vulnerability of social systems. These are topics the IAV community itself needs to pursue but they also should form the basis for more integrated collaborations with the IA community.

3.2.3 Interdependencies and Critical Connections

Needed improvements in the foundations of IAV science are too extensive to describe in this document, which is focused on relationships between IAV and IA research and modeling. For these relationships, some of the programmatic directions in the coming years are clear, such as continuing to strengthen the IAV-IAM connection and benefiting from linkages with other ongoing activities like those undertaken by the U.S. Global Changes Research Program, IPCC, and the NAS and NRC.

Ultimately, the progress that IA researchers are able to make in incorporating the concerns and knowledge of the IAV community is limited by the IAV community's progress on its own priorities. Even though significant gaps remain in understanding certain aspects of IAV topics, there is enough specific knowledge in some sectors and domains to enable enhanced interaction between IAMs and IAV research that will lead to new insights.

3.2.4 Implications of Improvements

The potential for IAM-IAV interactions to produce new capacities and emergent knowledge for the science of climate change response is especially exciting and in some cases potentially transformational. Exploiting these opportunities will require effective collaboration and program support. Examples of potential improvements include the following:

- Capacities for IAMs to incorporate climate change impacts and adaptations for carbon emission sources and sinks into projections of net carbon emissions under different scenarios
- Capacities for IAMs to answer decision makers' questions about the effects of different climate change response strategies on climate futures, integrating both mitigation and adaptation strategies and policies, as well as the costs and benefits of various options
- Improved capacities for the IAV community to view impacts and adaptations in an integrated way across sectors and regions
- Increased attention by the IAM community to regional and local scales and to relationships among processes and phenomena at different scales
- Collaboration between the IAM and IAV communities in developing families of socioeconomic scenarios and storylines that can be used to enhance consistency in this regard across the portfolios of IAM and IAV research.

3.3 Spatial and Temporal Resolution

Planners and resource managers need detailed information about the local and regional effects of climate change, projections of societal development options, and the combined economic and risk implications. Understanding these effects at spatial and temporal scales that matter to decision makers poses a critical challenge and opportunity for next-generation IAMs.

Key Research Questions

- What are the appropriate methodologies and numerical techniques for downscaling and upscaling within IAMs and across modeling domains?
- What can be learned from downscaling national IAMs to provide regional insights?
- What might be learned through a new class of regionally specific IAMs? How might both upscaled versions of these and downscaled versions of national IAMs provide complementary perspectives and accelerate learning and model development within the field of IA?
- What are the inherent differences and similarities in scaling across mitigation and adaptation and, more specifically, economics, natural Earth systems, and impact sectors? How do the scales differ for these various aspects of decision making?
- Are the data available at the required scales?

3.3.1 Current Status

Decision makers are expressing growing interest in questions concerning climate change and adaptation, mitigation, and impacts at local and regional scales. Currently, however, a gap exists between what IAMs provide and what decision makers need to explore the regional consequences of responses to climate change for either mitigation or adaptation.

Although substantial confidence is placed in the ability of climate models to predict global and continental mean climate changes caused by anthropogenic GHG forcing (IPCC WG I 2007), large uncertainties remain in climate model projections of temperature, precipitation, and other changes at the regional scale. The climate modeling community has adopted two distinct approaches to using current-generation global climate models to project regional or local climate change (see, for example, Hayhoe et al. 2008). Such projections are generated either by providing boundary conditions for higher-resolution regional or global climate models (dynamical downscaling) or by using relationships between simulated large-scale conditions and observed climate data to predict regional or local climate (statistical downscaling). Although both methods provide added value at the regional scale by explicitly or implicitly including the effects of regional-scale processes, their accuracy depends on the large-scale circulation simulated by global models (Giorgi et al. 1998; Leung et al. 2004).

To address uncertainty in climate change projections, a few coordinated projects have used a multimodel approach in which multiple regional models driven by multiple global models are used to generate an ensemble of regional climate change scenarios to characterize uncertainty (Christensen et al. 2007; Giorgi et al. 1998). Upscaling from the regional to global scale is not considered in these approaches, except when high- or variable-resolution global models are used in dynamical downscaling.

Downscaling is used in IAMs to provide finer-resolution emissions of GHGs and SLS as well as land cover or land-use scenarios for climate models to project future climate. The MiniCAM model, for example, downscales land use from 14 MiniCAM regions to a 0.5-degree grid. Emissions are distributed from the 14 regions to individual countries, and dated country-scale emissions projections are distributed to a 0.5-degree grid by scaling base-year-gridded emissions.

Although downscaling can be used to provide more spatially resolved scenarios for climate projections, models that are used to develop scenarios for emissions, land cover, or land use have coarse resolution, so regional processes are not considered explicitly in IAMs. Recently, researchers have developed economic models with better sectoral resolution (IPCC WG I 2007) and higher geospatial disaggregation to improve resolution of individual countries rather than economic zones. For example, the AIM model is designed to resolve individual countries in the Asian Pacific, as opposed to three economic blocks in other IAMs such as the IMAGE model. Improving both sectoral and geospatial resolution is an ongoing task for IA modeling.

3.3.2 Major Scientific Challenges

To achieve regional specificity in next-generation models, four major scientific challenges must be addressed. These challenges and the associated requirements for both IAMs and ESMs are discussed below because (1) these models depend on each other to provide more detailed descriptions of human and Earth systems, respectively, and (2) the IAM and ESM communities have begun to fully integrate their models to simulate the feedbacks between human and Earth systems that determine their evolution. The goal is to enable IAMs to resolve regional processes so that the models can address—in a single modeling framework—mitigation, impacts, and adaptation issues relevant to regional policy and can take advantage of future-generation computing environments.

Process Scaling and Nonlinearities. Nonlinearity in human and Earth system processes suggests that modeling such processes at the regional scale is important to improve simulations at both the regional and global scale. Although high resolution is desirable, models are only as good as the knowledge, insights, and data used to develop them. Ultimately, the resolution of models should be determined by the scale of the processes involved. Hence, a major scientific challenge is to elucidate the spatial and temporal scales appropriate for modeling different components in IAMs and ESMs and to develop modeling approaches and evaluation techniques that respect the scales of the processes involved.

Increases in computational resources and availability of datasets with high spatial resolution will enable next-generation models to be applied at much higher resolution. The path to achieving this goal is not straightforward. In climate models, many computational, mathematical, and parameterization constraints need to be resolved before models resolvable at the regional scale become a reality. A program to create these high-spatial-resolution models will need to further develop and test mass-, energy-, and momentum-conserving numerical schemes that are stable, scalable, and robust when operating on hundreds of millions of grid cells and computational time steps of a few seconds. Capabilities to handle model input and output of data also are important.

While future climate models will be able to resolve mesoscale and even cloud processes, human system models also must increase their spatial specificity to provide insights into human-Earth system interactions at the regional scale and to address climate impacts and adaptations. However, unlike for physical models, determining which scales are more appropriate for modeling human systems is less clear, as is establishing how to ensure aggregated results from regional models correspond with coarser-scale models. As economic models become more representative of regional economies, online coupling of climate and economic models will become feasible. This will enable regional-scale simulations to accurately represent feedbacks between climate and climate extremes and land use, the carbon cycle, and emissions of GHGs and aerosols.

Interfaces Among Physical, Economic, and IAV Model Components. Given the disparity of scales across different systems and the limitations imposed by computational resources and available data, future-generation IAMs and ESMs likely will adopt different spatial resolution or attributes (e.g., grid versus region) for modeling different systems, and nesting may be required to achieve higher resolution. A major scientific challenge is to develop model interfaces and downscaling and upscaling approaches that preserve and use insights gained through regional-scale modeling and analysis.

Different components of IAMs and ESMs probably will operate at different spatial resolutions and domains to allow different processes to be represented most accurately and efficiently at their own temporal and spatial scales. Upscaling and downscaling thus must serve the purposes of linking across scales and across processes or components (e.g., between human and natural processes). An important property of upscaling and downscaling methods is that they preserve certain quantities across different scales and processes. For models of the physical Earth system, the flux exchanges across models or nests must be conserved. For models of a human system, such as an economy, criteria for effective interfaces involve ensuring that information from global- and continental-scale analyses is used to provide constraints or boundary conditions for regional analyses. Conversely, criteria also are needed to ensure that insights from regional-scale analyses are communicated effectively to the larger or global scale and that conservation is maintained for certain quantities. One-way couplings of IAMs and ESMs already demonstrate that, at a minimum, emissions of both GHGs and chemically active species that are calculated by IAMs as a result of economic drivers need to be passed consistently to ESMs. In addition, emissions from land-use histories need to be reconciled between the two for the initial carbon cycle representations in the models to converge in the modern period. More research is needed to assess the adequacy of existing upscaling and downscaling methods and to determine developments needed to address model interfaces across different components with possibly widely varying spatial and temporal scales (see Fig. 3.9).

An additional conceptual challenge is that of matching temporal scales of the models involved. As with spatial scales, processes in both ESMs and IAMs have their own intrinsic dynamics that need to be respected in each model. For example, weather forecasting does not demand careful representation of the heat content of the deep ocean, but climate simulations do. Similarly, most IAMs are not designed to track year-to-year fluctuations in energy demand or prices, and it is not clear that they should. However, tracking energy-related processes on time scales as short as 5 years, for example, raises new considerations for tracking the evolution of the energy infrastructure that coarser temporal resolution does not demand. These issues of appropriately matching the temporal scales of different processes in ESMs and IAMs will need the same level of attention as moving to more highly resolved spatial scales.

Data Matching. Developing a new generation of high-resolution models requires synthesis of past data and new observational datasets to provide the necessary information for parameterizing human and Earth system processes and evaluating model effectiveness. The disparate temporal and spatial scales across different datasets also must be reconciled to make them more useful to the modeling community.

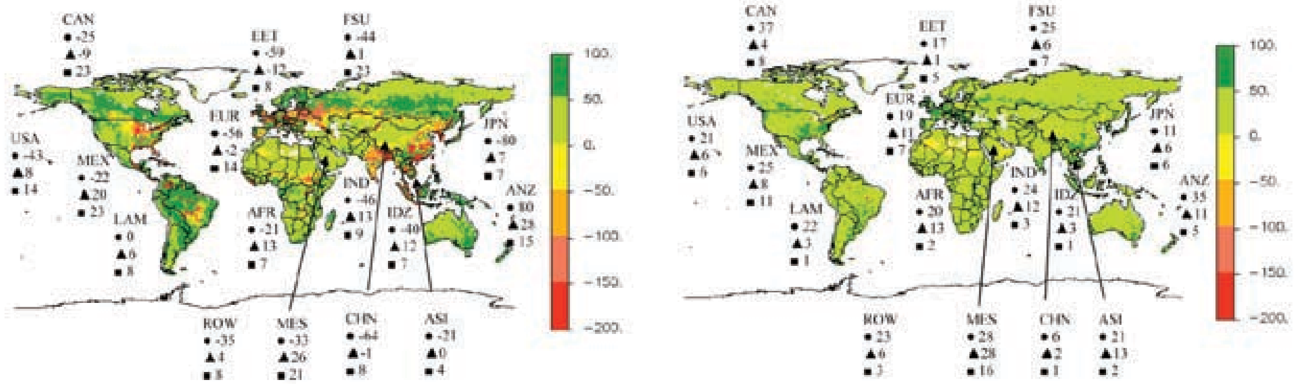
High-resolution data are needed to support the development and evaluation of high-resolution models. An effort to develop high-resolution data should include evaluating and integrating available datasets at local and regional scales (e.g., the Global Trade Analysis Project); producing grid-based data collections for geography, climate, vegetation, soils, and land management; identifying critical, currently unmet data needs for model evaluations at local to regional scales; and initiating new data collection and archiving efforts.

On a regional basis, data needs can vary widely for significant climate impacts such as agriculture, health, and hydrology. Factors that describe the local environment are vitally important in explaining future responses, resilience, and thresholds. Examples of these factors, which also are region-specific, include historical soil development, plant genotype diversity, abundance of invasive species, and land-use intensity. Developing regional-based approaches for data collection may be more effective in supporting modeling needs, yet a central archiving facility and standard archiving formats and procedures will facilitate cross-referencing and wider data use. A standard geospatial referencing system for both Earth system and human system data should be considered.

Scale and Model Uncertainties. Analyzing uncertainty is an important aspect of climate change assessment, whether the goals are related to mitigation, impacts, or adaptations. Additional challenges in moving toward higher spatial specificity in models include characterizing uncertainty at the regional scale and understanding and modeling the propagation of uncertainty across global, regional, and local scales.

New developments in models must be validated with observational data. Establishing a robust validation process that spans local, regional, and global scales is of highest priority. Such a process includes comparison of model simulations with observations, analysis to diagnose model sensitivity and biases, model intercomparison, and development of metrics to systematically assess and document model skill. The climate modeling community has

Exploring the Regional Consequences of a Changing Climate on the Terrestrial Environment



High Urban Pollution, No GHG Control **GHG and Pollution Capped**

● = crops ◆ = pasture ■ = forests

Fig. 3.9. Exploring the Regional Consequences of a Changing Climate on the Terrestrial Environment. Crop, pasture, and forest productivity are influenced significantly by climate change, CO_2 fertilization, and damage from ozone resulting from urban air pollution. For each of the economic regions in MIT's IGSM, the figures show the effects on yield (crops) and net primary productivity (pasture and forestry) between 2000 and 2100 (gC/m^2/yr).

significant experience in these processes, but previous activities have focused more on coarser global scales. Model evaluation at local and regional scales brings new challenges because regional processes or phenomena are wide ranging, and the separation between time and space scales is less well defined. Thus, the metrics and analysis and diagnostic tools developed for the larger scale must be expanded to evaluate model simulations at the regional scale. An example is extreme events, which are expected to be simulated more realistically at high resolution. Climate impacts, adaptation, and economic costs related to future changes in extreme events are significant motivations for improving the regional specificity of IAMs and ESMs.

The IA research community has used similar model evaluation processes such as model intercomparison and sensitivity analysis to assess IAMs and understand model behavior. Coordinated efforts to develop a common set of model experimental protocols, analysis and diagnostics tools, and metrics are effective ways to establish standard practices that can be adopted by the IA community. Such activities can provide the foundations for research to evaluate IAMs at the regional scale.

Providing information on model uncertainty is important if modeling or assessment results are to be used to inform policy decisions. While some progress has been made in recent years—typically by using a multimodel ensemble approach to characterize uncertainties and assess their sources—additional research is needed to develop more robust mathematical and statistical frameworks to assess model uncertainty. More specific to regional scales, research is needed to understand and characterize the propagation of uncertainty across scales. This characterization is particularly important because future models probably will adopt different model domains or resolutions for the different systems being modeled, so propagation of uncertainty across the systems and scales will be inevitable and must be addressed. A potential growth of errors from the global to regional scale has significant implications, including the need for larger ensembles of model simulations to reduce noise (which requires even more computational resources in addition to the large requirements for model simulations at high resolution) and difficulty in interpreting results.

3.3.3. Interdependencies and Critical Connections

For IAMs and ESMs to succeed in increasing regional specificity, significant advances are needed in computing environments and data management. The community responsible for data collection, curation, and synthesis can play an important role in supporting regional data needed for regional-scale modeling. The ESM and IAM communities will be completely interconnected in moving to finer regional and temporal scales and in assessing the performance of new, integrated models of both human and physical Earth systems. Each community's progress therefore is ultimately co-dependent upon improvements in the other.

3.3.4 Implications of Improvements

Successful development and implementation of research that focuses on improving the spatial specificity and temporal resolution of next-generation models will elucidate regional human-Earth systems interactions critical to assessing climate change impacts, adaptations, and mitigation. The resultant information can be used to inform decision makers on the regional consequences of mitigation or adaptation responses to climate change policy and the actual implementation of such responses on regional scales.

3.4 Risk, Uncertainty, and Diagnostic Methods

Human decisions, such as locating settlements in vulnerable areas, are complicated by the challenges of addressing probabilities in models of human–Earth system interactions. IA models are only beginning to explicitly address dimensions of risk and uncertainty.

Key Research Questions

- How can risk and uncertainty information be developed in IAMs that will help inform decision makers?
- How do we reconcile and treat different categories of uncertainty—from human behaviors to global earth processes?
- In exploring more interoperable modeling frameworks, such as linkages between IAMs, ESMs, and IAV models, how do we handle uncertainty propagation across modeling domains?
- What visual and other display methods can best facilitate decision making? How do we communicate risk?
- How can economic and risk perspectives be combined to provide more powerful insights than either independently?
- What new insights can be developed, both regarding model characteristics and the modeled processes, through improved model intercomparisons and testing?

3.4.1 Current Status

This section discusses the interrelated topics of dealing with uncertainty in IA and IAM validation. A crucial part of assessing what constitutes a good approach to uncertainty analysis and a good way to validate an IAM is to always make that evaluation relative to the specific question being asked. A particular model is only "good" or "bad" in providing useful information relative to a specific decision under consideration. Likewise, a particular model is only "better" or "worse" than any other model relative to its usefulness in addressing a particular question. No one model can be expected to be good for answering all questions that might be asked, and a model might be good for answering certain types of questions but not others. Correspondingly, this section also addresses the fundamental issues of whether IAMs can be assessed independently from how they are used and by whom.

Uncertainty pervades the climate issue, and much attention has been given to its analysis by both the climate modeling community and IAM groups. However, a serious gap remains: the development of ways to express uncertainty in projections in a way that is useful for understanding climate change risk and managing that risk at the local level. Studies of a local climate threat often are conducted using one or a few climate scenarios, perhaps applying results at the scale of current GCMs, a grid scale of a box several hundreds of kilometers on a side, which is incapable of describing local effects at sufficient detail. Several challenges remain to be met to ultimately improve model performance. The first is to downscale from the GCM level to a smaller region and to integrate the results into analyses of the relevant climate effects. Even more challenging is the task of providing risk information, which frequently is needed by decision makers. The following example illustrates the need for a more comprehensive approach. Most states and cities have standards for the sizes of roof and street drains, and these standards are determined by calculations of a downpour of certain frequency and intensity. To date, this calculation has been based on a rainfall record considered to have stable statistical characteristics. However, this assumption no longer holds. To serve the new needs of these states and cities, assessment of their engineering standards must be integrated with analysis of GHG emissions, the global climate response, and the best possible representation of its local manifestation in precipitation patterns.

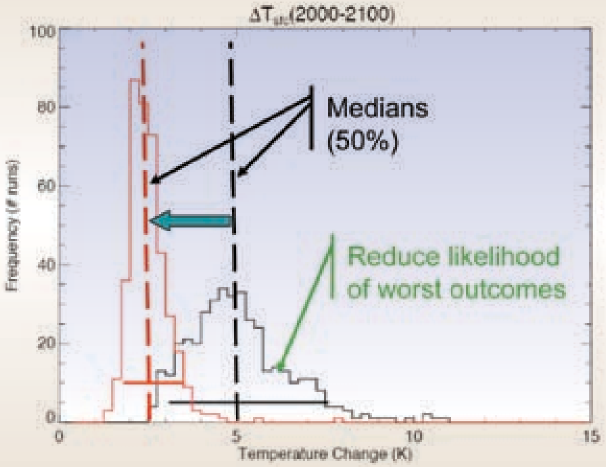
Three basic approaches to uncertainty analysis (with many variants) have been employed by the IA community: sensitivity analysis, stochastic simulation, and sequential decision making under uncertainty.

In sensitivity analysis, individual model inputs or parameters are varied systematically, individually, and collectively to determine how these variations affect the results produced. Simultaneously varying several key parameters is important to avoid underestimating the possibility of particularly good or bad outcomes. The sensitivity analysis approach also has been used by the climate change and climate impacts modeling communities.

In the stochastic simulation approach, probability distributions are assessed over the inputs and parameters of a model; then model simulations—in which values for the inputs and parameters are sampled from those distributions—are run so that corresponding distributions over key outputs can be developed (see Fig. 3.10). One challenge in implementing this approach is to identify and measure correlations among inputs that can have large impacts on outputs. In addition, extreme outcomes in general can be particularly important but also very difficult to quantify. Climate and ecosystem modelers also have used this type of uncertainty analysis, probably more consistently than the IA community.

The third approach to uncertainty analysis used by the IA community is sequential decision making under uncertainty. In this approach, initial decisions

Improving Our Understanding of the Tails of Probability Distributions



Black curve: No CO_2 stabilization policy
Red curve: Stabilization at 4.7 W/m2, implying CO_2 stabilization at approximately 550 ppmv

Fig. 3.10. Improving Our Understanding of the Tails of Probability Distributions. Stabilizing GHGs in the atmosphere would yield two benefits: (1) lowering the projection of the median temperature change over the 21st century, which is the level with a 50% probability of being exceeded, and (2) most affecting the upper tail of the distribution of change, lowering the likelihood of the most dangerous outcomes. The figure illustrates this phenomenon, showing results of uncertainty analysis using the MIT IGSM.

are followed by changes in the probability distributions over key inputs and outputs. Future decisions, contingent on how those probabilities adjust, can then be made after a specified period of time, and this process can be repeated for as many time periods as practicable and desirable. Because this type of contingent decision making is possible only with human intervention, it typically has not been used in physical and biological climate modeling.

Related to approaches to uncertainty analysis are approaches to model validation used by the IA community. These have included simple logic and conceptual tests of insights; model intercomparisons; and traditional peer review, both for academic journals as well as reviews and assessments organized by model developers or those who fund model development. Both the Energy Modeling Forum and the CCSP Science and Assessment Product 2.1a used model intercomparisons successfully to understand why different models perform differently when challenged with the same question. This approach also has been used successfully within the physical and biological climate and ecological modeling communities. Ultimately, model intercomparison does not address which models are more likely correct for the questions addressed, but it does perform a useful service for understanding why different models give the results they do.

3.4.2 Major Scientific Challenges

Modeling Risk and Quantifying Different Kinds of Uncertainty—Data, Parameters, and Model Structure. Using some of the model comparison and model assessment techniques employed by the physical science community on the physical science modules in IAMs is desirable. The standard techniques of running models with the human dimension components frozen and then experimenting with different formulations of the physical science components quickly would establish how well those components of IAMs functioned.

However, such methods are less well developed for the human systems represented in IAMs. Developing methods for characterizing the uncertainty in the socioeconomic drivers and structural elements of IAMs would be extremely useful. These uncertainties then could be combined with those for climate change and climate change impacts, resulting in comprehensive uncertainty assessments of climate policy options. This is a matter of both assessing data quality and evaluating the degree to which our fundamental understanding of those drivers is represented in IAMs.

Interpreting and Communicating Risk and Uncertainty. IAMs often have been used to develop policy insights rather than to make precise projections of key system variables. In these applications, the objective primarily is to determine whether a particular policy measure is likely to make some performance measure of interest better or worse (or sometimes provide a rough estimate of how much better or worse) or whether one policy is better than another in achieving a particular objective (or give a rough idea of how much better). In such studies, uncertainty largely is considered in relation to identifying conditions under which insights about policy interventions or system behavior are robust or not.

This focus on modeling for “insights rather than numbers” contrasts strongly with the typical uses of physical and biological climate models, whose main objectives generally have been to project key system variables like mean global surface temperature and to evaluate the accuracy of such projections through various approaches to uncertainty assessment. While the IA community will continue to spend a significant amount of effort developing and substantiating policy insights, its activities now have expanded to address questions regarding the accuracy of the forecasts it produces. There are two main reasons for such expansion. First, IA researchers are being asked by those involved in policy development to answer questions regarding more specific short-run policies and measures that can have direct and immediate impacts on the people who decision makers represent. For example, projections of direct economic or climate change impacts expected to result from specific policies—along with more precise measures of their projection uncertainty—have greater value than simply knowing whether such impacts are positive or negative, or whether the impacts resulting from one policy are better or worse than those resulting from another.

The growing focus on accuracy in addition to insights makes the development of both theoretical and computable methods for illustrating risk and uncertainty all the more important for the new generation of IAMs, especially as they become more closely linked to sophisticated ESMs and ecological (or other impact domain) models. Current practice focusing on producing probability distribution functions for particular model outcomes is computationally intensive and can be difficult to communicate. The analogue in the physical sciences of using large ensembles is computationally intensive, though tractable, but lacks a strong theoretical basis. This is an area in which new methodological development could yield important results fairly quickly.

Propagation of Uncertainty Across Model Components. There is a growing interest in integrating uncertainties in emissions projections with those in climate and impacts analyses to quantify uncertainties in impacts contingent upon policy interventions in the physical and biological climate system. Noncontrollable uncertainties regarding the state and operation of the climate system also must be quantified in these types of analyses. Another challenge is to characterize the net vulnerabilities to climate change that are contingent on both policy interventions on emissions and the application of adaptation strategies.

The different potential combinations of mitigation and adaptation decisions are essentially endless. Rather than attempting to explore all of the available decision space, fully integrated IAMs and ESMs, with appropriate inclusion of IAV components, will need to be explored in sampled subsets of parameter space. Careful attention then should be paid to how uncertainty in all the subsystems of the models is propagated across the integrated system and how that uncertainty will affect the interpretation of model outputs.

It would be extremely valuable to develop such a set of fully integrated models capable of analyzing sequential policy and research options under uncertainty. Crucial to this model development is the active participation of experts in subjective probability assessment because the formulation, estimation, computational, and interpretational dimensions of the assessment need to be designed and implemented in an integrated manner.

Validation: Confronting Models with Data and Observations. Unlike the climate and ecosystems modeling communities, IA researchers have not relied on running models over historical periods and comparing outputs with actual outcomes during that period, which is the so-called "backcasting" approach to model validation. There are at least three reasons for that choice. First, there are insufficient data on the historical period on social economic variables, including what the economic agents whose behavior is being modeled were expecting about future conditions when they made investments and consumption decisions. Second, most of the available historical data are used in estimating or calibrating model parameters, so a subsequent comparison of model and actual outputs would be highly biased. Third, given the structural changes that have occurred in the world economy, a model that predicted the past well would not necessarily predict the future well.

Despite difficulties in backcasting with IAMs, comparing IAM results with actual outcomes in a historical period that has taken place since the model was run could be useful in developing a set of case studies. This process would allow separating factors that are hard to project—like the demise of the Soviet economy—from those that should be easier to project—like the price elasticity of energy demand. Such studies could yield both benchmarks for future model-building efforts and lessons on the predictability of major trends in the structure of the world economy.

Model Intercomparisons. Model intercomparisons, like backcasting, have been an important tool in understanding why physical and ecological models' performances on similar tasks often produce different results. This approach has not been used as commonly in IAMs, but both the Energy Modeling Forum and CCSP have provided recent examples in which model intercomparisons have yielded important insights into initial decisions made by modelers and the effects of those decisions on model performance. For example, costs of stabilization scenarios are strongly dependent on whether a large or smaller suite of energy technologies is available within IAMs, especially in the second half of the 21st century. Although model intercomparison does not reveal whether having a large or smaller suite of technologies is correct or not, it does show that having this choice in the model structure significantly affects how different models perform a similar task, in this case stabilizing radiative forcing of the atmosphere. Other examples include different formulations of particular subsystems of an IAM. Understanding the implications of different ways in which the carbon cycle might operate, for example, can have important lessons for carbon management and thus point to specific scientific priorities and investments that could have high payoffs. It would be logical to continue to develop insights from IAMs to guide science priorities in a way that helps improve policy development.

Another possible approach to IAM intercomparison would be the development of a "community" IAM similar to the community climate model. The community model would be constructed by the modeling community as a whole to supply results that can be used in benchmarking those from each individual model, thus providing both pedagogical and validation benefits. Strict guidelines should accompany use of the community model to ensure that it is not run inappropriately, yielding nonsensical results.

3.4.3 Interdependencies and Critical Connections

Because most of the challenges discussed above involve strengthening interdisciplinary communication and cooperation, improvements in uncertainty analysis and model validation for integrated modeling require steady and decisive progress in these areas. Without mutual trust and respect, and mutual goals, progress will be slow at best.

3.4.4 Implications of Improvements

The ultimate goal of improving our ability to model under uncertainty is to give policy makers and the scientific community validated probability distributions for key climate policy outputs contingent only on the alternative policies policy makers are contemplating. These assessments would be extremely useful to individuals involved in policy development and implementation. They also would be valuable in helping to focus scientific research and IAM development in areas with the highest societal payoff.

3.5 Interoperable and Accessible Modeling Frameworks and Collaborations

Photo courtesy of Oak Ridge National Laboratory

National and global collaborations have improved the coupling of models used in IA; Earth systems simulation; and impact, adaptation, and vulnerability assessment. However, this interaction also is revealing compatibility challenges with model transferability and varying computational platforms, the latter illustrated by Oak Ridge National Laboratory's Jaguar supercomputer, which is used for climate change modeling and analysis.

Key Research Questions

- How can the field of IA be accelerated through experimentation with open source, community-based modeling methods?
- What are the current and anticipated future interdependencies between the three main modeling communities, and what are the areas of common research interest? What joint study opportunities may provide the greatest leverage in bringing these communities and models together?
- How do characteristics of different user classes and needs help shape our thinking about the desirable, interoperable model elements that will best meet the demands of the future?
- What are the input and output compatibility issues that must be addressed to facilitate improved interoperability across IAM, ESM, and IAV models?
- What can the IAM community do to help the IAV community develop the appropriate sectoral models for incorporation into IAMs? What can be learned from the European experience in IAM leadership toward this end?
- Given the innovative, interactive approach adopted for the IPCC's Fifth Assessment Report—an approach bringing the three communities and Working Groups together in a connected, iterative scenarios development and modeling process—what ideas and new concepts should we consider to advance this progress in the Sixth Assessment Report?

3.5.1 Current Status

IA is a process of multidisciplinary collaboration, often involving the development and application of mathematical models but also requiring incorporation of modes of analysis that are not subjects for mathematical treatment. Understanding climate change, its consequences, and assessment of mitigation and adaptation options requires different forms of this type of activity. Nearly always, however, developing that understanding involves aspects that are not only analytical or intellectual, but also institutional.

Great advancements have been made in the climate area, most notably in the development of GCMs, which has required interdisciplinary collaboration over many decades among different communities of physical scientists. Models have progressed from the early derivatives of numerical weather prediction models, focusing only on the fast processes of the atmosphere and ocean surface, to the much more complex ESMs of today, which include representations of terrestrial biogeochemistry and atmospheric chemistry.

Integrated assessment modeling has centered around a somewhat different challenge: the development of frameworks that integrate representations of the Earth system (frequently in reduced-form versions) with models of population and economic growth, technology change, and GHG emissions and with studies of the potential effects of climate change. These developments have enabled researchers to prepare climate studies that include analysis of the human side of human-climate interaction and to study the costs and advantages of action to mitigate the climate change threat and potentially cope with or adapt to its consequences.

3.5.2 Major Scientific Challenges

Many climate change assessment tasks do not require close collaboration among researchers with different areas of expertise. However, some topics devoted to understanding the human-climate system do require such collaborations and face particularly difficult scientific challenges. Often these areas involve the social, behavioral, and decision sciences as well as the natural sciences.

Interoperable Inputs and Output Detail, Time Steps, and Scales: Treating Feedbacks. Useful model analyses of potential anthropogenic climate change have been conducted with no analysis of the human drivers (e.g., doubled CO_2 experiments and scenarios with CO_2 rising at 1 percent per year) and without consideration of human or ecosystem effects and responses. However, to assess human-climate interactions and various levels of emissions control and adaptation efforts, feedbacks need to be considered, which may require integrating analytical inputs with different disciplinary foundations.

One task in which feedbacks intervene is the projection of the atmospheric concentration of GHGs (or climate change) that will result from a particular global climate agreement. In a simple one-way analysis that ignores feedbacks, models could be used to project land-use conditions, GHGs, aerosols, and other relevant substances; these results would be passed to ESMs, which then could solve for the resulting concentrations (or climate conditions). Minimal collaboration would be needed between analysts projecting the emissions (perhaps economists) and climate scientists analyzing the system response. Unfortunately, this common approach does not consider feedbacks that need to be understood. Several such feedbacks may be important to the result, but three are described below.

- The lifetime of CH_4 and the creation and fate of warming and cooling aerosols are functions of chemical processes at urban and global scales, which in turn depend on the climate response being projected.
- Natural emissions of CH_4 and N_2O as well as the level of tropospheric ozone (which need to be considered in assessing a policy's effectiveness)

are functions of climate variables and atmospheric chemistry, and, for ozone, of measures to control urban air pollution.

- Projected climate change and terrestrial ozone levels feed back onto the productivity of agriculture and forestry, which may stimulate changes in projected human land use, then feeding back on climate.

Adequate understanding of the relative importance of these feedbacks requires collaboration across several scientific disciplines to provide and integrate models of the various components of the system and their interactions.

Similar feedback issues in IAM applications are created by the influence of climate on energy demand, the potential climate effects of renewable energy at large scales, the influence of water availability and water temperature on agriculture, and land use and energy production.

Interdisciplinary Modeling Environments. Effective integration of Earth science, economic, and ecological aspects of IAV presents a difficult scientific challenge because there are many potential climate change effects, each with specialized needs for climate information. Moreover, many are not studied using methods easily compatible with modeling methods conventional in the natural sciences. The relevant effects encompass a huge range, including climate impacts on grain crops, migrating bird populations, national political stability and the potential for international conflict, and coastal damage and the value of protection and zoning choices. Proper design of analysis methods and, where appropriate, formal models used by these disparate analysts frequently cannot be adequately achieved by inputs of generic climate information. For example, analyzing the effects of climate change on water resource systems requires coordination not only of the relevant geographical scale of the system of interest but of the form of climate information that is useful, including the particular variables of interest (temperature, evapotranspiration, precipitation, and soil moisture) and the types of results needed (mean values versus extrema).

Agile Modeling Frameworks for Approaching Questions of Different User Communities. Applying IA research to support particular areas of public and private decision making raises challenges for the social and behavioral sciences and the decision sciences. Most natural-science processes follow established laws. Human systems are different in fundamental ways, creating problems for effective communication and integration of scientific components. For example:

- Relevant physical, chemical, and biological systems do not respond to expectations about the future, whereas human systems do. Dealing with this phenomenon is a particular challenge in economic analysis.
- Natural laws can be treated as immutable: Atoms and molecules do not innovate. Humans constantly are inventing new ways to achieve desired outcomes (e.g., through technology).
- Applications to decision support frequently involve valuation. The natural sciences do not confront this task. For example, a climate model does not need to resolve whether the temperature changes in a particular place over 100 years is profitable or costly.

Analysis components need to be integrated into representations of the choices faced, in processes that may include stakeholder involvement and complex relationships between climate choices and nonclimate issues. For example, analysis of potential global emissions targets and burden-sharing agreements, perhaps prepared to support participants in international negotiations, needs to be informed by knowledge of how such agreements may form and evolve over time. The components of an assessment—including the emissions and control costs, the response of the climate system, and any assessment of IAV—may differ depending on the particular decision at issue and the analysis framework devised by policy analysts to represent it.

Community Modeling Approaches. Areas within the physical sciences—especially in the development of atmosphere-ocean GCMs and ESMs—have made great use of "community modeling" (i.e., the creation of model frameworks that are open source and thus enable a broad range of contributors from many institutions to address particular model deficiencies). Neither the ecosystem modelers within the IAV community nor the IAM community has been structured in this way. However, as the complexity of their tasks has grown, these groups have begun to investigate the community approach to model development, in part because the breadth of the problems faced require involvement from numerous scientific disciplines. One principal investigator or one small team realistically cannot encompass all the expertise and disciplines involved in the research that the IA community is now outlining for IAMs.

The ability to reproduce an experiment performed by others is at the heart of the scientific method. In the case of computational experiments, this ability requires that data, models, and model output be available to other researchers. If they are not, then the ability to validate, understand, and build on the work of other researchers is compromised. The IA community has a long tradition of model intercomparisons and sharing of results through community forums such as the Energy Modeling Forum, but it has not taken the big step of creating an open modeling architecture. IA's approach is similar to that of many other environmental modeling communities, such as ecosystem modelers, but considering the complexity of the systems that IAMs are attempting to simulate and the breadth of disciplines involved, an open model development architecture should be explored (see Fig. 3.11).

The complexity of IAM data methods, error analysis, and input datasets requires principled methods of design and development. Because IAMs involve scientists from multiple disciplines and institutions, more tools and methods are needed for documenting and communicating design decisions and implementation details. Furthermore, the complexity of the proposed simulations (e.g., the variety of input data types, large

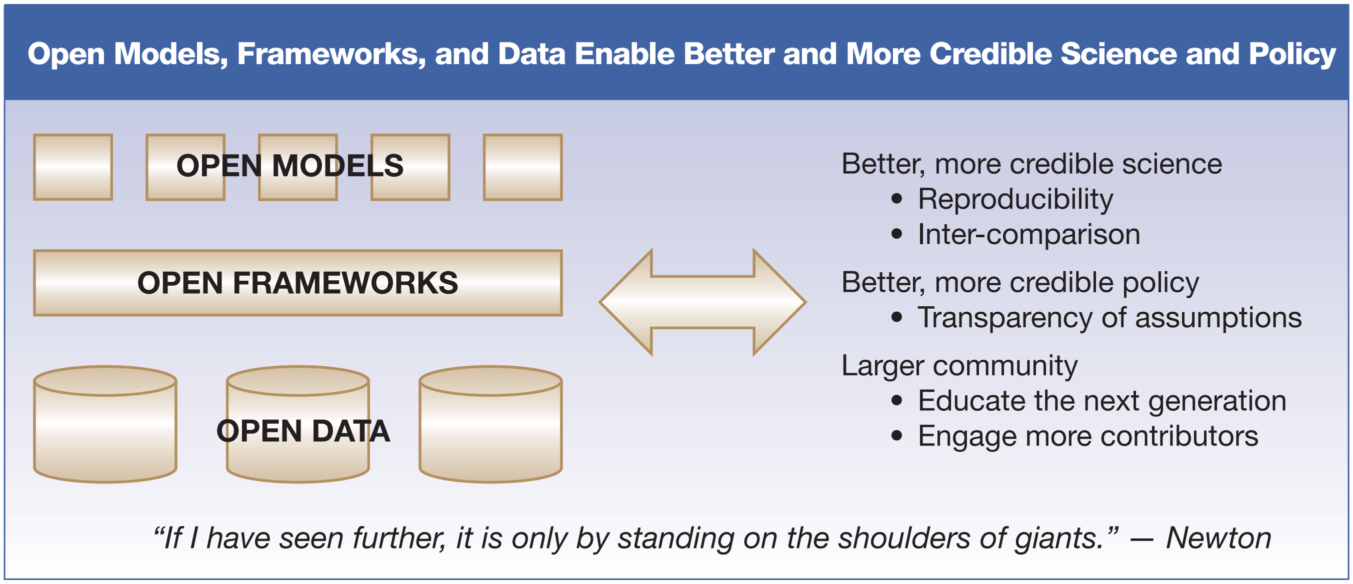


Fig. 3.11. Open Models, Frameworks, and Data Enable Better and More Credible Science and Policy. This figure shows the benefits of interactions that can occur under a community modeling approach. The openness of the approach can engage more researchers, improve the science, and contribute to better policy options.

temporal and spatial extents, and the magnitude of output data) suggests the need for a robust interactive simulation test bed. In addition, community modeling and, in particular, distributed model development raise issues of remote access. Finally, the computational requirements of the resulting modeling system indicate a growing need for high-performance computing resources.

Multiple Models for Scientific Learning. IAM development primarily is carried out in interdisciplinary teams large enough to house a critical mass of investigators in different disciplines but small enough that true interactions among disciplines can occur. While other modes of operation are possible, including a community modeling approach as discussed above, the general consensus is that differences in form and structure among the existing suite of models are important to maintain. (It is premature to consider coalescing to only one approach to such complex problems.) For example, current IAMs have different strengths, ranging from how much detail they have on various energy technologies to their uses for calculating probabilistic results of different combinations of physical parameters. These differences are useful because they provide a variety of insights on different aspects of understanding the combined human-Earth system.

Enabling Computation and Networks. Many of the scientific tasks outlined in this report present new challenges for computational resources and networking. Existing IAMs already require supercomputing resources to do the many thousands of model realizations necessary to calculate the probabilities of a particular environmental outcome, given some distribution of physical parameter values elsewhere in the model. However, obtaining access to even the current generation of supercomputing resources has been difficult for the IAM community overall. The tasks identified in this report will only raise the level of computing resources that will be required to address more completely linked representations of human-Earth systems and to study how model and parameterization uncertainties propagate through the overall system. Additional demands for observational data and a more complete linkage with ESMs also will have important ramifications for data volumes and decisions about data storage and access. The ESM community has considerable expertise with such challenges, and this interaction will be useful for the IAM community to explore.

3.5.3 Interdependencies and Critical Connections

Three supporting areas of scientific development and modeling methodology are worth highlighting.

Modeling of Climate at Regional Scale, with Uncertainty. Extending the capability of IAMs to describe decision-making processes at regional scales while also retaining the ability to examine the consequences and responses to climate change at those scales will require the creation of new interfaces with the climate modeling community. For this linkage to succeed, the climate modeling community itself must make substantial progress on the thorny issue of the methods for moving to finer and more highly resolved spatial scales. Inherent in this problem for the climate modeling community is the need to describe how uncertainty in model structure, parameterizations, and the underlying data is communicated across scales.

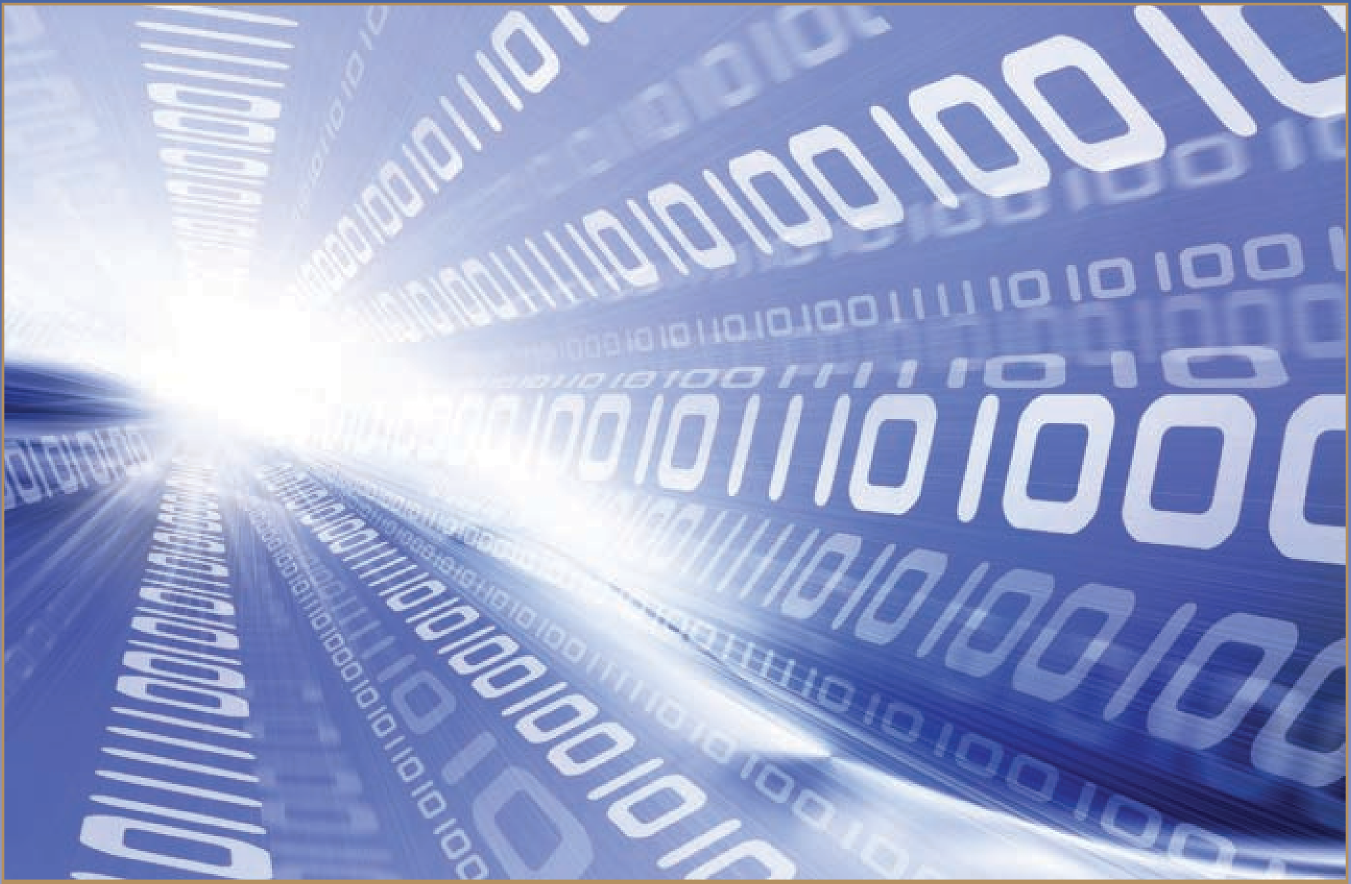
IAV Frameworks Suitable for Integration. Some modeling frameworks within the IAV community (e.g., ecosystem and hydrologic models) clearly are able to be incorporated into an IAM framework. The challenges are technical rather than conceptual. However, this is not true for other important aspects of IAV research. For example, the concept of vulnerability itself depends on an evaluation of human capital, access to resources and wealth, and the role of governance in ways that are not clearly amenable to numerical modeling. The IAV community will need to continue to make progress in identifying components that can be modeled appropriately (e.g., adaptation strategies) and those for which other research approaches must be pursued.

Extensions of Decision Science Methods. Decision science methods applied to the climate issue frequently are based on a single-decision-maker model of a simple game-theory formulation. Research is needed on methods appropriate for the multiple-actor environments in domestic decisions and international negotiations and for the simultaneous handling of decisions over time under uncertainty and partial learning. Alternative decision frameworks also should be investigated (e.g., the behavior of risk minimizers as opposed to idealized approaches for economic decision-making).

3.5.4 Implications of Improvements

Decisions about GHG mitigation will be a concern for the foreseeable future, with key choices to be revisited repeatedly during the coming decades. Moreover, the United States and other nations likely are already committed to some degree of climate change; more change probably will be built into the system as atmospheric concentrations increase. It is crucially important that these choices be informed by analysis that integrates key components of the human-climate system. Success in the research and analysis laid out in this report will make an extremely valuable contribution to the ability of society to manage the difficult problem of climate change.

3.6 Data Development and Accessibility



In IA, demands are growing for insights, details, and model precision. These demands drive requirements for regional data, techniques to address sparse datasets, data quality and verification, and overall information sharing and access.

Key Research Questions

- How can we overcome the major data challenges as models turn to finer spatial and temporal scales to meet the increasing demands for regional decision support in mitigation and adaptation? What are the particular challenges and potential solutions for dealing with the many, divergent information (sectoral and other) domains?
- Recognizing that migration to finer scales will require data from many more and different sources, how do we assure data quality and integrity?
- What innovative tools can be used to overcome data limitations and draw inferences from sparse datasets?
- How should the community best approach the management of data to enable improved access and use?
- What are the computational, networking, and data storage and handling barriers that must be overcome to facilitate more effective collaborations in IA and across the IAM, ESM, and IAV communities, and what can be done within IA to help address some of these issues?

3.6.1 Current Status

The complexity of the socioeconomic and environmental processes and interactions dealt with by IA research leads to a need for data from many different sources, sectors, disciplines, and geographic regions. The output and credibility of IA research depend on the availability, quality, and accessibility of those data as much as on the model frameworks. However, not all the desired data are available; some data exist but are not easily accessible or usable, and many data have uncertain or undocumented quality.

New data sources, such as high-resolution satellite imagery and digitized data from many resources, can be combined and analyzed in powerful ways to meet some of these needs. For example, Oak Ridge National Laboratory's LandScan database (Bhaduri et al. 2007) combines census data and satellite imagery to generate high-resolution population data. However, these new data sources and their greater data volumes introduce new data analysis and management challenges.

3.6.2 Major Scientific Challenges

We identify significant challenges for IA research in several distinct areas: data requirements, data quality, data management and accessibility, and the need for supporting cyberinfrastructure.

Observations: Harmonizing Regional Data, Dealing with Sparse Datasets, Incorporating and Querying Large Datasets. Integrated assessment research requires accurate historical and contemporary datasets in an extraordinarily wide variety of areas. Workshop participants identified needs to understand past and contemporary activity and to develop and test models—for spatially and temporally disaggregated data on population, economic activity, infrastructure investments, commodity costs, trade, land use, and emissions. Data also are needed on specialized economic parameters such as innovation rates, elasticities of substitution, and valuation of ecosystem services.

IA research would benefit from a concerted effort to identify and fill commonly known data gaps, such as information about the actual technologies being adopted in developing countries that are rapidly expanding energy production. Before such an effort is launched, IAM groups across the country should reach a consensus set of recommendations concerning which data gaps among the many that exist are the most important to fill quickly.

Related problems involve identifying and filling gaps for new sorts of data, where actual observations may exist but are not well known in the IA community. For example, many datasets are available on land cover, historical land use, the recent distribution of forests on the landscape, and a wide variety of climatic data, but the IA community is largely unfamiliar with these sources of information. There are simultaneous needs, therefore, for collaborating with the disciplinary communities familiar with these data sources and for enhancing the IA community's ability to access, manage, and redistribute such data for its own purposes. Some of these datasets are extremely large, and the methods for accessing and querying them efficiently will need to be either developed for IA purposes or imported and adapted for IA use from other communities that have more experience with such data.

Data Quality and Verification. While the underlying process-level science and numerical techniques associated with climate and ecosystem simulations are relatively mature, IAMs based on economic principles are quite different in nature. There has been substantial effort within the IAM community to understand the consequences of parameter uncertainty, but considerably less attention has been given to the underlying uncertainty introduced by the data themselves. The challenge for IA research is twofold. First, attention must be given to the issue of how well human decision-making, economic, and technological information is known (or how well it is calculated). Second, because IAMs also incorporate atmospheric and ecological information, as well as information about the built infrastructure, there is also an issue of data quality in those potentially observable domains. Methods will need to be developed and sensitivity studies performed to determine how IAM results might (or might not) be influenced by uncertainties in the underlying physical data themselves.

Data Management, Distribution, and Access. The data required by IA research come from many sources, with different conventions regarding access methods and syntax, description, and semantics. Within the IA community, different research groups have developed data and model architectures to accommodate the diversity of required information but without much regard to standardization or other parameters that might enable data to be shared much more broadly. Although current data often are inadequate, the IA community's data challenges in providing a systematic remedy are similar to those of many other research communities. Individual research groups expend significant effort on data acquisition and management, but there are no community standards for exchanging information on existing data sources and their properties, analyses, and applications. Neither are there standards for determining priority needs for new data, as motivated by priority research questions and knowledge about key uncertainties. The IA community should develop a more systematic and open approach to data collection, organization, and access. This new approach must be able to deal with a wide variety of data sources, scale to the extremely large datasets that are becoming available in both environmental and economic science, and address issues of uncertainty and provenance.

Supporting Cyber-infrastructure. Moving to a new generation of data management and distribution, especially if combined with a move to a more community-based modeling approach, will generate enormous demands on the existing cyber-infrastructure of many IAM groups. Other research communities have considerable expertise in efficient and effective ways to store, manage, query, and share data in a distributed way. Both the climate modeling and remote sensing communities, for example, have had to deal with large data volumes, difficulties in accessing and querying datasets, efficient storage techniques, and ways to maximize the use of data by a wide variety of user communities. Approaches to these problems have ranged from the technical (e.g., agreeing on standard formats for particular types of data and metadata) to the institutional (e.g., setting up specialized programs and groups charged specifically with managing large datasets and providing user support). This area requires substantially more attention as IA research becomes more linked with both climate modeling and aspects of the IAV research agenda. The problem is not yet acute, so there is time to plan carefully for an approach that makes sense for the community.

3.6.3 Interdependencies and Critical Connections

The IA modeling and research community clearly will be dependent on other research communities and institutions for most of its unfilled data needs. For example, land-cover and land-use data are not collected or error-checked within the IA community or its major sponsors, yet the IA community is now clearly dependent on having such data. Similarly, economic data, especially those that are important for understanding climate impacts and adaptation, largely are not collected or verified by the major IA sponsors. Yet here, too, the IA community is dependent on continual access to such data and on their quality.

3.6.4 Implications of Improvements

Improvements in data quality, access, and management clearly are needed within the IA community. Attention to these details will result in an increased level of credibility and quality of analyses performed with IAMs and should lead to enhanced confidence in results on the part of the decision-making communities that IA researchers serve.

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4.0

Synthesis and Integration: Creating a New Analysis and Decision-Making Environment

Climate change is a global problem that requires global solutions. Integrated assessment models must provide global insights into the drivers and consequences of climate change, build on international expertise, and use data from throughout the world. We must develop the tools that will transform our understanding of what may be the greatest challenge for this and subsequent generations: stabilizing the progression of climate change while adapting to its unfolding consequences.

4.0 Synthesis and Integration: Creating a New Analysis and Decision-Making Environment

This chapter presents conclusions based on the research challenges identified in Chapters 2 and 3 of this report. It recapitulates emerging challenges for decision makers and the scientific community, identifies the highest priority areas for IA research, examines institutional barriers to success, and offers a vision for the future.

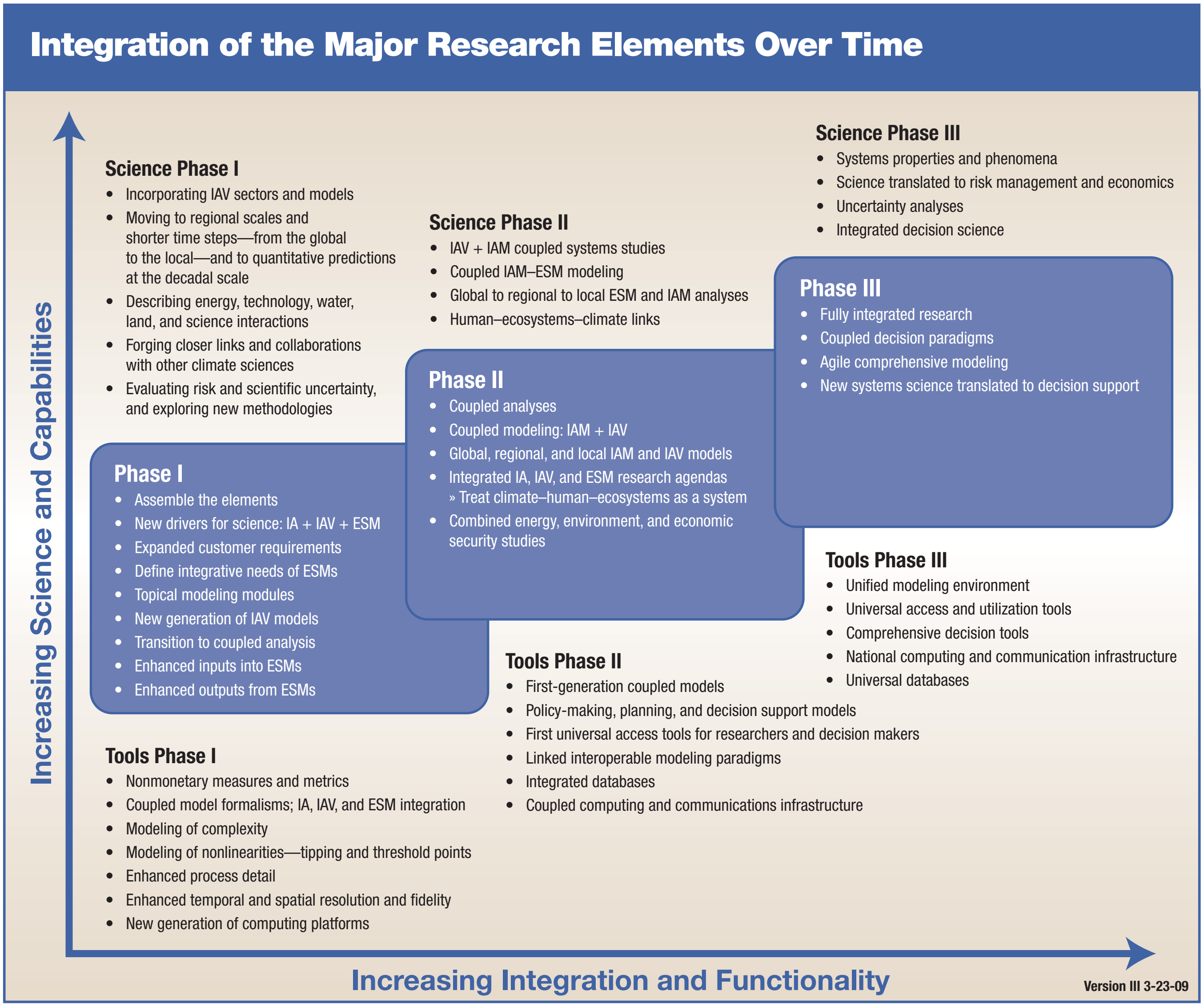
A continually changing context for decision-making and the science that supports it is now moving toward concerns about implementing responses to climate change and its consequences. This shift is creating new demand to expand the horizon of IA research from its roots in strategic decisions about energy and economics to a more comprehensive view of regional decisions about mitigation and adaptation, especially over the next several decades, and a more complete coupling to ESMs. Investments in both the IA community and the scientific communities with which it works will be necessary to enable closer collaborations than typically have occurred in the past.

The decision-making and climate research communities jointly face an expanding set of tightly interrelated challenges involving new questions and issues, new science, and new tools and techniques. Together, these three dimensions define the following opportunities and challenges:

- An expanded range of topics
- More detailed descriptions and models
- Expansion of spatial range—from global to local—in analysis and models
- Greater temporal resolution and a focus on the near- and mid-terms
- Integrated analysis, modeling, and conclusions across disciplines and topical areas
- Ultimately, an agile and flexible modeling environment for integrated science and decision support.

The coordinated development of new functionality and abilities to respond to more complex questions, the science to enable this functionality, and the tools that couple new science to applications must follow a natural progression, as shown in Fig. 4.1. In the initial phase, the requirements for new science and tools must be better defined, and the modules for individual topics in science and new tools developed. In ensuing phases, analyses and models begin to be coupled, leading to a modeling and analysis environment that will allow a fully integrated view of the factors controlling climate, important human actions, and the impacts on and responses from human systems.

The tools identified in Figure 4.1 reveal insights into the types of outcomes that are envisioned for this research should the anticipated progress be realized. In a very real sense, the improved tools are the outcomes. That is to say, Phase I delivers to decision makers ways to explore and analyze the non-monetary consequences of climate change. An example is the case of ecological impacts where ecological services do not exist, are too diffuse, or are not amenable to assignment of monetary value. In addition, topical modules of the models provide a means for addressing not only scientifically challenging components of the modeling effort, but also items of particular interest for decision makers, such as the interaction of one or more key human and/or natural systems or the build-out of particular areas where increased detail can inform strategies. In Phase II, one obvious outcome pertains to improved tools for coupled computing and communications between model types (IAM, ESM, IAV). Progress here will improve capabilities for analyzing issues at the intersections of the models, including land use and hydrology as two notable areas. Phase II also delivers linked databases,



Integration of the Major Research Elements Over Time

Science Phase I

- Incorporating IAV sectors and models
- Moving to regional scales and shorter time steps—from the global to the local—and to quantitative predictions at the decadal scale
- Describing energy, technology, water, land, and science interactions
- Forging closer links and collaborations with other climate sciences
- Evaluating risk and scientific uncertainty, and exploring new methodologies

Phase I

- Assemble the elements
- New drivers for science: IA + IAV + ESM
- Expanded customer requirements
- Define integrative needs of ESMs
- Topical modeling modules
- New generation of IAV models
- Transition to coupled analysis
- Enhanced inputs into ESMs
- Enhanced outputs from ESMs

Tools Phase I

- Nonmonetary measures and metrics
- Coupled model formalisms; IA, IAV, and ESM integration
- Modeling of complexity
- Modeling of nonlinearities—tipping and threshold points
- Enhanced process detail
- Enhanced temporal and spatial resolution and fidelity
- New generation of computing platforms

Science Phase II

- IAV + IAM coupled systems studies
- Coupled IAM–ESM modeling
- Global to regional to local ESM and IAM analyses
- Human–ecosystems–climate links

Phase II

- Coupled analyses
- Coupled modeling: IAM + IAV
- Global, regional, and local IAM and IAV models
- Integrated IA, IAV, and ESM research agendas
  - » Treat climate–human–ecosystems as a system
- Combined energy, environment, and economic security studies

Tools Phase II

- First-generation coupled models
- Policy-making, planning, and decision support models
- First universal access tools for researchers and decision makers
- Linked interoperable modeling paradigms
- Integrated databases
- Coupled computing and communications infrastructure

Science Phase III

- Systems properties and phenomena
- Science translated to risk management and economics
- Uncertainty analyses
- Integrated decision science

Phase III

- Fully integrated research
- Coupled decision paradigms
- Agile comprehensive modeling
- New systems science translated to decision support

Tools Phase III

- Unified modeling environment
- Universal access and utilization tools
- Comprehensive decision tools
- National computing and communication infrastructure
- Universal databases

Fig. 4.1. Integration of the Major Research Elements Over Time. Progress in meeting the challenges of the future using IAMs will come in overlapping phases. In the first, the three research communities (climate modeling, IAV modeling, and IA modeling) begin to define outputs and next-generation modeling aspects that align and coordinate work to address the challenges. In Phase II, coupled models and analyses begin to produce results, and fully open infrastructure is established. The third phase features both fully integrated modeling and research and comprehensive decision support.

which provide a resource, not only for IAMs but also for climate research generally and for decision makers. Phase III witnesses the realization of highly integrated capabilities, signaling the transformation of the field of IA. Outcomes include fully accessible models, utilization support and comprehensive decision support tools, and more. Ultimately, these outcomes translate into better science and better decisions, discussed in Section 4.5.

4.1 Emerging Challenges for Decision Makers

The decision-making context for climate change is in the midst of a significant shift. Many studies have shown the potential for very large changes in the climate system if GHG emissions continue essentially unabated. There is a growing consensus that mitigation of these emissions is necessary, and vigorous international and domestic debates are occurring over the best means to accomplish emissions reductions. Even if very aggressive measures for emissions mitigation were to be undertaken quickly, considerable future change essentially is built into the climate system already, and global average temperatures are projected to continue to rise over the next several decades (IPCC WG I 2007; CCSP SAP 4.3 2008). Clearly, in addition to decisions about mitigating GHG emissions, decisions about adapting to climate change and its impacts also are prudent and worthwhile.

4.2 Emerging Scientific Challenges

This report has identified major scientific challenges facing the IA community as it expands its focus from traditional treatments of mitigation choices and technologies toward inclusion of similar insights and representations of IAV.

4.2.1 Strengthening Complex Interactions among Energy, Environment, and Economics

The major scientific challenges below reflect the complexity of incorporating into integrated assessment models (IAMs) information about human decision-making on energy systems coupled with information on both the physical and biological climate system and the climate consequences of energy decisions for humanity. Concerns about how to represent the links between the generalized topics of mitigation and adaptation as well as about how technologies themselves are represented in IAMs are clearly among the most important challenges confronting the IA modeling and research communities.

Energy-Water-Land Connections. A key challenge will be the development of more sophisticated coupled treatments of natural resources and energy systems, including more detailed representations of terrestrial systems, such as the terrestrial carbon and nitrogen cycles. This will include more complete representations of land uses by type and their linkages to food, forest products, and bioenergy demands. Because water is an important resource for mitigation strategies, including those related to agriculture and land use, explicitly incorporating water demand, use, and management into IAMs is key. Currently, even the models that have some way to simulate precipitation and runoff do not adequately represent water demand and management. This deficiency is linked tightly to the challenge of increasing the regional specificity of IAMs, since water demand and management are inherently regional and even local problems. This nexus of interactions among energy, water, and land systems is but one example of the more general issue concerning the fact that these systems are affected in unexpected ways by climate change and decisions about managing natural resources. IAMs are uniquely situated to investigate such interactions precisely because they treat management and adaptation decisions about these resources and about energy explicitly.

For example, changes in climate will affect temperature, evapotranspiration, and the timing and intensity of precipitation, leading to changes not only in runoff and water availability for urban and industrial uses (and ecosystem survival), but also for land use. This land-use adjustment, perhaps magnified by the expansion of biofuels, will feed back on both downstream water availability and the climate itself. Decisions based on an isolated study of any one part of this interdependent system can lead to serious errors. Most often an adequate analysis requires integrating climate science; studies on agriculture, land use, and water resource systems; and monetary and nonmonetary valuation. Importantly, this information is needed at a regional scale. Many major river systems, nationally and internationally, will require such comprehensive analyses—management of the Colorado River under projected climate change being a textbook example of the urgency and complexity of the challenge.

Potential Role of Transformational Science and Technology. The prospect of considerable new investments in energy technologies to reduce GHG emissions emphasizes the importance of continuing to make progress in one of the historically important objectives of IAMs: analyzing how technologies enter the energy system, how they spread, and what difference they can make in emissions under different decision-making scenarios. Progress in these areas continues to be critical for serving decision makers and complements the need for IAMs to become more regionally specific. These advancements also will be important in understanding how future energy systems might differ from those of the past and how technology pathways in the developing world might differ from those in developed countries.

An important frontier for IA research is developing a better understanding of the interactions between scientific discovery and technology. These connections remain poorly understood, yet energy technology is widely acknowledged to be one of the most important determinants of the feasibility and cost of emissions mitigation. Also well established is the idea that limiting anthropogenic climate change implies a long commitment to emissions mitigation, with most of that mitigation occurring in the second half of the 21st century. Scientific breakthroughs at the beginning of the century thus would have ample time to transform energy and other mitigating technology.

Research reported in the U.S. Climate Change Research Program's SAP 2.1a (Clarke et al. 2007) on scenarios demonstrated the importance of technology in determining the cost of actions to limit atmospheric concentrations of GHGs. This report showed that technology availability in the post-2050 period also is extremely important to the cost and degree of emissions mitigation in the near term. If advanced technology is unavailable in the post-2050 period, the cost of emissions mitigation would be much larger. Post-2050 technology will be built on the foundations of scientific and technical progress in the decades immediately ahead, underscoring the importance of understanding the process of technology innovation and adoption. Figure 4.2 is a typical analysis of the impact of timing in technology development and insertion.

Integrating a Framework for Mitigation, Impacts, and Adaptation. Linkages and feedbacks between prospective actions and climate responses are important to understand as society moves toward making a series of complex decisions on these issues. Mitigation actions will interact with both a changed climate and with options for adaptation. For example, existing research from IAMs demonstrates that carbon sinks associated with forests and other natural ecosystems are a function of regional ground-level ozone concentrations, which themselves are functions of decisions made in the energy and transportation sectors as they interact with climate. Similarly, agricultural productivity as a carbon management strategy must be understood in its relationship to economics (e.g., in pricing for terrestrial carbon) and to climate change. These are only two of many possible examples of the interaction between climate, mitigation decisions and impacts and adaptation.

4.2.2 Incorporating Impacts, Adaptation, and Vulnerability

Climate change will have ubiquitous impacts on human and natural systems that need to be understood. Achieving this understanding clearly is one of the grand challenges for IA modeling and research. Issues surrounding the explicit representation of water, energy, and changes in land cover and use have been identified as reasonable starting points for IAM improvement, but progress should not end once these domains have been incorporated. There is no consensus yet on how to treat adaptation decisions in any IAM framework, although previous workshops have generated ideas about how this might be done. Of particular importance and relevance to IAMs, given

The Challenge of Scale Grows with Time—the Mid to Long Term

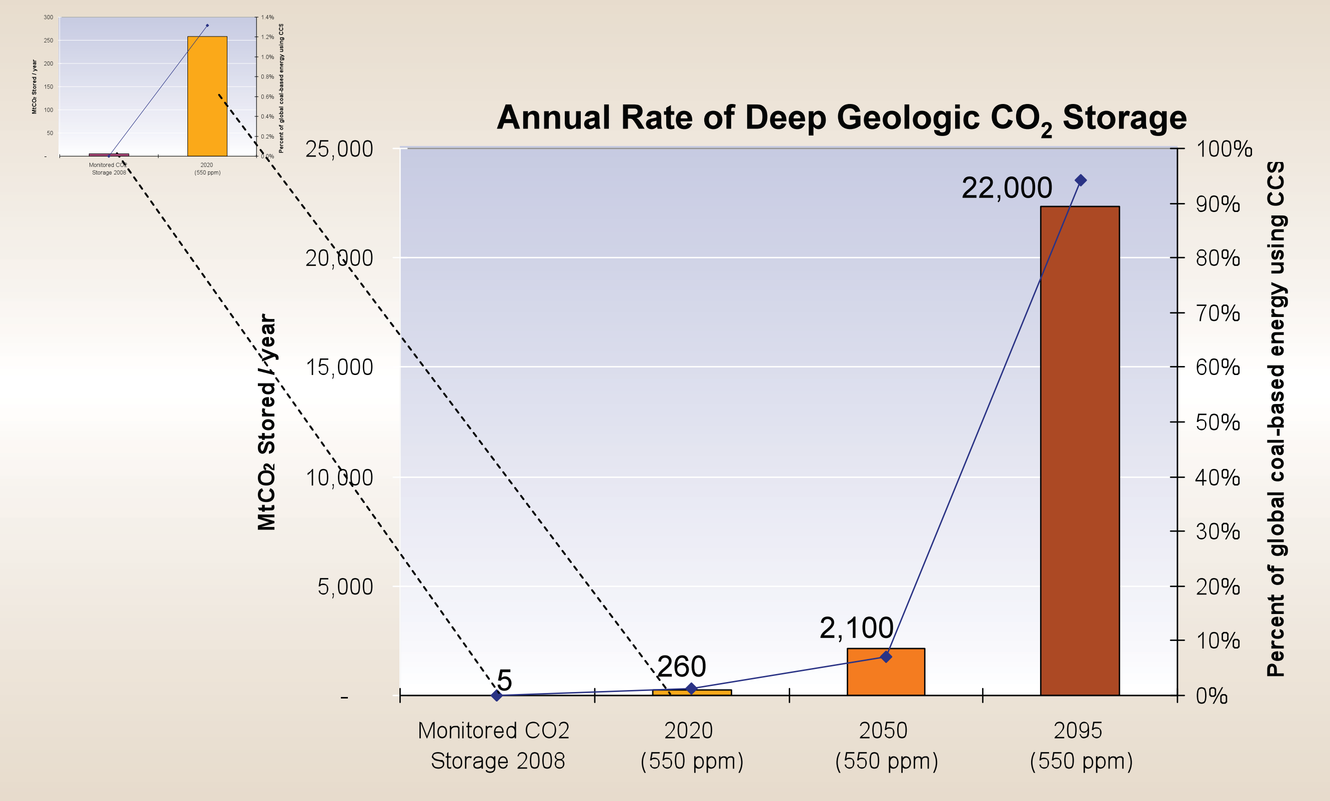


Fig. 4.2. The Challenge of Scale Grows with Time–the Mid to Long Term. IA reveals the magnitude of the scale-up challenge for emissions-reducing technologies such as CCS. From the current four large commercial end-to-end CCS facilities that store a total of 5 mtCO$_2$ per year, CCS must, for a 550-ppm stabilization case, increase by 3 to 4 orders of magnitude, indicated here by the two different scales.

that they already are highly sophisticated with respect to GHG mitigation decisions, is investigation of the links between climate impacts and adaptations and mitigation decisions.

IAMs will need to begin to link their frameworks with external models of impacts and adaptation; explicitly include decision-making on resource management; investigate the implications of “nonrational” actors in decision-making; and, ultimately, explore tradeoffs among mitigation and adaptation decisions. Models will need improved representations of key human systems such as agriculture, forestry, energy, transportation, and water. Some energy-related issues are outlined in Fig. 4.3.

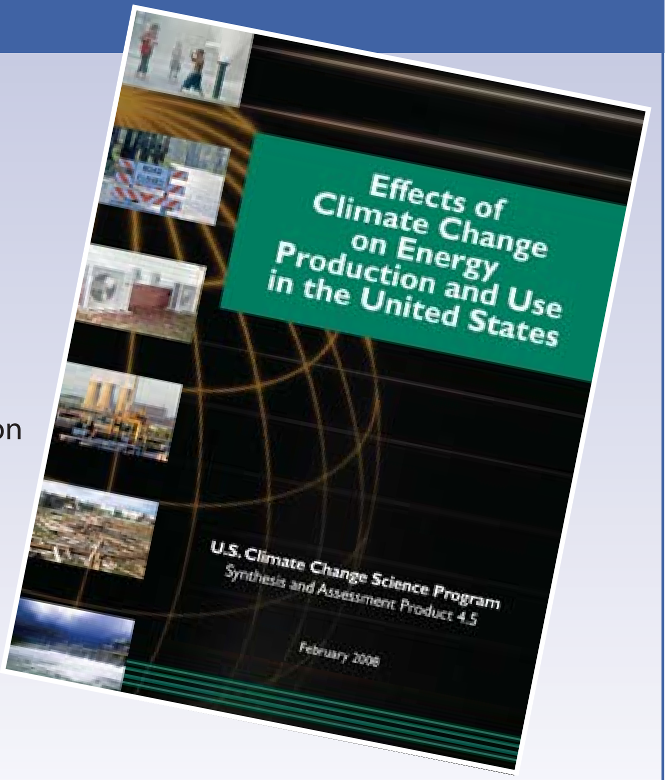
Recent progress on understanding the significance of land use, agriculture, and forestry in mitigation further emphasizes the importance of gaining deeper insights into the elements of IAV and how they interact with mitigation; this progress also underscores the importance of beginning to incorporate these elements into IAM frameworks explicitly. However, many social determinants of vulnerability do not necessarily lend themselves easily to numerical modeling, so considerable thought will be needed to decide how these are to be represented.

The ability to incorporate aspects of mitigation, impacts, and adaptation is beginning to enable IAMs to investigate the interaction of climate impacts,

IAV and the Interactions of Complex Systems

Climate Change Will Affect U.S. Energy Production and Consumption

- Direct demand effects
  - Increased demand for more cooling/warming = higher electricity demand
- Direct supply effects
  - Disruptions from more intense storms
  - Varying water availability for hydropower
  - Less efficient thermonuclear power generation due to higher temperatures
  - Changes in energy facility siting, based on availability
- Indirect effects
  - Altered investments in energy-related risk management
  - Altered investments in energy technology R&D
  - Different energy technology and resource choices
  - Changes in international energy markets, affecting U.S. energy security policies



Effects of Climate Change on Energy Production and Use in the United States

U.S. Climate Change Science Program
Synthesis and Assessment Product 4.5

February 2008

Fig. 4.3. IAV and the Interactions of Complex Systems. Changes in climate have direct impacts on discreet energy systems, but the effects spread to larger systems and eventually to business, financial, and international trade systems that influence development pathways and ultimately affect energy and other systems in turn.

adaptation decisions, and mitigation decisions. Early studies are yielding, for example, the following insights:

- The interaction of mitigation strategies affecting surface ozone concentrations, and thus carbon sequestration potentials of ecosystems, is beginning to be explored.
- The ability to maintain many unmanaged ecosystems around the world amid the demand for biofuels may depend on mitigation decisions to value biological carbon.
- Advances in the biological sciences that can maintain the rate of agricultural productivity improvement have the potential to reduce global CO_2 emissions at scales similar to more familiar technologies such as solar power.

IAV research has progressed on many fronts simultaneously but also largely independently, but the IAV community's relationship with the rest of the climate change research community is now developing. To jointly solve a new suite of problems, multiple strategies will be needed, including the development of new collaborations with the IAV community. For example, models will be challenged to begin to describe impacts for systems currently not incorporated in IAMs, such as human health and ocean acidification.

4.2.3 Extending to Regional Scales and Shorter Times

Historically, the spatial, temporal, and process scales in both climate and integrated assessment modeling have been coarse because the focus was on long-term strategic questions at a global level; specifically, how will different scenarios of human activities affect global climate? While the processes of climate are inherently global—dependent on large-scale and long-term flows of energy and mass—IAV, as well as the details of mitigation options, have an inherently local and regional character. Decision-making about the responses to climate change increasingly is focused on the near term and more often on the regional implications of those decisions. This has been true for IAV decision makers and natural resource managers for some time, but it is also becoming true for decision makers concerned with GHG mitigation and energy technologies. There is far more concern about understanding climate effects and potential actions in the next several decades because (1) decisions made during this period will determine what paths might be achievable through the end of the century and (2) there is growing understanding that not all climate impacts will be avoidable over this short time frame. In addition, decision makers and other stakeholders understandably are interested in knowing what the potential consequences of both climate change and climate policy might be for the regions in which they live. The situation for IAMs is in many ways analogous to the challenges faced by climate modelers, as they too respond to the desire for more regional information. Effectively bridging the divide between global drivers of climate and the highly detailed aspects critical to understanding regional climate effects and ensuing agroeconomic impacts requires a shift in strategy and technical approach for the IAM, ESM, and IAV communities. Analyses must downshift in spatial and temporal scales and represent processes and activities at levels of detail appropriate for this new realm. Global models might evolve to higher resolution, facilitated by greater computing power and more complete data, but in some cases, a new generation of regional-scale models will be required.

4.2.4 Quantifying Uncertainty in Models and Data

IAMs have proven to be highly useful tools in addressing science questions and providing decision support. Given a particular decision about mitigation strategies, IAMs can be used to identify and quantify the risk of exceeding particular environmental outcomes, but with inherent uncertainties in the physical or economic parameters used in the models. Because IAMs are such commonly used tools for providing insights to decision- and policy-making communities and because these users increasingly are interested in more accurate evaluations of the implications of their decisions for energy, economics, climate impacts, and adaptations, quantifying uncertainties becomes extraordinarily important.

A major challenge for IAMs is to be transparent and quantitative about sources and propagation of uncertainties in both model formulations and data. This quantification will need to take several forms, including (1) evaluating data quality and ensuring protocols exist for assessing and sharing data quickly and carefully; (2) evaluating model performance using model intercomparisons and various other procedures like backcasting; and (3) investigating the influence of different parameterizations on model uncertainties and on the implications of sequential decision-making in which future decisions are contingent on the context created by decisions of the past.

One example is the work of the MIT Joint Program on the Science and Policy of Global Change, which showed that policy intervention not only reduced the most frequent climate change scenario (relative to a no-policy case) but also dramatically reduced the number of scenarios that exhibited extreme climate change, as shown in Fig. 4.4.

Expanding IA Research on Risk and Uncertainty

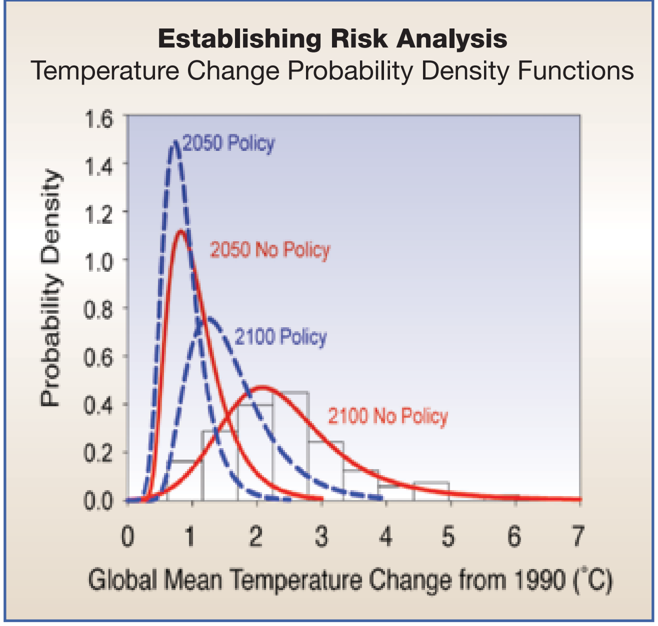


Fig. 4.4. Expanding IA Research on Risk and Uncertainty. Research at the MIT Joint Program on the Science and Policy of Global Change has explored the implication of uncertainty in human and natural systems. By applying methods to systematically sample potential combinations of IAM inputs, this research evaluates literally thousands of potential futures. One such exercise, illustrated in the figure, shows the results of these scenarios with a hypothetical "climate policy" imposed as a tax over varying time frames. The climate policy led to reduced GHG emissions, which in turn reduced the concentration of GHGs and Earth surface temperatures. These early efforts by this one modeling research team are paving the way for a new way to think about modeling risks within the IA community. Source: Webster et al. 2003

Other methodologies also have proved useful in understanding the implications of uncertainties in knowledge. For example, decision analysis has been applied to IAMs. This methodology has produced insights such as "act-then-learn-then-act-again." In contrast to deterministic methodologies that derive policy prescriptions based on an entire century-long policy regime, decision analysis recognizes that decisions must be made amid uncertainty and that over time, new knowledge will become available that could, in turn, modify the policy. The key then is to develop useful near-term actions that take into account a wide range of potential future developments.

Important challenges remain. Models would benefit from improved uncertainty, cost-benefit, and decision analysis methods. Uncertainty and decision analysis are computationally expensive; increasing the use of higher-performance computing would benefit IAMs. Uncertainty analysis ultimately is limited by the fact that it relies on good data inputs for historical values of model input data but also requires distributions of potential values. For model input data that are cross-correlated (e.g., labor productivity growth in Europe and North America), estimates of covariance are needed. Developing these distributions is time-consuming and sensitive to the methods used. Improved methods for generating distributions would benefit IAMs.

In addition, uncertainty analysis implicitly assumes that all uncertainty lies in model inputs. Implicitly, the models are assumed to be known with certainty. This is, of course, not the case. Through its numerous model intercomparison studies, the Stanford Energy Modeling Forum is an important contributor to understanding the relative roles of models and data in explaining variation in research results. Expanding and deepening such studies can help accelerate improved model performance and an improved understanding of uncertainty propagation within the models.

4.2.5 Linking Climate Models and Communities – ESMs, IAMs, and IAV

Much of the planning within the ESM and IA communities over the past several years has revolved around preparing for the next IPCC assessment. Specifically, this has involved preparing datasets derived from IAMs for use by ESMs to generate the next round of climate scenarios. Abundantly clear from the magnitude of this effort is the existence of feedbacks between the physical and biological climate system and the human decision-making represented in IAMs. These feedbacks arise from carbon, albedo, water, and other physical and biological processes that have the potential to make a substantial difference in both climate forecasts and the effects that a changing climate has on processes represented in IAMs. High-performance computing makes linking IAMs to ESMs or their output more feasible than in the past. Prioritizing individual research tasks could be accomplished by using a structured set of model experiments and studies identifying which feedbacks are quantitatively important and which are not. Because of the importance of anthropogenic forcings in the future 21st century climate system, the IAM-ESM linkage could have significant benefits for better climate forecasts and improved IAM simulations. Within the physical and biological climate modeling community, the rise of geoengineering as a serious topic of study makes quickly advancing the links between IAMs and ESMs even more important. Although conducting modeling studies of many geoengineering ideas using climate models is now potentially feasible, researchers—without effectively coupling these studies with IAMs—cannot evaluate the degree to which risk is actually reduced and at what cost or with what other side effects.

At the time of the IPCC Second Assessment Report (SAR), interactions among the three major climate change research communities were weak to nonexistent. The advent of better data and computing tools; a growing recognition that the climate problem is complex, nonlinear, and highly interconnected; and increasing demands for more comprehensive assessments of regional options for mitigation, impacts, and adaptation led to an expanded and more integrated research scope within each climate change research domain and stimulated interactions between them (see Fig. 4.5). At the time of the SAR, the carbon cycling research community was the only group that interacted with researchers in both the climate and IAM communities. IAV researchers sometimes used outputs from the climate modeling community and sometimes developed their own scenarios. Little information passed between the IAV and IAM domains.

Since the publication of SAR in 1996, much has changed. In 2008, the ESM, IAM, and IAV research communities met in Noordwijkerhout, the Netherlands, to jointly develop a coordinated research design for the three groups. The IAM and climate modeling communities both have developed ecosystem models within their respective modeling paradigms. For climate modelers, the inclusion of interactive terrestrial systems led to the need to understand how land use and land management will evolve over time. Four IAM research teams presently are engaged in delivering time-dependent, spatially resolved emissions scenarios for GHGs, SLS, land use, and land cover to the climate modeling community as input for its ensemble calculations. In addition, the research design for the IPCC's Fifth Assessment Report creates unprecedented coordination between the IAM and IAV communities.

For the IAM community, the challenge and opportunity to move forward depend on building upon these foundations. The unique dual role of IAM research in delivering scenarios of human activities to the IAV and climate modeling communities and in integrating human and natural Earth system climate science presents two major new directions of work. First, successfully integrating and coupling of human systems from IAMs with natural systems in ESMs will create a new, integrated modeling capability that will facilitate novel avenues of scientific research. Second, in addition to IAMs' traditional role as a point of global reference for IAV researchers, both these communities stand to benefit from collaborations aimed at assimilating IAV research into IAMs. For example, as IAMs develop endogenous models of freshwater systems integrated with agriculture, land use, energy, and the economy, important new potential is created to contribute to both IAV and IAM research literature.

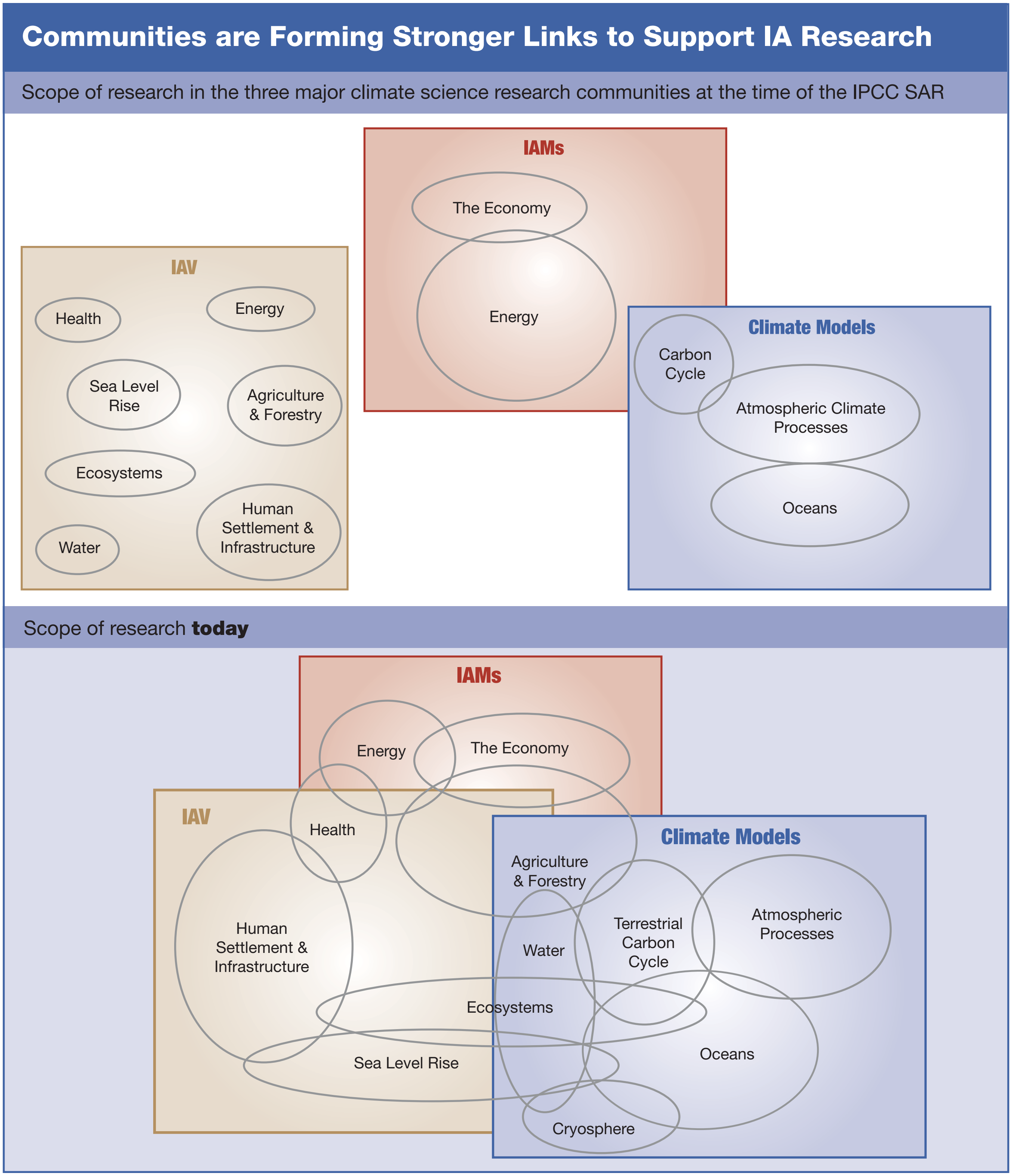


Fig. 4.5. Communities are Forming Stronger Links to Support IA Research. This figure shows that the loose coupling among the three research communities (IAM; IAV; and climate models) has become closer as common areas of interest and interdependencies are identified, such as agriculture and forestry, ecosystems, and sea level rise. These links will strengthen as the research challenges are addressed.

4.2.6 Advancing Community Model Approaches and Accessibility

A major challenge in interdisciplinary activities is determining how to maximize the use of all relevant and available knowledge, because no one research community can possibly encompass all the required expertise. Some research groups, such as climate modelers, have addressed this problem by developing "community" processes through which many independent investigators can contribute to the development of individual modeling modules in which they have expertise. These modules then can be combined in an open, accessible framework. This community approach is of great potential utility in the IAM community as the demands for model development and the sharing of both input data and model results grow exponentially.

A consistent theme throughout this report is the IA community's desire to develop the processes and infrastructure needed to embark on establishment of a community model. Adopting such an approach would be a major programmatic shift in IA strategy and potentially could maximize the opportunity for contributions from many scientists in a wide range of disciplines. However, because community models are such a departure from the current mode of doing research—which is centered around traditional, painstaking collaborations in small groups and then additional collaborations among groups—such an enterprise would require careful planning if pursued. Many infrastructure and information technology issues would need to be addressed, but the highest initial priority would be initiating a thorough planning effort to determine how to proceed.

A crucial component of advancing community modeling approaches and accessibility is making the underlying data fully available to all researchers. Underlying datasets on energy supply, use, and infrastructure; land use; and agricultural productivity, as well as model runs from a wide variety of studies, need to be archived, indexed, and made available in ways that can benefit the entire community of researchers and analysts. Accomplishing this goal will require both technical capacity and institutional changes within the IA modeling and research communities to ensure that open access to data and results is achieved in a timely way.

Despite the clear need, several barriers stand in the way of more effective and more widely available analysis. Of obvious importance are advancements in climate modeling, particularly the representation at regional and local scales, and in the science of vulnerability and impacts. Beyond these requirements lies a set of needs in integration methodologies. Better methods are required for linking models of mitigation measures, impacts, and adaptation as well as for representing possible developments in the science and technology of energy supply and use. For more widespread application, additional community or more generic models are needed that might be applied, without beginning from scratch, to several regions and different regional issues. Important to all this work is the development of better ways to communicate results in a form useful for decision-making and informing the public. Moreover, achieving these objectives will require fostering and supporting interdisciplinary groups that can bring together the knowledge and modeling expertise necessary to analyze some of these complex issues.

4.3 Barriers to Progress

Progress in the research challenges identified in this report will not be easy. Numerous scientific and institutional barriers must be overcome within both the IA community itself and the other scientific groups on which it depends. Developing and using IAMs and research are inherently interdisciplinary and must encompass a range of disciplinary expertise that can be daunting. Building and maintaining interdisciplinary teams capable of incorporating the breadth of topics involved have proven to be difficult but possible. However, there are other inherent barriers to maintaining progress. Chief among them is the challenge of representing growth in knowledge in the underlying disciplines, which themselves continue to develop and change. At a fundamental level, progress in IAMs is limited by concomitant progress in the disciplines underlying the science of the physical and biological climate system, ecosystems, human decision-making, adaptation, and vulnerabilities. While the agenda for IA research and modeling depends on making progress in these other areas, these disciplines also have their own priorities that need to be pursued.

Limited representation of the linkages between modeling of impacts and modeling of mitigation. State-of-the-art IAMs do not fully account for many of the feedbacks that might influence the effectiveness of particular mitigation actions. Among the most important of these interactions is that between a changed climate, agricultural production, afforestation options, and the viability and character of biofuels as an option for mitigation in sectors such as transportation or electricity. Another important feedback from a changed climate will be alterations in the demand for energy, particularly for heating and cooling in buildings.

Highly aggregate or economically based representations of technology systems. IA research has largely developed around economic, production function–based approaches to technology representations. For this reason and because IA research is expected to cover such a wide swath of disciplines (e.g., energy and agricultural systems, climate, carbon cycle, and demographics), the IA community's focus on the details of radically different technological systems and its ability to understand such systems will be especially important.

Generic regional representations. Although IA research and IAMs disaggregate the world into multiple regions, these regional representations often are symmetric in many key dimensions across regions. Current characteristics may be captured through the production function characteristics of models, but the nature of the evolution of regions over time and the particulars of regional resource bases, demographic structures, infrastructures, and social structures are limited.

Limited supporting research on technology potentials. The IA community does not have a coherent body of research on the probable advances in technology to draw on when creating scenarios of future technological developments. In fact, most research that does exist in this regard has been domain-specific (e.g., looking at solar photovoltaics alone) rather than comprehensive in its explorations of energy systems, as would be desired by IA researchers.

Aggregate representations of technology in IA research and more detailed and focused technology systems research. Because IAMs have such breadth of scope, they must rely on relatively aggregate representations of a variety of key processes for exploring and understanding climate change. Representations of technological systems are one such example.

Placing IAMs in a larger context of multiple driving forces and development issues. Although climate change is now widely acknowledged to be an impediment to sustainable development, it generally does not drive such development itself. IAMs thus need to place development issues—including the use of natural resources and the vulnerability of human populations—in a broader context of environmental, economic, and social drivers.

Describing baseline scenarios clearly. Distinguishing what is in a baseline scenario and what is in a policy-intervention scenario is difficult because there are numerous policy makers at many levels implementing many types of policies now and in the future. This dimension of human behavior, which has no direct analogue in physical systems, means great care must be taken to specify which variations in behavior are being considered.

Analyzing iterative decision-making. Decision makers have the ability to redirect their policies over time based on observations of the behavior of the climate system and of the effectiveness of their previous decisions. Again, this is an important aspect of decision-making and human behavior that has no analogue in physical systems.

Difficulty in creating and sustaining effective interdisciplinary groups. One barrier to successful collaboration is the difficulty in creating and sustaining the needed interdisciplinary collaborations. Success in IA research and analysis is dependent on developing an understanding of the terminology of other disciplines, having some perception of their underlying assumptions and analytical frameworks, and respecting others researchers' disciplines and contributions to the joint effort.

Organizational challenges in linking to the IAV community. Unlike ESM and IAM, which are characterized by relatively few research teams organized around large models and computing facilities, IAV research is scattered across a wide range of sectors and geographic areas and frequently is conducted by individuals doing focused analyses and case studies rather than using models. Moreover, this research often is not directly connected with climate change scenarios. These circumstances make it difficult for ESM and IAM experts to access IAV knowledge and also for the IAV community to interact effectively with their ESM and IAM colleagues. In addition, the IAV knowledge base is uneven and sometimes limited, and IAV studies often are conducted at a scale that is difficult to link with ESM and IAM.

4.4 Interdependencies and Critical Connections

A strong theme throughout this report is the interdependence of IA research with other scientific research communities and the institutions that are their primary sponsors. IA research and modeling ultimately depend on the progress made in several areas, including ecological research, studies on natural resource management, social science research on adaptation and vulnerability, understanding of the physical and biological climate system, and technological research. Each of these areas has its own research traditions, primary sponsoring agencies and institutions, challenges, pace of progress, and research priorities. The IA community does not intend to supplant these or to substitute its own priorities for theirs. Existing collaborations and partnerships will be the initial impetus for making more progress in IA research and modeling. However, at some point, advancements in IA will depend on these other fields continuing to make progress themselves. All the participants in this overall interdisciplinary endeavor therefore are linked to each other in a substantial way.

The research agenda required to support the opportunities presented in this report is extremely ambitious. However, given sufficient time and resources, the IA community believes this agenda is achievable. Currently, the major supporter of IA research and modeling development is the DOE Office of Science. There also is a great deal of participation from other federal agencies, other parts of DOE, the private sector, and several charitable foundations, but this support is largely for applying IAMs to specific sectors or for issues in which sponsors are particularly interested. Overall, the United States has lagged other countries in Europe and Asia in supporting IA research, even as the impetus for it has grown tremendously. The sense of the IA community is that the capabilities for moving quickly in the directions charted here already are in place, so rapid progress should be able to follow resources as they become available.

However, because of strong interdependencies with other disciplines, the phasing of new IA research also critically depends on progress being made in IAV research, climate science, and other fields. In this respect, the phasing of new IA research therefore also depends on the phasing and support of research in these other disciplines and among other sponsors. Nonetheless, the IA community has the sense that sufficient interdisciplinary collaborations and partnerships already are in place and that rapid progress can be made now.

4.4.1 Intersection with Nonclimate Domains of National Concern

The climate threat and measures taken to mitigate it or adapt to change as it comes are intertwined with other national concerns. In some cases, these concerns need to be integrated into climate studies and IAM calculations lest important aspects be overlooked. For example, measures to control urban and regional air pollution have an effect on the emissions and lifetimes of GHGs, and GHG controls affect the release of urban pollutants. Understanding this interaction thus requires consideration of the atmospheric chemistry of urban gases (including, in particular, ozone precursors) and the health benefits of GHG control. As another example, national security concerns are closely integrated with both the threat of climate change (e.g., the risk of failed states) and the effects of mitigation through its influence on oil imports. In some cases, analyses need to be extended to integrate these features.

Each of these cases, and others in the previous sections, involve fundamental research in the natural, social, and behavioral sciences and the integration of this work into coherent analyses. Separation of these components can lead to an inappropriate response to the climate threat, but effective integration is a research task in itself.

4.4.2 Investments in Science, Human Capital, and Access

Progress in IA research and modeling will require continuing investment in and development of scientific infrastructure and personnel. The IA community generally has taken little advantage of the tremendous increases in scientific computing and data management capabilities of the last several years and clearly could benefit from continuing investment in cyberinfrastructure. But as important as investment in the IA community itself can be, IA research also benefits explicitly from investments in the other research communities from which it draws knowledge and on which it thus depends. Under-investment in other disciplinary areas, as has happened with the IAV community, inevitably makes progress on those components more problematic. This creates challenges in the overall structure and priority-setting of the entire research enterprise and in how the knowledge it creates finds its way into IA and modeling.

4.5 Implications of Improvements

Although IAMs already have proven useful to both decision-making and scientific communities, this report envisions a future in which their utility to both continues to grow. A more sophisticated generation of IAMs—drawing on new collaborations with climate modelers, experts on technological innovation and diffusion, and experts in IAV—will be able to provide important new insights to decision makers in both public and private sectors who are wrestling with the balance of mitigation and adaptation decisions. As decisions continue to be made over several decades, steady improvements in IAMs should consistently enhance their usefulness. More sophisticated merging of IAMs with the physical and IAV sciences also will yield unexpected new scientific insights into the magnitude and dynamics of human decisions in the total Earth system.

4.5.1 Better Science

In preparation for the IPCC's Fifth Assessment Report, the IAM, climate modeling, and IAV communities have developed a research agenda to advance scientific understanding of potential climate change, its impacts, and options for adaptation and mitigation. While the new research design is a major step forward, advances envisioned in this document would create a new generation of models and tools to explore important climate science questions that have heretofore remained inaccessible. For example, the potential for a combined IAM-ESM modeling capacity opens the door to exploring human and natural system interactions in unprecedented ways. Incorporating natural system models of climate impacts and adaptation directly into IAMs similarly creates a new capability, enabling exploration of human and natural system interactions at resolutions still finer than those inherent in ESMs.

4.5.2 Better Decisions

IAMs already are being used by regional, national, and global decision-makers in both the public and private sectors. National governments have used IAMs to help inform decisions for decades. Fewer and fewer global corporations make decisions without considering climate change as an element of their strategic planning. IAMs increasingly are being used by regional decision makers, such as those in individual states of the United States. But, as noted above, IAMs are being pushed to provide more and better information to facilitate planning to both mitigate and adapt to climate change. While IAMs have become increasingly sophisticated, today's models will not be adequate to answer tomorrow's questions. Today's decision support tools that can be applied to IAMs to assess risk and uncertainty also will need to evolve. However, climate change, and our responses to it, present challenges that will not be resolved overnight, and societies will continue to make a wide variety of decisions related to climate for many decades to come. The potential benefits for aiding those decisions are very high.

4.6 Summary

A continually changing context for decision-making and the science that supports it is now moving toward concerns about implementing responses to climate change and its consequences. This shift is creating new demands to expand the horizon of IA from its roots in strategic decisions about energy and economics to a more comprehensive view of regional decisions about mitigation and adaptation, especially those required over the next several decades. Investments in both the IA community and the communities of scientists with whom it collaborates will be necessary to enable closer collaborations than typically have occurred in the past. Our vision for the benefits of IA and research demands no less.

4.7 References

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Appendix A: Workshop Program

Science Challenges and Future Directions for Integrated Assessment Research - Workshop

November 13-14, 2008 • Key Bridge Marriott, Arlington, VA

November 13, 2008

8:30-9:00 am Coffee and Pastries, Introductions

9:00-10:00 am

Lead-in Presentations

Welcome and Charge – Tony Janetos
Drivers, Context, and Expectations – Bob Vallario
Perspectives from DOE BER – Anna Palmisano
Current State of the Science in Integrated Assessment – Jae Edmonds
Framing issues for Global Change Science and Integrated Assessment Research – Tony Janetos

10:00-10:45 am

Decision Support and the Frontiers of Integrating Systems Science – Challenges in Understanding Mitigation and Adaptation and the Intersections of Energy, Environmental, and Economic Security
- Peter Schultz
- Jae Edmonds

10:45-11:15 am

Break

11:15 am -12:00 pm

The Grand Challenge of Impacts, Adaptation, Vulnerability – Understanding the Determinants of Vulnerability, Adaptive Capacity, and Representing Impacts Appropriately
- Tom Wilbanks
- Kris Ebi

12:00-1:30 pm

Lunch

1:30-2:15 pm

Research Needs for Mitigation – Finer Spatial and Temporal Scales, Developing Countries, Pre-2050 Analyses, Geoengineering, Governance, and Economics Issues
- Richard Richels
- Graham Pugh

2:15-3:00 pm

Scales: Regional and Next-Generation Sectoral Modeling at Finer Time Scales - Toward Finer Spatial and Temporal Scales
- Rick Stevens
- Ruby Leung

3:00-3:45 pm

Collaborations and Interoperable Frameworks for the New Science Challenges: Structuring Collaborations and Interactive Modeling Across a Span of Disciplines
- Jake Jacoby
- Bill Collins

3:45-4:15 pm

Break

4:15-5:00 pm

Understanding the Role of Transformational Science and Technology - Implications for Future Mitigation, Adaptation, and the Shadow for Present Decision-Making
- Richard Newell
- Leon Clarke

November 14, 2008

8:30-9:00 am Coffee and Pastries

9:00-9:45 am

Critical Challenges for Integrated Assessment Data and Data Management - Implications of High Spatial and Temporal Resolutions and New, Diverse Datasets (e.g., impacts/adaptation)
- Dennis Ojima
- Ian Foster

9:45-10:30 am

New Frontiers in Risk, Uncertainty –Testing and Diagnostic Methods – Representing Confidence in Underlying Knowledge, Communicating Risk and Uncertainty to Decision Makers
- John Weyant
- Alan Sandstad

10:30-11:15 am

New Horizons in Integrated Assessment Foundational Research - From Metrics to Tipping Points, Human and Institutional Behaviors, and Advanced Mathematics and Economics
- Tony Janetos
- Ken Judd

11:15 am -1:00 pm

Rapporteurs, Final Discussion, and Path Forward

Appendix B: Participant List

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Richard Newell

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Kristie Ebi

ExxonMobil
Brian Flannery

The Heinz Center
Dennis Ojima

Consultant
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National Oceanic and Atmospheric Administration (NOAA)
Chet Koblinsky

National Science Foundation
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