Monitoring Climate Change Impacts: Metrics at the Intersection of the Human and Earth Systems

ISBN
978-0-309-15871-8

110 pages
8 1/2 x 11
PAPERBACK (2010)

Committee on Indicators for Understanding Global Climate Change; National Research Council

MONITORING CLIMATE CHANGE IMPACTS

Metrics at the Intersection of the Human and Earth Systems

Committee on Indicators for Understanding Global Climate Change

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

The National Academies Press
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS • 500 Fifth Street, N.W. • Washington, DC 20001

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This study was supported by the United States intelligence community. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the intelligence community or any of its sub-agencies.

International Standard Book Number-13: 978-0-309-15871-8
International Standard Book Number-10: 0-309-15871-0

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Preface

In early 2008, the National Academy of Sciences began a series of activities to facilitate the increased involvement of scientists in answering questions related to climate and environmental change, energy, natural disasters, and national security. The goal is to advance scientific understanding of global climate change and other environmental and disaster-related phenomena, while considering the implications of this understanding for U.S. national security. As part of a suite of activities on climate, energy, and national security, the National Research Council (NRC) appointed the Committee on Indicators for Understanding Global Climate Change, which was tasked with identifying indicators that can increase the understanding of global climate change and environmental sustainability (see Appendix A for Statement of Task).

To begin, the committee sought input from a broad cross-section of physical, biological, and social scientists engaged in research in areas broadly related to environmental sustainability and climate change. Eight panels provided input (see pages v and vi for membership): cryosphere, land-surface and terrestrial ecosystems, hydrology and water resources, atmosphere, human health and other dimensions, oceans (both physical and biological/chemical), and natural disasters. The panels identified measurements and then metrics that, in their expert judgment, could serve as useful indicators. The panels also suggested illustrative locations around the globe where measurements of the underlying observations could be gathered. The exercise was intended to draw upon the scientific imagination of the participants and not the capabilities of any particular observing platform.

What follows in this report is the committee's judgment of potential key metrics for monitoring climate change with an eye toward environmental sustainability.

The committee would like to thank Ric Cicone, Pam Matson, and Tom Parris for sharing their knowledge of environmental sustainability with the committee and panels. We would also like to thank the members of the topical panels for their hard work and dedication throughout the process and the writing of this report. The tables of indicators of climate change that they provided are an integral part of this report. Our sincerest thanks are extended to BASC Director Chris Elfring, Study Director Curtis Marshall, Associate Program Officer Katie Weller, Administrative Coordinator Rita Gaskins, and Senior Program Assistant Ricardo Payne for facilitating the committee process and the production of this report.

Mark Abbott, Chair
Committee on Indicators for Understanding Global Climate Change

Acknowledgments

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

Kristen Ebi, ESS LLC., Stanford, California
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Eugene Rosa, Washington State University, Pullman
Steve Running, University of Montana, Missoula
Ronald Smith, Yale University, New Haven, Connecticut
Karl Turekian, Yale University, New Haven, Connecticut

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by **Mary Albert**, Dartmouth College, Hanover, New Hampshire, appointed by the Division on Earth and Life Studies, and **Robert E. Dickinson**, University of Texas, Austin, appointed by the Report Review Committee, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

Human civilization is inextricably linked with the Earth system and the ecosystem services it provides. The sustainability of both human and Earth systems depends in large part on their vulnerability and resilience to system threats. Climate change is a significant component of the people-environment link. Because changes in climate threaten multiple Earth systems, such as the atmosphere and oceans, it also threatens many human systems.

The stresses associated with climate change are expected to be felt keenly as human population grows to a projected 9 billion by the middle of this century, increasing the demand for resources and supporting infrastructure. Therefore, information to assess vulnerabilities to climate change is needed to support policies and investments designed to increase resilience in human and Earth systems.

There are currently many observing systems that capture elements of *how* climate is changing, for example, direct measurements of atmospheric and ocean temperature. Although those measurements are essential for understanding the scale and nature of climate change, they do not necessarily provide information about the impacts of climate change on humans that are especially relevant for political and economic planning and decision making.

The challenge to the report's authoring committee was to develop an illustrative suite of indicators, measurements (and the locations around the globe where the measurements can be applied), and metrics that are important for understanding global climate change and providing insight into environmental sustainability (Box S-1 for definitions). Eight panels provided input on: cryosphere, land-surface and terrestrial ecosystems, hydrology and water resources, atmosphere, human health and other dimensions, oceans (both physical and biological/chemical), and natural disasters. The committee developed an illustrative set of metrics (Chapter 3 tables) that are likely to be affected by climate change over the next 20-25 years and, when taken together, can potentially give advance warning of climate-related changes to the human and environment systems.

BOX S-1
Definitions of Key Terms

Measurement: A quantitative, physical attribute.

Metric: A category that reflects a combination of individual measurements and that can be used to provide a large-scale view of a system and gauge system performance. It may be quantitative or qualitative.

Indicator: A selected subset of metrics that is judged helpful for projecting future performance of a system.

This report is envisioned as a technical document for use by analysts in the intelligence community, as well as researchers, as they delve more deeply into climate change and its ramifications worldwide. Developing interdisciplinary metrics that intersect with environmental sustainability and human well-being, as done in this report, is an important step in thinking about how to monitor the impacts of climate change.

DOMAINS OF HUMAN VULNERABILITY

The committee began by identifying examples of domains of human vulnerability where change is likely to occur in the near term and where climate change impacts on humans begin to be significant. Each domain is an area of critical importance to society, is vulnerable to the impacts of climate change, and highlights the intersection of human needs and climate change. This report concludes that indicators of environmental sustainability, in a climate change context, can be found at the intersection of how the climate is changing and how those changes will affect five domains of human vulnerability.

These five domains are:

- **Food:** Climate change impacts may result in competition for declining food resources (both fisheries and agriculture) as well as shifting patterns of harvest. This could lead to food shortages and famines in less developed countries, as well as a variety of economic ramifications.
- **Water:** Climate change stands to affect future water distribution, quantity, and quality. This could lead to lack of water, water of poor quality, or too much water at the wrong time in many locations around the globe.
- **Energy:** Anthropogenic input of CO_2 to the atmosphere is well established as a cause of climate change. The pressure to "decarbonize" over the next few decades will inevitably result in new approaches to energy use, which will, in turn, have potentially unforeseen environmental impacts.
- **Shelter:** Humans need shelter as a basic element for quality of life. Natural disasters such as flood, drought, and wildfire both threaten existing shelter and increase the need for shelter. Many of these extreme events may be exacerbated by climate change.
- **Health:** A changing climate may affect any health outcome that is influenced by environmental conditions, such as an increase in mosquito- and water- borne diseases.

CLIMATE CHANGE METRICS AT THE INTERSECTION OF THE HUMAN AND EARTH SYSTEMS

A global-scale process is one that is manifested in all regions of the planet, such as the biogeochemical cycles of carbon and nitrogen or the hydrologic cycle. The committee finds that observations of global-scale processes are especially valuable from an indicators perspective, because they link the impacts of climate change to the feedbacks and forcings that can change the direction, scale, or timeframe of those impacts. The linkages extend across the Earth system, from the atmosphere to the oceans, from the cryosphere to the hydrosphere, and include the land-surface and natural disasters.

Chapter 3 presents tables of metrics, measurements, and locations by topical areas of human and Earth systems. The metrics vary, with some being clearly quantifiable and others being more qualitative. Some metrics are indicators of distinctly measurable change, whereas others are more exploratory and offer new perspectives.

Several metrics such as sea level rise, seasonal snow cover, and air quality appear in multiple tables because of the fundamental linkages across systems. Sea level rise is a function of oceanic, land ice, and hydrological processes, but it also acts as an "amplifier" for natural disasters such as tropical cyclones by increasing the risk potential. Thus the metrics of climate change presented in this report cross many disciplines.

A broad array of indicators, based on a great diversity of measurements, could to some degree provide advance warning of the impacts of global climate change. But because it is uneconomical and, indeed, fundamentally impossible to measure everything, it is important to develop priorities—to select a finite suite of indicators that, taken together, provide a generally accurate and informative basis for anticipating problems.

The committee concluded that certain characteristics tend to make a metric particularly useful, including the following:

- Direct (e.g., loss of mass of an ice sheet leads to rising sea level)
- Significant (i.e., represents a large change in one or more resources including water, energy, shelter, health, and food)
- Dominant (i.e., outweighs other factors and processes)
- Measurable (i.e., capable of being quantified)
- Historical (i.e., provides the foundation of understanding and measurement)
- Well documented (i.e., data are complete and consistent)

Given the diverse nature of metrics, a uniform process for categorizing and prioritizing the metrics presented in this report is not possible. Therefore, each panel, in addition to considering the criteria described above, explains in the text preceding each table the processes and criteria it used when categorizing or prioritizing its metrics.

CONSIDERATIONS FOR THE FUTURE

Having metrics that illustrate how climate change is affecting human systems will prove useful as climate change impacts become more prominent. Climate is changing simultaneously with an increase in the global human population, which in turn increases environmental stresses and reduces human resilience[1]. Increasing information about climate change when its impacts most affect human needs is a logical step in informing decision makers and improving our ability to adapt and/or embrace societal resilience.

[1] As concluded by reports such as the Intergovernmental Panel on Climate Change's *Fourth Assessment Report: Climate Change 2007*, the National Research Council's *Advancing the Science of Climate Change*; and the U.S. Global Change Research Program's *Global Climate Change Impacts in the United States*.

1

Introduction

The committee was tasked with developing a technical document proposing an illustrative suite of indicators, measurements (and the locations around the globe where the measurements can be applied), and metrics that are most important for understanding global climate change and provide insights into environmental sustainability issues (Box 1-1 for definitions). This information could be useful in the consideration of a coordinated climate observing strategy. The report is not a comprehensive analysis of all of the human-environment interactions that are stressed by climate change. Instead, it focuses on developing a representative set of measurable metrics that are likely to be affected by climate change over the next 20-25 years (rather than the longer term or highly uncertain stresses of the next century) and that, when taken together, can be used as indicators of environmental sustainability. Moreover, there is a wide array of social issues that are beyond the charge of the committee and therefore were not considered for extensive integration into the list of metrics: comprehensive measures of vulnerability, resilience, and adaptation; national security; and political and social contexts of decisions under conditions of uncertainty. The committee identifies potential metrics and draws lessons about their uses, but, following the guidance in the statement of task, it does not make recommendations.

BOX 1-1
Definitions of Key Terms

Ecosystem services: The many life-sustaining benefits we receive from nature—clean air and water, fertile soil for crop production, pollination, and flood control. They are important to our health and well-being, yet they are limited and often taken for granted as being without cost.

Environmental sustainability (in the context of a changing climate): The ability of an environmental system to maintain processes, functions, biodiversity, and productivity. This is particularly relevant in a changing climate and under additional influences resulting from the possible implementation of strategies to mitigate and/or adapt to climate change.

Indicator: A selected subset of metrics that is judged helpful for projecting future performance of a system.

Measurement: A quantitative, physical attribute.

Metric: A category that reflects a combination of individual measurements and that can be used to provide a large-scale view of a system and gauge system performance. It may be quantitative or qualitative (NRC, 2005).

Resilience: A capability to anticipate, prepare for, respond to, and recover from significant threats with minimum damage to social well-being, the economy, and the environment.

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes.

As a technical document, this report is intended to be used by analysts in the intelligence community, as well as researchers, as they delve more deeply into climate change and its ramifications worldwide (Box 1-2). The process of prioritizing the metrics (described in Chapter 3) was developed with this audience in mind. The types of measurements mostly focused upon are generally those obtained by remote sensing; however, there are some cases for which in situ measurements are particularly useful. The committee recognizes that the metrics suggested in the report are not perfect, but hopes they will serve as a catalyst for further thinking.

As an informational foundation for this study, eight groups ("topical panels") were assigned the task of developing lists of measurements, metrics, and indicators of environmental sustainability in their respective areas of expertise. Two workshops were held, which included invited presentations and breakout sessions, from which preliminary lists and supporting information were generated. (See Appendix B for more information on the guidance provided to the panels. Note that the format of the tables and definitions evolved over time as the committee did its work.) Committee judgment formed the basis from which the tables in Chapter 3 were constructed.

BOX 1-2
Background for This Study:
Science in Support of the Intelligence Community's Work on Climate Change

During the 1990s, a program known as MEDEA brought together environmental scientists and members of the intelligence community to further understanding of environmental change. Prominent scientists were granted security clearances to participate in a review of national security systems, data, and archives with the objective of identifying scientifically relevant materials. Through analyses of classified data and systems, the scientists worked with the intelligence community and the White House on several emerging environmental issues, including global climate change. The MEDEA program helped justify the eventual declassification and release of scientifically important, high-resolution imagery from the archives, which were subsequently used by the scientific research community to complement publicly available, but less detailed, imagery of several environmental systems. These data have since been applied across a broad spectrum of the environmental sciences including oceanography, geologic processes, ecology, forestry, desertification, land use and agriculture, natural disasters and, more recently, Arctic sea-ice processes (NRC, 2009a).

In the mid-1990s, MEDEA scientists and their colleagues in the intelligence community instituted a program to ensure continued collection of classified imagery at environmentally sensitive locations around the globe. The purpose of the program, known as the Global Fiducials Project, was to ensure the collection of classified imagery of areas vulnerable to environmental shifts and damage that, when monitored with detailed capability, provide early warning of environmental stresses. The understanding was that the images would be held in trust in classified archives, with the eventual goal of declassification and release to the broader scientific community for research purposes. Initially, data were collected at approximately 285 sites globally. The MEDEA program was disbanded in 2001 when the Administration changed and different priorities were instituted. By 2005, only a small number (about 75) of legacy observations continued, mostly in North America.

The utility of the fiducials project rested on the premise that certain locations around the world could serve as "pulse points" that, when monitored with detailed capability, could provide early warning of environmental stresses. The program was conceived as the nation's intelligence community began to weigh the national security implications of climate change and to take steps to apply its unique monitoring capabilities to further the understanding of climate change. The data obtained have proven invaluable for a wide range of climate-related scientific studies.

CLIMATE CHANGE AS AN ENVIRONMENTAL STRESSOR

The human-environment system includes a complex set of nonlinear interactions between the natural world and human society (e.g., see reports such as *Ecosystems and Human Well-being: General Synthesis* [MEA, 2005], *Ecological Impacts of Climate Change* [NRC, 2008a], and *Climate Change 2007: Working Group II: Impacts, Adaption and Vulnerability* [IPCC, 2007a]. Of the many environmental stressors having impacts with human ramifications, climate change is perhaps the most significant. By the middle of this century, the human population is expected to grow to about 9 billion, resulting in increased demands for energy, food, water, health, and shelter just to maintain standards of living, much less to increase them (Figure 1-1). This growing demand for resources will lead to substantially less resilience in the Earth system. Any shortfalls or disruptions in the supply of critical ecosystem services will be magnified throughout various processes within the Earth system.

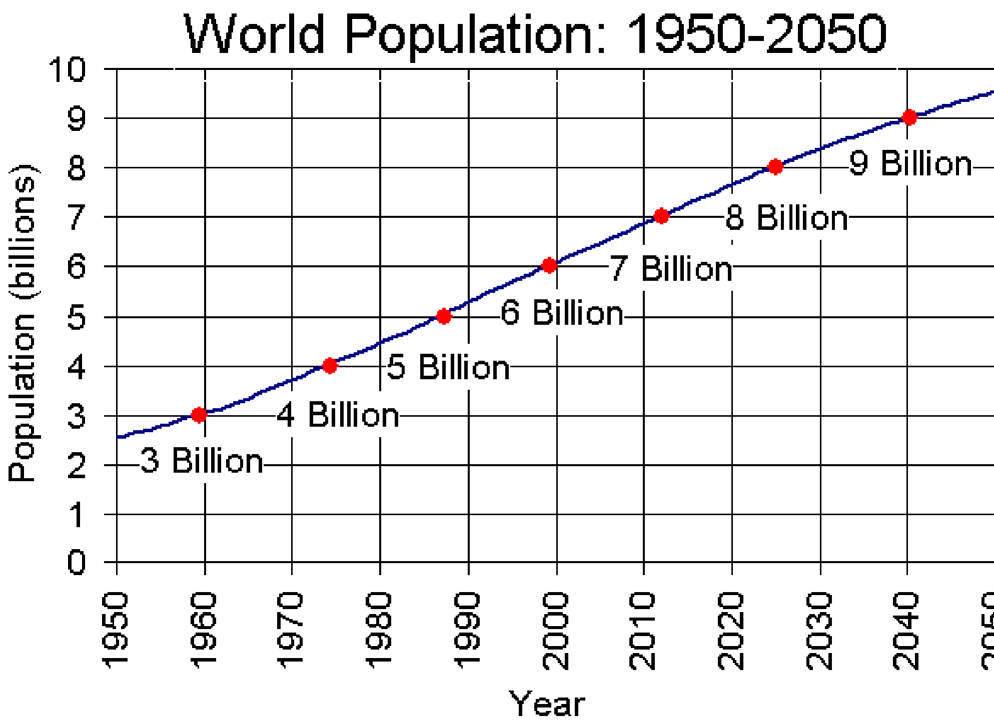

FIGURE 1-1 The world population increased from 3 billion in 1959 to 6 billion in 1999, a doubling over 40 years. The Census Bureau projects that population growth will continue into the 21st century, albeit more slowly. The world population is projected to grow from 6 billion in 1999 to 9 billion by 2040, an increase of 50 percent over 41 years. SOURCE: U.S. Census Bureau, International Database, December 2008 update.

The interconnections among systems and the linkages between global- and local-scale processes, and between short and long timescales, greatly complicate both research and observing systems. Moreover, it is difficult for governments, businesses, and individuals to develop climate-adaptive strategies for an uncertain future. For example, consider wind energy systems, which involve the fundamental engineering challenge of matching wind energy supply patterns with transmission capabilities and electrical demand patterns. All of these factors are complicated by climate, political, and economic issues. How will the economics of wind energy systems evolve as wind patterns are altered by climate change, or if there are changes in government-mandated renewable energy portfolios or in county land-use and zoning restrictions in rural areas? Society needs information and tools to assess vulnerabilities to environmental stressors, and in particular climate change, both in the short term and the long term to increase resilience in human and Earth systems.

THE COMMITTEE'S CHALLENGE

Many organizations have proposed potential climate change indicators. Examples include the Global Climate Observing System's Essential Climate Variables,[2] the

[2] See *http://www.wmo.ch/pages/prog/gcos/index.php?name=EssentialClimateVariables*.

National Aeronautics and Space Administration's Key Indicators of Climate Change,[3] the National Oceanic and Atmospheric Administration's Arctic Indicators,[4] the National Climatic Data Center's Global Climate Change Indicators,[5] Indicators of Climate Change in California,[6] the Environmental Protection Agency's Climate Change Indicators in the United States,[7] and the International Geosphere-Biosphere Programme's Climate Change Index.[8]

These published sets of climate change indicators generally highlight the fundamental physical science of climate processes and their associated impacts on the natural world. Observations such as these will continue to be important. But traditional climate change indicators are typically selected to tell us how the climate is changing and provide relatively little insight into the human dimensions of climate change. However, in this report, the committee identifies climate change metrics, that, when taken together, might provide advance warning of climate-related changes and their impacts on environmental sustainability. Furthermore, they can aid the scientific community in testing and developing models and hypotheses about how Earth and human systems are changing.

This perspective is especially relevant for political and economic planning and decision making rather than for specific climate forecasting. Understanding the range of possibilities and probable disruptive events will lead to an improved process of risk assessment with regard to the impacts of climate change. The linkage between risk and impact is another essential component of the indicators: Unlikely, high-impact events can be as important as likely, moderate-impact events.

The intellectual foundation for the committee's charge is the Millennium Ecosystem Assessment (MEA), which documents the rationale for why the committee looked beyond simply identifying indicators that emphasize the fundamental physical science of climate change (Box 1-3). The MEA describes the dependence of human well-being on healthy ecosystems as well as the global loss of ecosystem services. Ecosystem services are the benefits that ecosystems provide, and they result from interactions of plants, animals, and microbes with one another and with the environment. The delivery of ecosystem services is affected by changes in biodiversity, habitat fragmentation and conversion, alterations to biogeochemical cycles, and climate change. The inextricable linkage between human civilization and the ecosystem services upon which it relies is at the core of environmental sustainability.

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[3] See *http://climate.nasa.gov/keyIndicators/*.
[4] See *http://www.arctic.noaa.gov/detect/indicators.shtml*.
[5] See *http://www.ncdc.noaa.gov/indicators/*.
[6] See *http://oehha.ca.gov/multimedia/epic/pdf/ClimateChangeIndicatorsApril2009.pdf*.
[7] See *http://www.epa.gov/climatechange/indicators.html*.
[8] See *http://www.igbp.net/page.php?pid=504*.

BOX 1-3
The Millennium Ecosystem Assessment

The Millennium Ecosystem Assessment (MEA) reports evaluate the condition of and trends in the world's ecosystems, the services they provide, and the options to restore, conserve, or enhance their sustainable use. The four main findings are as follows:

1. "Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fiber, and fuel. This has resulted in a substantial and largely irreversible loss in the diversity of life on Earth.
2. The changes to ecosystems have contributed to substantial net gains in human well-being and economic development, but these gains have been achieved at growing costs in the form of the degradation of many ecosystem services, increased risks of nonlinear changes, and the exacerbation of poverty for some groups of people. These problems, unless addressed, will substantially diminish the benefits that future generations obtain from ecosystems.
3. The degradation of ecosystem services could grow significantly worse during the first half of this century and is a barrier to achieving the Millennium Development Goals[9].
4. The challenge of reversing the degradation of ecosystems while meeting increasing demand for services can be partially met under some scenarios considered by the MEA, but will involve significant changes in policies, institutions, and practices that are not currently under way. Many options exist to conserve or enhance specific ecosystem services in ways that reduce negative trade-offs or that provide positive synergies with other ecosystem services" (MEA, 2005).

This committee's fundamental challenge was incorporating consideration of environmental sustainability into the indicators concept. Sustainability is an often-used term with multiple, relatively subjective definitions, and its use in a report such as this one can be confusing. At its core, the term "environmental sustainability" involves a union among environment, society, and economics. The sustainability of human and Earth systems is in large part a function of the vulnerability and resilience to system threats. Moreover, just as with natural ecosystems, human systems have the capacity to adapt and evolve in response to unforeseen changes in the environment, but this capacity is limited in terms of time and space as well as by the intensity of the change. For example, a severe hurricane may disrupt a local region of the U.S. Gulf Coast for a year or two, but a repeated series of severe hurricanes in the region would likely lead to a permanent redistribution of people and infrastructure. Thus, it is the nature of the disruptive events (e.g., their intensity, frequency, extent) that can overstress society's

[9] For more information on the Millennium Development Goals see UN, 2008.

resilience. We focused on those environmental processes that would likely be in this "disruptive" scale.

The committee sorted through the many possible indicators of climate change and identified metrics within key sectors that may give advance warning of climate-related changes and their impacts. The overarching aim was to provide a conceptual foundation for the selected observations that integrate across a wide range of both local- and global-scale observing systems in order to deliver useful information. The committee would like to emphasize that the discussion, findings, and conclusions found in this report should be considered exploratory rather than definitive.

The premise behind the committee's charge is that climate change is a threat to the sustainability of various components within the Earth system (cryosphere, land-surface, hydrology, atmosphere, and oceans), and, consequently, to human systems. In response to the charge, the committee viewed climate change metrics through a "sustainability filter"—that is, the committee decided that for a metric to be deemed an indicator of environmental sustainability it must inform how climate change affects the five domains of human vulnerability: water, food, energy, health, and shelter. Chapter 2 explores examples of these concepts in more depth and draws on examples of the metrics in Chapter 3. Tables (divided by topical area) of these metrics and others are found in Chapter 3. These tables also include measurements, locations, and statements as to how the proposed metrics can be used as indicators of environmental sustainability. The report concludes in Chapter 4 with final thoughts.

2

Domains of Human Vulnerability and Global-Scale Processes

Domains of human vulnerability—food, water, energy, shelter, and health—are areas of critical importance to society and each is vulnerable to the impacts of climate change. As climate change impacts have the potential to affect the interaction of human vulnerabilities and exposure(s) to some environmental change, it is valuable to examine the link between a climate-relevant global process and the critical systems upon which humans depend, specifically the domains of human vulnerability, in order to better understand indicators of environmental sustainability.

Identifying the Earth observing systems that would be appropriate for monitoring environmental change and, ultimately, environmental sustainability could be an endless task. However, it is feasible to sort through the myriad of possibilities to distinguish areas of particular importance within the domains of human vulnerability where change is likely to be dramatic and occur in the near-term, and where impacts on humans start to be significant. Incorporate one more factor—measurability (i.e., that the indicator is significant enough to measure and methods exist to do so)—and we begin to develop an approach to identifying indicators of environmental sustainability.

The following sections examine domains of human vulnerability to illustrate the types of linkages that the committee considers to be possible. These domains constitute one defining feature of global environmental change, are not place-bound, but are replications of stress in many locations across the globe.

FOOD

Agriculture

Agriculture has complex vulnerabilities to climate change and is very sensitive to hydrological and economic conditions. As agriculture becomes industrialized, crops are produced in less than ideal environments. Wheat, for example, would grow best in regions that are dedicated to the more profitable crop, maize. Crops also are often produced in proximity to the infrastructure for their processing and transporting. In this sense, crops sometimes are decoupled from the most fertile climate conditions.

There are at least five broad agricultural systems that might be monitored to produce insights into environmental sustainability. Four categories can be formed from the combinations of rain-fed versus irrigated agriculture with C3-photosynthetic[10] versus C4-photosynthetic plants[11]. A fifth category involves animal pasturing. These five pathways provide the majority of food consumed by humans.

Rain-fed agriculture is clearly a system at risk in places where climate change brings decreased rainfall and/or increased temperatures during the growing season (and an associated increased demand for water by the plants). Irrigated agriculture may be relatively less vulnerable to the direct consequences of climate change, but the increased use of irrigated water competes with other demands for water. C3 plants are potentially aided by increased atmospheric carbon dioxide (CO_2) in terms of an increased photosynthesis rate and increased water-use efficiency; C4 plants do not feature this response (Derner et al., 2003). Grazing systems are vulnerable to water supply for plant productivity and for animal consumption. With climate change, grazing systems can feature catastrophic collapse and can result in longer-term systems degradation.

Agricultural systems are monitored by a variety of technologies including overhead surveillance, which are used in designing production strategies, monitoring irrigation schemes, and assessing the state of crops (DeFries, 2008; NRC, 2008b). Remote-sensing technologies also are significantly applied in commodities prediction (Supit, 1997; Haboudane et al., 2002). Many models are successful at predicting agricultural production for a variety of crops (McCown et al., 1996; Stoorvogel et al., 2004). However, their application to altered climatic conditions is an existing challenge.

Unlike fisheries systems discussed in the next section, mass agricultural production systems are primarily engineered by humans and feature organisms (both plants and animals) that are highly modified genetically through domestication. This coupling of modern agriculture's technological dependency with the nature of the agricultural species makes the response of agricultural systems to climate change extremely complex to interpret. Additionally the market-driven economic drivers of global commodities markets and agricultural policy restrictions on crop overproduction also complicate the interpretation of vulnerabilities. Food is an essential commodity in world trade, and wealthy nations can buy food when poorer nations cannot.

In early assessments of the potential consequences on agriculture of climate change, it generally was thought that the crop production systems would adjust by using new breeds of crop varieties and/or use crops or varieties of crops from other regions to maintain local and regional agricultural productivity. The remarkable climatic domain within which one can grow a crop such as maize formed some of the basis for these opinions. So did the success of the "Green Revolution" in increasing crop yields in previously marginal situations. However, the metrics in the Land-Surface and Terrestrial Ecosystems Table (Chapter 3) emphasize the monitoring of rain-fed, subsistence agricultural systems, which have less of a technological buffer from climate variation than do advanced technology agricultural systems. Similarly, dry-land grazing systems are also considered. These production systems have the potential to serve as early-

[10] All of carbon fixation and photosynthesis happens in mesophyll cells just on the surface of the leaf in C3-photosynthetic plants. These plants are well-adapted to habitats with cool, moist conditions under normal light.

[11] Carbon fixation and photosynthesis are split between the mesophyll cells and bundle sheath cells in C4-photosynthetic plants. These plants are well-adapted to habitats with high daytime temperatures and intense sunlight.

warning systems for climate's effects on crops. They also are the modes of food production for some of the regions that are most vulnerable to climate-related food shortages.

Fisheries

Fisheries are another example of a domain of human vulnerability (food), highlighting the intersection of human needs and climate change. As documented in numerous reports (e.g., MEA, 2005), the world's fisheries are under enormous stress, with some of them severely overfished (Figure 2-1), even without the added stress of climate change. Pressures have spread to more distant locations as well as to new species (FAO, 2005). How do we sustain resilient marine ecosystems in the face of these pressures?

FIGURE 2-1 Thousands of pounds of jack mackerel taken from the Pacific Ocean. Photo credit: C. Ortiz Rojas, NOAA.

Aquaculture (both in confined facilities and in more traditional hatcheries) has altered the composition of the food supply, as well as of wild fish populations (Naylor et al., 2000). Moreover, aquaculture in many regions has resulted in significant changes in land and ocean use (e.g., conversion of mangrove forests into shrimp farms in Southeast Asia, blocking off fjords in Norway and Chile for salmon and halibut farms). Both confined and at-sea aquaculture systems can alter the genetic diversity of wild populations as well as introduce diseases into the environment. Additionally, human activity indirectly impacts marine ecosystems. Conversion of wetlands and estuaries to agriculture and urban areas, river channels, and dams and levees reduces the availability of critical nursery grounds, and hydroelectric facilities can impede the migration of anadromous fish. Furthermore, riverborne pollution can create hypoxic ocean environments; harmful algal blooms have been increasing in abundance in U.S. coastal waters, thus reducing the availability of a wide range of seafood.

Adding to these already-existing stresses, climate change will alter the underlying physical environment, with significant impacts on all levels of oceanic ecosystems. Shifts in ocean temperatures and currents are enabling warmer water species to move into subarctic waters (Perry et al., 2005). Most nutrients are limiting in the euphotic ("lighted") zone; the largest nutrient reserves are found at depth (not from land or atmospheric inputs). A warmer ocean is more stratified, thus reducing vertical mixing, which is the main pathway for these deep, nutrient-rich waters to support primary productivity in the upper ocean. This effect, while reducing nutrient input to the upper ocean, may lower global primary productivity (Behrenfeld et al., 2009).

Sea level rise may further reduce the extent of wetlands and estuaries. Ocean acidification, caused by increased CO_2, will have implications for marine calcifers, which provide habitat for marine fish and organisms and form the base of the marine food chain. Thus, the interactions between large-scale and regional-scale climate processes and between the natural and the human environments lead to a complex set of interacting issues.

Given that fish, both wild and farmed, provide a substantial amount of protein to the world's population, including some countries for which they are the dominant source (FAO, 2009), fishery health is an important metric to monitor. Fishery health can be assessed by measuring fishing intensity, ocean productivity, coastal land use, and extent of aquaculture. Spatial and temporal changes in this metric will provide an indication of long-term ecosystem health and environmental sustainability.

WATER

Water of sufficient quality and quantity for consumption, washing, agriculture, energy, transportation, and other uses is a critical need for all societies, yet the need is not met for more than 1 billion of Earth's people (WHO/UNICEF, 2005). The stresses to societies resulting from the lack of water, water of poor quality, or too much water at the wrong time may lead to unsustainable situations. The three feedbacks associated with human society that are most critical to future water distribution, quantity, and quality are climate change, population growth, and modification of land use and land cover.

The global population was estimated at 6.85 billion in 2010 and is expected to grow to 9 billion by mid-century (U.S. Census Bureau, 2010). Water will be affected by population growth through diversion, increased demand, and increased contamination with human waste and industrial byproducts (Dozier et al., 2009). .

To illustrate the ways that water availability might be affected by climate change and add to environmental stress, one can examine and contrast two different environmental settings, alpine and coastal. The committee chose this approach over a comprehensive review of the relationship between water and climate in order to provide depth over breadth. In alpine environments, much of the water is delivered to high elevations as snow. The winter snowpack gradually melts, releasing water to local ecosystems, initiating springtime vegetative growth and faunal behavior, and filling lakes and reservoirs. Later in the season, when the snow has melted, glaciers, if present, gradually release additional water (Figure 2-2).

FIGURE 2-2 The glaciers that drape the Huayna Potosí mountain near El Alto, Bolivia help keep streams flowing during Bolivia's dry season, supplying drinking water and hydroelectric power to the city's burgeoning population. But the smaller glaciers are shrinking, threatening future water supplies.
SOURCE: James Balog, National Geographic

When the distance between source and use is large, methods of transport (e.g., soil seepage, underground aquifers, and surface streams and rivers) also come into play. Ecosystems come to depend on the particular pattern and timing of water's availability. Populations without effective reservoirs (either natural or artificial) are more vulnerable to changes in precipitation patterns (amount, timing, and type) and declining glaciers (Bales et al., 2006). Shorter winters and an increase of rain versus snow, cause relatively wetter winters and drier summers, because of runoff during the winter months and a more homogeneous distribution of precipitation owing to a lack of redistribution by wind. Increased atmospheric temperatures or dust or soot in the snow can lead to a similar result, with runoff starting a few weeks earlier and before downstream evaporative demand requires additional water. Glacier loss removes a critical summer water source (Figure 2-3). Changes in soil wetness and in the type of groundcover, driven by altered land uses, also affect the movement of water. Faster transport diminishes the ability to retain water, thereby increasing the need for artificial reservoirs, lest the opportunity to use the water is lost. Faster transport can be self-reinforcing as erosion removes soil and decreases water retention capability (Trimble and Crosson, 2000).

Possible metrics that can be used to indicate the environmental sustainability of the polar environment include the condition and extent of permafrost and the temporal variability of sea ice extent and volume. In the alpine environment, the seasonal progression of the winter's snowpack and the timing of river and lake ice breakup are already proving to be important cryospheric metrics with direct impact on humans, as is the mass balance of glaciers, ice caps, and ice sheets, through its direct connection to sea

FIGURE 2-3 This pair of photographs from Grinnell Glacier's southeast edge shows the dramatic change in the glacier's volume and area. Note the glacier's depth along the headwall and its extent at the terminal moraine in the historic photograph.
SOURCE: W.C. Alden (left); Chris Miller (right), USGS Photographic Library.

level. More than 1 billion people depend on snowmelt for their water resources (Barnett et al., 2005), and the heterogeneous redistribution of snow by wind leaves areas of deeper snow that persist well into the summer and provide late-season soil moisture.

The coastal urban environment is considerably different from the alpine environment and is particularly important because nearly half the world's population lives at or near the coast. At these lower elevations, precipitation generally is received as rain rather than snow. Although the ocean affords a seemingly endless reservoir of water, desalination of ocean water has proven to be difficult and expensive (Cooley et al., 2006). Rising sea level (Figure 2-4), which can occur as a result of melting ice sheets or glaciers, warming ocean temperatures, and vertical lithospheric motions, can threaten coastal facilities, especially if combined with severe weather events (e.g., hurricanes) and storm surges during elevated tidal conditions (Figure 2-5).

Possible metrics that can be used to indicate the environmental sustainability of coastal environments include river flow, ice sheet and glacier mass changes, local precipitation trends, hurricane frequency and location, and sea level rise.

Monitoring water-related metrics—such as total terrestrial water storage, seasonal snow, and water quality—and improving scientific understanding will enable more reliable predictions of the response of Earth and human systems to varying climate and changing human interventions in the water cycle. Monitoring these metrics, may be one tool that can help decision makers employ predictive, adaptive management.

Dozier et al. determined that monitoring water poses the following three major challenges (2009):

1. "In general, the water cycle, with its intrinsic variability and the changes that human activities cause at all scales, is a unifying concept. However, closing the water balance and predicting flows between stores in our coupled natural and engineered water systems remain difficult.
2. The human need for reliable and safe water supplies and protection from floods has created complex engineering systems, along with

societal decision making processes, that are essential but sometimes fail.

3. The variability of the water cycle and the interaction of humans with the natural and engineered environments have led to social structures and organizations that add complexity and uncertainty.*"*

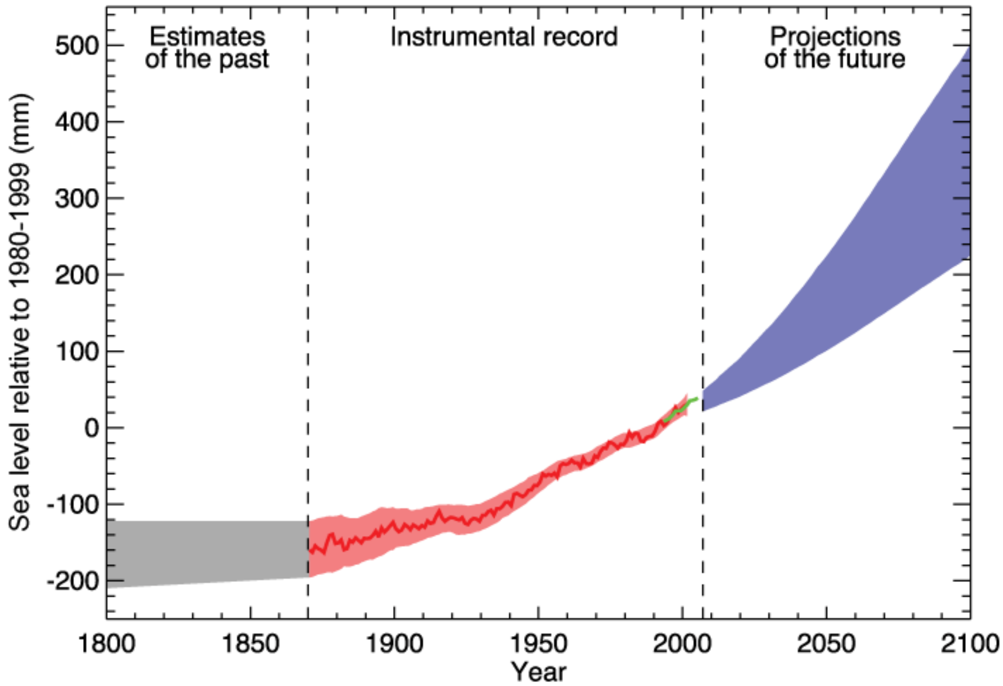

FIGURE 2-4 The Intergovernmental Panel on Climate Change (IPCC) estimates that the global average sea level will rise by 7.2 to 23.6 inches (18-59 cm or 0.18-0.59 m) by 2100 relative to 1980-1999 under a range of scenarios. Note that these estimates assume that ice flow from Greenland and Antarctica will continue at the same rates as those observed from 1993 to 2003. The IPCC cautions that these rates could increase or decrease in the future.
SOURCE: IPCC, 2007b.

The quantity and quality of our water environment is altered by human development either through intentional intervention or as a result of urbanization, agriculture, energy generation, and economic development (Dozier et al., 2009). For example, growing urban areas are associated with high-volume runoff events, which induce poorer water quality downstream. Alterations to the water cycle are increasing and are frequently observed on larger scales. Growing nutrient loadings in a given drainage basin typically results in coastal hypoxia (Figure 2-6; Dozier et al., 2009). Evidence suggests that an increase in ambient CO_2 inhibits plants' assimilation of nitrate from the soil, meaning they cannot process a larger CO_2 load when nitrate from soil is their primary source of nitrogen. Researchers note that plants may yet adapt to increased CO_2 levels, but once this occurs, plants will need to draw more and more nitrate from the soil (Bloom et al., 2010; Finzi et al., 2006). Humans may be able to restore soil balance with ammonium- and nitrate-based fertilizers, but that would increase reliance on fertilizers, which ultimately will lead to more hypoxia and algal blooms.

FIGURE 2-5 The Maeslant barrier is a massive flood gate barrier in the Nieuwe Waterweg waterway in the Netherlands. When a storm causes the North Sea to rise, the doors will swing shut (as shown in this image), closing off the river and keeping the water out.
SOURCE: Rijkswaterstaat, Netherlands—Geo-Information and ICT (AGI), available at *http://www.deltawerken.org*.

The interactions between and couplings of climate, population, urbanization, and development, as well as how they affect water, have been largely outside the scope of most analyses. Population growth and the consequent increase in water demand must cause the strategies for water management to change. Historically, we have tried to manage supply to meet demand, but in the future we must also manage demand itself. Climate change requires reorientation of analyses involving water from their traditional focus on forecasting and risk analysis to embracing decision making under uncertainty. Rarely will all uncertainties about climate change and relevant stressors be resolved before decisions should be made about water infrastructure or response to floods or droughts. Anticipating and predicting water issues means that future scenarios that fall outside of historical experience must be considered, along with the consequences of specific decisions in a complex coupled human-environment system. Identifying and monitoring metrics that can be used to indicate the environmental sustainability of water will require not only the biophysical elements of the water cycle but also relevant information about human interactions and feedbacks.

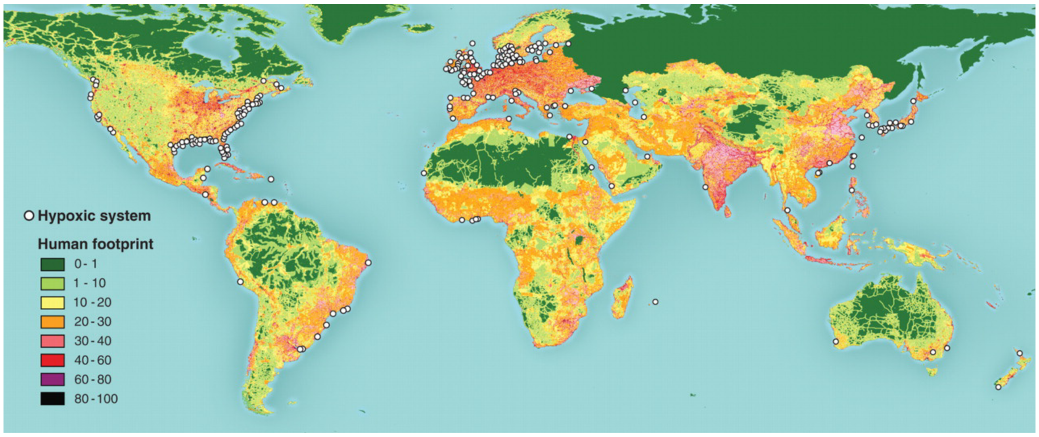

FIGURE 2-6 Global distribution of 400-plus systems that have reported eutrophication-associated dead zones. Their distribution matches the global human footprint (i.e., the concentrations of people and their impacts) in the Northern Hemisphere. For intensely populated parts of Asia and the Southern Hemisphere, occurrence of dead zones only recently has been reported (Diaz and Rosenberg, 2008). The presence of a dot on the map indicates coastal hypoxia, and the absence signifies either that no measurement was made or that the measurement yielded no hypoxia.

ENERGY

Another critical domain of human vulnerability is energy. Energy systems have a significant impact on human-environment interactions. From fossil fuel-based power plants, to hydroelectric systems, to automobiles and airplanes, production and utilization of energy not only sustain human systems but also drive anthropogenic input of CO_2 to the atmosphere. Over the next few decades, there will be significant political and economic pressures to "decarbonize" as well as to increase the efficiency of energy systems. These pressures will inevitably result in new sources of energy, all of which may have potentially unforeseen, environmental impact.

There has been considerable research on the role of the energy sector in emissions of CO_2 and on the development of technologies that could result in increased energy efficiency (NRC, 2009b). However, there has been considerably less research on the implications of deployment of these technologies on the coupled human-environment system. Biofuels will place pressure on food availability as well as increase demands on water supplies as crops are switched from food to fuel production (NRC, 2008c). Offshore energy systems (ranging from deep ocean drilling platforms to wave and tidal energy systems) will affect ocean circulation and marine ecosystems (Figure 2-7). Low-capacity but highly distributed nuclear reactors (in the few megawatt range) as well as increased numbers of larger plants could increase the risks of nuclear proliferation while carbon emissions are decreased (NRC 2009b).

All of these interactions will be further stressed by the patterns of climate change. For example, changes in natural disasters such as hurricanes, floods, and droughts will potentially disrupt a wide range of energy system operations, including transmission lines, oil and gas platforms, ports, refineries, wind farms, and solar installations. As air

FIGURE 2-7 The world's first commercial axial turbine tidal stream generator—SeaGen—in Strangford Lough. The strong wake shows the power in the tidal current. SOURCE: Courtesy of Marine Current Turbines Ltd.

temperatures rise in many regions, there will be an increase in energy demands for cooling and a decrease in energy demands for heating. Water limitations in parts of the world, and an increased demand for water for other uses, could result in less water for use in cooling at thermal electric plants as well effects on hydropower sites (NRC, 2010a).

Given that climate change will affect our energy systems and that energy systems play a significant role in the coupled human-earth system, it may be important in the future to develop metrics that will provide an indication of environmental sustainability.

"SHELTER" AND NATURAL DISASTERS

"Shelter" is added to the list of critical systems on which human beings depend because although we have adapted ourselves and our activities to average conditions on Earth (e.g., temperature, precipitation, wind), we have been less successful in accommodating extremes. Extremes such as heat and cold, flood and drought, and wildfire are not incidental to Earth system processes. Rather, they are fundamental. As a result, natural disasters are sensitive (albeit noisy) indicators of environmental sustainability. Disaster costs vary globally and significantly from year-to-year, but they are trending upward more rapidly than are inflation and growth in world gross domestic product (Munich Re, 2010), a trend that reflects several factors. The first is the increased exposure to hazards, that is, an increase in population combined with increasing property values and patterns of urbanization, especially in high-risk areas such as coasts, floodplains, and seismically active zones. The globalization of economic activity and its

FIGURE 2-8 At least 1,500 homes were destroyed and more than 500,000 acres of land burned from Santa Barbara County to the U.S.-Mexico border during wildfires in October 2007.
SOURCE: Courtesy of Jeff Turner, *http://jeffturner.info*.

increasing reliance on critical infrastructure also play a role. Frequently, disruption of the economy competes with damage to structures as the main economic loss from a natural disaster. Finally, there is the influence of climate change itself on natural disasters, such as floods, droughts, wildfires, and severe storms. While not all natural disasters are related to climate change, some, such as wildfires, may be and thereby serve as another intersection of climate change and human systems (Figure 2-8).

Wildfire provides a clear illustration of the potential relationship between the impact of climate change and human vulnerability to a climate-related natural disaster. Humans and climate both play roles in determining fire patterns. In turn, fire influences the climate through release to the atmosphere of carbon stored in the biomass (Bowman et al., 2009). Weather/climate, fuels, ignition agents, and human activities all have a strong influence on fire activity. (Flannigan, 2009). Climate drives large, regional fire through antecedent wet periods that create substantial herbaceous fuels or drought and warming that extend conducive fire weather (Bowman et al., 2009). Although wildfires are influenced by a range of climate parameters (e.g., temperature, humidity, precipitation, wind speed, lightning occurrence), in the long term, temperature may be one of the best predictors of future area burned. For example, in Canada, it appears that warmer temperatures are associated with increased area burned (Flannigan et al., 2005).

The role of human activities is another important factor. People enhance a region's vulnerability to wildfires by fragmenting or abutting forests with development.

In North America, population growth and expanding development into traditionally non-urban areas have increasingly brought humans into contact with wildfires. In the western United States alone, 38 percent of new home construction is adjacent to or intermixed with the wildland-urban interface. People also cause fires. The U.S. National Association of State Foresters (2010) estimates that 90 percent of all U.S. wildfires are caused by people. In Canada, human-caused fires make up a little more than 50 percent of all fires (Flannigan, 2010).

Fire frequency in a given area is largely dependent on the existing "fire regime," which is driven by ecological, meteorological, and human factors. A change in fire regime characteristics (and, thus, a given region's vulnerability to fire) due to a changing climate and human decisions (e.g., land use) may be an important driver of future ecosystem processes in many forested regions (Kasischke and Turetsky, 2006). Improved monitoring of fires and deforestation using satellite imagery could allow for a better quantification of wildfire activity. For more information on metrics related to natural disasters, see Tables 3-6 and 3-7.

HUMAN HEALTH

Human health is the fifth domain of human vulnerability. Understanding societal impacts of climate change at the global level requires, first and foremost, the understanding that many factors interact with a given impact. Each factor derives from a complex mix of causes and effects. Effects of climate change on food supplies will potentially result in disputes and civil strife over competition for declining resources, especially with respect to fishery stocks and fish species. Similarly, agriculture at the international level will undergo shifting patterns of harvests and altered plantings of staple food crops. Changes in food supplies, and ultimately shortages, can be predicted, as well as reappearance of famine in the less-developed countries (Parry et al., 2005; Davis and Belkin, 2008).

Change in sea level is predicted to result in potentially catastrophic effects on island nations and low-lying coastal regions, with the most severe occurring in densely populated countries like Bangladesh, where a portion of the country would become uninhabitable (Dasgupta et al., 2007). The resulting millions of refugees would pose enormous social, civil, economic, and security challenges for those nations most likely to receive them, namely the United States, and countries within Europe and Latin America. Africa and the Middle East, already embroiled in conflicts, will be impacted not only by population ebb and flow due to sea level rise, but also refugee populations escaping the areas of military action, further destabilizing a relatively fragile political environment (NIC, 2009).

This population ebb and flow in developing countries as a result of sea level rise may increase the risk of diseases spreading (Spokes, 2004). Furthermore, sea level rise combined with higher temperatures in many coastal regions will create new reservoirs of warm, brackish, stagnant water, ideal for breeding mosquitoes that can transmit malaria, dengue fever, and many other tropical mosquito-borne diseases (Craig, 2010). The warming sea itself is a reservoir of disease bacteria and viruses, and rising sea levels could expose new and more extensive populations to diseases such as cholera (Craig, 2010).

Water source and safety represent the most critical indicators with direct measureable impacts on health. Waterborne diseases are directly correlated with quality and quantity of clean water. Similarly air quality, food production, and other factors related to environmental sustainability of human systems are impacted by human health and other dimensions. Globally, diarrheal diseases currently represent the second most likely cause of death of children under the age of five in the less-developed countries (Bryce et al., 2005), meriting significant attention with respect to climate. Many cases are the result of poor drinking water quality. For example, receding glaciers and disappearance of snow in mountainous regions will threaten the availability of freshwater sources for populated regions. These changes, in addition to those caused by inadequate government services in terms of water supply management and health infrastructure, if extensive, can be predicted to foment civil disruption and social/economic irregularities, not the least of which may be more extensive epidemics and concomitant social stress (Campbell et al., 2007; CNA, 2007). If a government is dealing with a serious cholera epidemic caused by the interruption of drinking water treatment and if its water supply is significantly reduced in quantity and quality, then the civil and social disturbances caused by the epidemic will be exacerbated. In addition, on a global scale, interruption of commerce, trade, and travel will be impacted. Millions of dollars were lost during the cholera epidemics in Latin America in 1991-1992 (Susrez and Bradford, 1993).

Any health outcome that is influenced by environmental conditions may be impacted by a changing climate. However, the linkages between climate change and shifting patterns of health threats and outcomes are complicated by factors such as wealth, distribution of income, status of public health infrastructure, provision of preventive and acute medical care, and access to and appropriate use of health care information. Furthermore, the severity of future health impacts will be influenced by strategies to limit and adapt to climate change (NRC 2010a). These factors make it difficult to identify climate change metrics for human health since human health, welfare, and social well-being will be affected in multiple ways, with the end results directly derived from complex interactions of the factors for which metrics are presented in Chapter 3.

EARTH SYSTEM LINKAGES TO GLOBAL CLIMATE CHANGE AND ENVIRONMENTAL SUSTAINABILITY

A broad array of indicators, based on a great diversity of measurements, could provide advance warning of the impacts of global climate change. But because it is both uneconomical and fundamentally impossible to measure everything, it is important to develop priorities—to identify some select, finite suite of indicators that, taken together, provide a generally accurate and informative basis for anticipating problems. This is not to say that all measures are not to some degree important, but rather that some measures are likely to be especially telling.

The committee finds that observations of global-scale processes are especially valuable from an indicators perspective. A global-scale process is one that is manifested in all regions of the planet, such as the biogeochemical cycles of carbon and nitrogen, the hydrologic cycle, or ocean acidification (Box 2-1). They reflect both the impacts of climate change, as well as the feedbacks and forcings that might change the direction, scale, or timeframe of the impacts.

BOX 2-1
Ocean Acidification

The oceans are natural sinks for carbon dioxide (CO_2), but as our understanding of this process has increased we can again see the complexity of the systems and feedbacks at work. To date, it is estimated that the oceans have absorbed about one-third of man-made CO_2, helping to regulate the amount of CO_2 in the atmosphere. However, recent observations have shown that changes in ocean chemistry, driven by increased atmospheric CO_2 during the past century, are lowering the pH of seawater and reducing the carbonate ion concentration (Figure 2-9). This results in ocean acidification, a phenomenon that has diverse implications for the marine environment (Feely et al., 2004, 2008; Iglesias-Rodriguez et al., 2008). The increase in ocean acidity is corrosive to marine shells and organisms, such as corals, foraminifera, coccolithophores, and pteropods, that provide habitat for marine fish and organisms and form the base of the marine food chain.

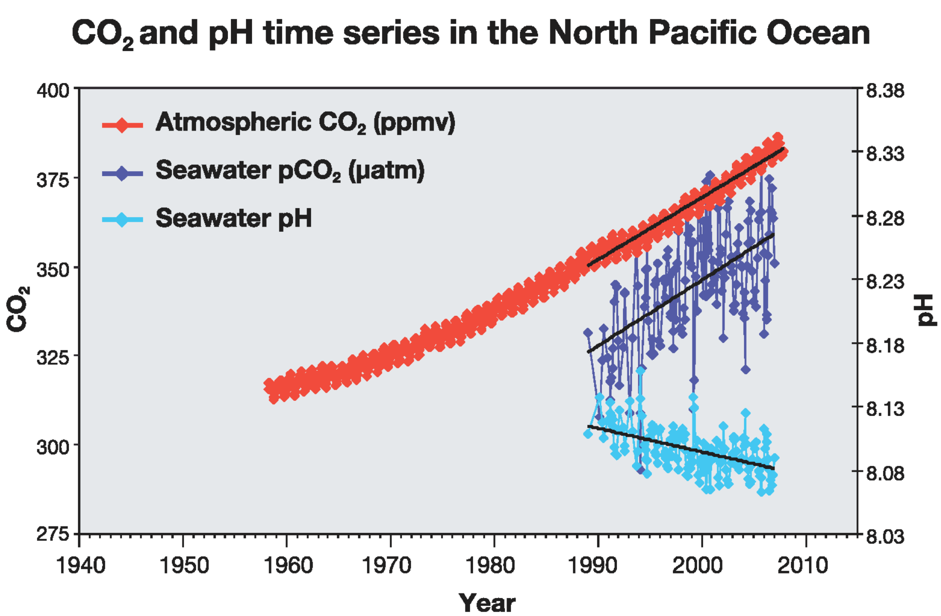

FIGURE 2-9 Observations collected over the past 20 years show consistent trends of increasing acidity in surface waters that follow increasing atmospheric CO_2. SOURCE: Richard A. Feely, Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, USA, with atmospheric data from Pieter Tans and seawater data from David Karl. Adapted from Feely (2008).

The full ecological impacts of ocean acidification are only beginning to be discerned. For example, coastal waters in the Pacific Northwest were found to be undersaturated in aragonite, which could have serious impacts for marine calcifiers for shell and skeleton formation (Feely et al., 2008). Decreased availability of aragonite and other calcium carbonates will lead to increases in both the energetic costs of shell building and the rate at which shells dissolve.

Understanding of ocean acidification and its impacts on marine ecosystems and biogeochemistry will require both long-term, comprehensive studies of physical/biological systems and detailed process studies in specific target areas (Doney et al., 2009). A global observing system (both spaced-based and in situ) will be required to monitor the large-scale patterns and dynamics of ocean circulation, heat content, primary productivity, carbon absorption, and other variables. Process studies will be needed to ascertain the ecosystem response to ocean acidification, which will vary considerably from system to system. These responses will include changes in ecosystem health composition. Coral reef ecosystems are likely candidates to show the detrimental effects of acidification, although coral reefs are stressed by other factors as well (e.g.., pollution, overfishing, climate change, and coral mining). Systems that support important ocean fisheries are also significant, such as the upwelling ecosystem off the Pacific Northwest, Georges Bank, coastal Chile, and the Bering Sea.

An emphasis on global-scale processes provides insights into linkages within the Earth system that extend from the atmosphere to the oceans, from the cryosphere to the hydrosphere, and include the land-surface, human health, and natural disasters (Box 2-2). Observations of selected indicators, taken in some careful combination, provide a fingerprint of change across multiple variables in multiple systems and can be used to search for high-level patterns. Factors to be considered when selecting global-scale processes for observation include:

- Is the global-scale process of societal relevance and likely to remain important over the next century?
- Is change in this process likely?
- Is the change measurable, especially given that small changes are difficult to measure in the presence of large variations related to, for example, seasonal or annual variability?
- Can the measurement be sustained given the realities of budgets and instruments?

BOX 2-2
Examples of Earth System Linkages to Global Climate Change and Environmental Sustainability

The committee has divided metrics into seven topical areas (oceanography, land-surface, atmosphere, cryosphere, hydrology, human health and dimensions, and natural disasters; see Chapter 3). However this division of the physical world can overlook important cross-links between areas. Some of these cross-links are extremely important but may not have received as much attention as discipline-focused areas of study because much of scientific inquiry is grounded in a single discipline. Some examples of important cross-links are as follows:

Global warming → leads to shifts in the atmospheric jet stream → which increases the intensity of upwelling events off the Pacific Northwest coast → resulting in more resuspension of iron-rich bottom sediments → leading to increased primary productivity in the coastal ocean → which in turn lowers oxygen levels in bottomwaters as blooms decay → resulting in hypoxic zones.

Ocean circulation and changes in the atmospheric circulation → drive the change in the type (temperature) of the water that reaches ice shelves → resulting in land ice loss → leading to sea level rise → and eventually coastal inundation/erosion.

Atmospheric wind and temperature fields → affect sea ice cover and the occurrence/extent of sea ice → which in turn directly changes the radiation budget → which feeds directly back to the atmospheric state.

Precipitation patterns → determine the amount of snowpack → which drives surface hydrology → affecting the relative success of vegetation and agriculture, and people's dependence thereupon.

Increased CO_2 emissions → some of which are absorbed by the oceans → result in increased ocean acidity → which is corrosive to marine shells and organisms → that provide critical habitat and/or food sources for other organisms → which will negatively impact fisheries worldwide.

3

Climate Change Metrics at the Intersection of the Human and Earth Systems

Scientists are accustomed to focusing their work by discipline, that is, by a particular topic of deep expertise. Thus, based on the knowledge in the respective disciplines, the committee presents the metrics that it considers to offer significant potential for giving advance warning of climate-related changes in the Earth system most likely to affect the domains of human vulnerabilities identified in Chapter 2. The eight panels worked from the assumption that the fundamental science of climate processes and the associated impacts on the natural world serve as the focus of an already existing and extensive set of observing systems. The panels did not attempt to re-create the efforts of programs such as the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS).

The panels sought to be as specific as possible with respect to the underlying component measurements and observations needed to construct a given metric. They also sought to identify illustrative locations where measurements would be most useful. Some metrics are indicators of clearly measurable change; others are more exploratory but offer new perspectives. Some metrics cannot be observed from space, but require instrumentation in situ. Some metrics are clearly quantifiable and others are more general but conceptually useful. The tables, of necessity, will be revisited as scientific data accumulate.

The introduction to each table describes the particular process and criteria used by the panel when categorizing and/or coarsely prioritizing the metrics. Given the diverse nature of metrics, a uniform process for categorizing and prioritizing the metrics presented in this report is not possible. However, certain characteristics tend to make a metric particularly useful, including:

- Direct (e.g., loss of mass of an ice sheet leads to rising sea level)
- Significant (i.e., represents a large change in one or more resources including water, energy, shelter, health, or food)
- Dominant (i.e., outweighs other factors and processes)
- Measureable (i.e., capable of being quantified)
- Historical (i.e., provides foundation of understanding and measurement)
- Well documented (i.e., data are complete and consistent)

OCEANOGRAPHY

The two panels initially charged with identifying ocean metrics (physical/chemical and biological) worked together to develop a single table covering physical, chemical, and biological processes. This integration recognizes that the fluid dynamics of the ocean underlie its chemistry and biology and that the three cannot be considered in isolation.

The panels focused on climate metrics that are highly integrated with the impacts of climate change (Table 3-1). For example, the panels proposed a metric for the health of fisheries, which depends in part on the primary productivity of the ocean. In contrast, the GCOS equivalent focuses on ocean productivity as a fundamental indicator.

The panels gave higher priority to metrics that either integrate human impacts (e.g., fisheries) or could have significant impacts on the ecosystem services that provide value to society (e.g., the impacts of harmful algal blooms). Therefore, the ocean metrics are strongly weighted toward the human dimension of ocean processes, not simply the fundamental processes of climate change. The panels then further refined the metrics toward those for which there is significant potential for risk and vulnerability. For example, the panels considered the impacts of climate change (i.e., rising sea level) on the infrastructures of ports and harbors, which are crucial to global trade, but not on coastal recreation.

Many of the proposed indicators focus on emerging issues, as well as on new management and development strategies. In other words, they do not simply recapitulate ongoing indicators. For example, new approaches to management, such as of marine protected areas, should be studied now in order to assess their effectiveness as well as their impacts on ocean ecosystems.

Finally, the ocean panels recognized that many of their metrics are “process based” rather than “place based.” For example, because the location and intensity of fisheries shift over time, we cannot define a set of key places to monitor. Rather, we must ensure that there is ongoing feedback between the systems being observed and the systems observing them. Thus, the ocean indicators are often iterative in nature and should be refined as knowledge improves.

The panels relied on the six criteria to prioritize the metrics. It became clear that metrics could be distinguished based on the strength of their connection to climate processes and to environmental sustainability. As a result, the panels identified three priority levels: (1) high climate, high environmental sustainability; (2) low climate, high environmental sustainability; and (3) low climate, moderate environmental sustainability. The panels chose to not include metrics that have high climate, low environmental sustainability because the special emphasis of the report is on the environmental sustainability connection. As noted earlier, many other reports have addressed traditional climate change indicators.

Two examples will highlight this process. Sea level rise has a direct link to the climate system, and it is significant, dominant, measurable, historical, and well documented. Therefore, it was placed in the high climate, high environmental sustainability category. In comparison, fisheries health is significant, measurable (with varying quality), historical, and well documented, but climate change is not the only (or most significant) pressure on fisheries, so it was placed in the low climate, high environmental sustainability category.

The panels considered the following two metrics to be important, but not correlated strongly enough at this time with climate change and environmental sustainability to warrant inclusion in the table: (1) location and extent of offshore energy production and supply including onshore infrastructure, and (2) location and extent of desalination facilities in coastal zones.

The location and extent of offshore energy production and supply could be measured by ocean productivity, high-resolution imagery of energy production infrastructure, seafloor morphology, and habitat imagery of the coastal zone and shoreline. Areas where it would be useful to apply this metric are those that are expected see increased development in the next 5- to 10 years, such as Denmark, the Gulf Coast, and France. Although offshore energy development may not have a strong connection to environmental sustainability and climate change at this time, it may become important in the future as sources of energy that do not depend on fossil fuel are developed. Many of these new sources will likely be located in coastal oceans and may impact ocean ecosystems.

The location and extent of desalination facilities in coastal zones also do not currently have strong ties to environmental sustainability and climate change but may in the future. The Global Desalination Report and Global Water Intelligence (UK) maintain a detailed and comprehensive data set of every desalination plant in the world by name, location, capacity, technology, form, and cost. This data set will be important in monitoring the effects and impacts of these plants in the future. There are many reasons to build such facilities, but climate change will increase the pressure to do so. As the population grows and climate change affects rainfall in some areas, there will be more demands for freshwater. Traditional sources will become increasingly scarce, and the possible proliferation of desalination plants to fill the gap could have a significant impact on near-shore ecosystems. It would be important to focus measurements in places such as Oman, the Gulf States, and California

TABLE 3-1 Key Metrics: Oceans

Oceans Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
High climate, high environmental sustainability			
Sea level rise (see Hydrology, Cryosphere, and Natural Disasters tables)	Global sea level height Glacial (ice) measurements High-resolution maps of terrestrial features Advanced circulation models of inundation Sea floor morphology (depth and substrate)	Low-lying oceanic island groups and Arctic coasts (e.g., Maldives, Micronesian Islands) Deltaic coasts (e.g., Bangladesh) Large coastal ports (e.g., New Orleans, Columbia River, Houston, Los Angeles) Coastal urban centers (e.g., Venice, New York)	Temporal and spatial patterns of changes in sea level will be an indicator of future risks to coastal populations and infrastructure. Higher sea level amplifies coastal erosion, storm damage, permanent flooding, and land inundation.
Acidification	pH Dissolved oxygen Ocean productivity Acoustic data	Places with varying levels of human pressure and predicted impacts on ecosystems as a result of acidification (e.g., Virgin Islands, Great Barrier Reef, Pacific Islands, Fiji, Philippines, Indonesia, Maldives, Georges Bank, northwest and southwest coasts of United States, Atlantic Bight south of Boston, New York City, Bering Sea)	The ocean is a long-term sink for atmospheric CO2, and pH will continue to drop for centuries. Trends in space and time of this metric will help predict its impact on coastal ecosystems and ecosystem services.

Oceans Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Changes and redistribution of heat (stability of global ocean circulation patterns)	Velocity Temperature Changes and redistribution of heat Salinity High-resolution maps of sea level	North Atlantic Ocean, Arctic Ocean, Antarctic Ocean, Greenland, Gulf Stream transport, Labrador, Antarctic peninsula	Monitoring this metric provides an indication of abrupt change, shifts in atmospheric circulation (storms), impacts on continental ice sheets and shelves (Antarctica and Greenland) and sea ice.
Ocean heat content	Surface and subsurface ocean temperatures Air-sea fluxes	Temperate and high latitudes Hawaii Coral reef ecosystems Polar areas	This metric is an indicator of vulnerability, sea level rise (thermal expansion) as well as impacts on ecosystems (shifts in species boundaries).
Changes in extent and composition of shorelines and wetlands due to sea level rise, erosion, and human activities (e.g., infrastructure construction)	Ground surface topography (via digital elevation models and high-resolution satellite imagery) Underwater depth of ocean floors (via bathymetric mapping; including substrate) Habitat mapping	Coast of Gulf of Mexico, Southern California, Barrow, Carolina Barrier Islands, Netherlands, North Japan, Venice	Monitoring this metric provides an indication of significant impacts on terrestrial ecosystems at the land/ocean interface as a result of growing human populations and activities (urbanization, transformation of natural wetlands into managed environments). This is an indicator of increased vulnerability to coastal inundation as well as impacts on coastal ecosystem services. Monitoring this metric will help project future impacts to continuing sea level rise.
Low climate, high environmental sustainability			
Health of wild and managed fisheries (including aquaculture)	Fishing intensity (spatial and temporal patterns) Ocean productivity Coastal land use Extent of aquaculture Statistics on aquaculture	Nations with significant fishing and aquaculture activities (e.g., Norway, Iceland, Chile, Ecuador, Indonesia, Thailand, China, Japan, Korea)	Fish is the main food interface with the ocean, conversion of wetlands to aquaculture, impacts of open-ocean aquaculture. Spatial and temporal changes in this metric will provide an indication of long-term ecosystem health and environmental sustainability.

Oceans Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Extent and depth of hypoxia	Temperature Salinity Oxygen Dissolved CO_2 Ocean productivity Seafloor morphology (depth and substrate)	Mississippi River Delta, Gulf of Mexico, Oregon and Washington coasts, west coast of India, eastern tropical Pacific and Arabian Sea, Baltic Sea Wadden Sea, Chesapeake Bay	Although most of the present hypoxic zones in the ocean are the result of terrestrial runoff of nutrients (which stimulate primary productivity), warming of the surface ocean and increasing CO_2 concentrations may greatly expand the extent of hypoxia at depth (Brewer and Peltzer, 2009). The increased use of fertilizers and particularly nitrogen with increasing CO_2 and growing demand for food from larger populations may make this directly dependent upon climate change. Mapping of hypoxic zones will provide an indication of changes in ocean chemistry and possible impacts on ecosystems. It will likely have a large and differential impact on fisheries (varies depending on location).
Occurrence and extent of harmful algal blooms	Nutrient levels Phytoplankton abundance Toxins Phytoplankton species Ocean productivity	Gulf of Maine, west coast of Florida, Puget Sound, Southeast Asia, Gulf of Oman, Arabian Gulf	Changes in ocean circulation and temperature as well as terrestrial runoff are increasing the frequency and extent of harmful algal blooms. This is at the intersection of climate change and environmental sustainability.
Low climate, moderate environmental sustainability			

Oceans Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Effectiveness of marine protected areas (MPAs)	Ocean productivity Ecological indicators such as biodiversity and fish reproductive potential Seafloor mapping	Locations of extensive marine reserves and protected areas (e.g., New Zealand) Channel Islands off California, northwest part of Hawaiian archipelago Belize	MPAs were initially conceived as a management tool for the long-term sustainability of fisheries and their associated ecosystems. In addition MPAs provide refugia for commercially harvested fish species, and communities that are under pressure from climate change (e.g., warming temperatures, acidification) MPAs can also increase ecosystem resilience in the face of climate change by reducing other human-caused environmental stresses such as fishing and resource extraction. Tracking this metric over time can gauge its effectiveness as a means to sustain ecosystem services and resilience in the face of climate change.

LAND-SURFACE AND TERRESTRIAL ECOSYSTEMS

The Land-Surface Panel recognized that the terrestrial surface is intrinsically heterogeneous at multiple scales. Unlike atmospheric and oceanic systems, which have the equations of motion as a unifying concept, change in terrestrial systems tends to be local or regional in its context. There is a long-standing tradition in ecological science of associating observed patterns with underlying processes, but understanding which processes are manifested at what scales of patterns is, and will likely continue to be, a research work in progress. One of the consequences of this aspect of the state of the science, and of the nature of the systems themselves, is a need to observe change extensively and synoptically to obtain indications of global-scale pattern changes.

The panel considered three broad classes of metrics:

1. *Metrics of change that focus on synchronous change in similar, dispersed ecological systems.* Such metrics gain interpretive importance when the underlying causes of these changes can be related directly to overarching drivers, which in turn are being modified by global environmental change. This class of metrics is very small and takes advantage of locations where so-called "natural experiments" are occurring. Such situations are at locations in space (or occurrences in time), that can be compared if the important environmental driving variables are known across a large set of globally distributed locations. One example would be a high-mountain, plant-growth or -vigor monitoring system that focuses on the ecosystems within which plant growth is increasing because of the positive effects of CO_2 on productivity or water-use efficiency. Because the partial pressure of CO_2 in the atmosphere is lowest in the highest altitude vegetation, the direct response of vegetation to elevated levels of CO_2 might be detected earlier in high-elevation locations than elsewhere.
2. *Metrics that capture the ecological and environmental state under conditions that either allow control (in a statistical sense) or correction (using existing models of ecosystem processes) to reduce the uncertainty and variability in large area evaluations.* Such applications might involve overlaying base maps of controlling factors across a regional monitoring system to control for environmental conditions. Examples of variables would include water resource levels, soil moisture, or soil nutrient status. In practice one would stratify the observations according to conditions and then use the data structures to look for "signatures" of different kinds of changes. As examples, an altered climatic condition might produce increased plant growth in nutrient-rich sites but not nutrient-poor sites, or droughts might affect south-facing slopes differently than north-facing slopes.
3. *Metrics that quantify the state of ecosystems.* These would include measurements of ecosystem attributes such as diversity, the nature of land cover, species composition, and the indicator species. Abrupt changes in these attributes of ecological systems would warn of an alteration of the ecosystem performance. This class of metrics challenges our ability to ascribe the cause

> of the changes in an unequivocal way. For example, in subtropical and warm-temperate grasslands there has been a global increase in "woody weeds"—increased woody plants and decreased grasses. This is an expected result for the direct effects of increased CO_2 on plant processes, which should favor C3-pathway trees over C4-pathway warm-season grasses. However, it might also be a consequence of increased cattle grazing or changes in fire regimes.

Many of the panel's metrics were intended to be applied over a sampling of the planetary surface, but there was an attempt to reduce the open-endedness of the implied monitoring by focusing on systems for which the observation of change would likely have more power to ascribe "cause" to the observed patterns. For this reason several of the metrics are place-based and thought of as being applied in particular locations or by environmental condition. The selection of these place-based metrics obviously derives from the current perception of important issues (e.g., direct effects of CO_2 on plant processes, climate change effects at transition zones of vegetation, changes in patterns of land use, loss of biotic diversity and change in diversity hot-spots, moisture conditions, crop productivity, livestock populations, and locations with potentially large changes in albedo). Clearly these priorities for monitoring may change with increased knowledge of terrestrial ecosystem functions and as new types of change are observed from the more global reconnaissance that is discussed in Table 3-2.

TABLE 3-2 Key Metrics: Land-Surface and Terrestrial Ecosystems

Land-Surface Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Metrics of change that focus on synchronous change in similar, dispersed ecological systems			
Increased vegetation vigor in response to CO_2 direct effects	Time series of fine-scale changes in LAI (leaf area index) Compositional changes in life forms	Tall tropical and subtropical mountains (vegetation in lowest natural CO_2 partial pressures) Vegetation changes in locations with naturally elevated CO_2	This would likely result in increased amount of vegetation and a shifting of vegetation zones to harsher conditions. This is one example of monitoring "natural experiments" on CO_2 direct effects. Unfortunately, as is the case with most natural experiments there is no contemporaneous control for global change. Many locations should be monitored for synchronous change.
Latitudinal and altitudinal shifts in species distributions	Geographical locations for representative species Population density and size for representative species	Altitudinal transects that have historical data (many of these are archived in the Swiss-based Mountain Climate Network and have worldwide distribution) Latitudinal transects	Species that experience range shifts are more sustainable in relation to global warming, but only to a point. If they meet impassable barriers that impede them, or reach the tops of mountains, they may be trapped and become unsustainable. Individual members of communities may have different abilities to change geographic ranges, so communities might become disrupted.
Cloud base height on tropical mountains	Measurements of cloud basal height Cloud cover	Eastern Andes and Ecuador Costa Rica Guatemala margins of Amazonian Basin	Cloud forests are important centers of diversity for taxa such as amphibians, insects, and plants, and changes in cloud lines can lead to great losses of biodiversity. Montane cloud forests are evolutionary hot spots that can serve as "species pumps" for adjacent lowlands.
Metrics that capture the ecological and environmental state under conditions that either allow control (in a statistical sense) or correction (using existing models of ecosystem processes) to reduce the uncertainty and variability in large area evaluations			

Land-Surface Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Soil moisture change (see Hydrology table)	Soil moisture Plant productivity Decomposition rate Soil formation rate	Agricultural regions worldwide Severe weather regions Areas where monitoring recharge is important (developing nations and places where surface water resources are contaminated or in decline) Agricultural regions where groundwater mining is active (e.g., Sahel region of Africa, Ganges-Brahmaputra plain, Yellow River)	Soil moisture is a major controlling variable for large-scale patterns in vegetation. Soil moisture dynamics are critical variables for many of the ecological models used for global carbon budgets and other global ecological processes.
Positive feedback between terrestrial surface change and climate change	Albedo Species composition	Boreal Forest in Eastern Siberian Larch zone	As a case example of other similar interactions, changes that involve positive feedbacks can amplify the consequences of change, promote system change, and destabilize the system.

Land-Surface Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Change in subtropical zones	Changes in vegetation (leaf area, numbers of plants, ratios of trees to shrubs to grasses) along significant and well-studied moisture-driven natural gradients of vegetation Change in the spatial arrangement of vegetation elements Measurements of vegetation, crops and other land use (via "enriched," sub-pixel civilian satellite archive) Trends of changes in leaf area and deaths of plants	Arid zone transects (e.g., Northern Australia transect, Sahel, Kalahari transect)	Vegetation transects tend to isolate the moisture component of change. They also represent land areas held by some of the poorest and most climate vulnerable nations.
Water resource levels (see Hydrology table)	Depth to water tables through time Water volume in upland glaciers (extent and thickness of glaciers)	Developing nations and places where surface water resources are contaminated or in decline Punjab, Himalayan glaciers Alpine glaciers in South America that are receding (e.g., Chacaltaya Glacier in Bolivia, Antizana Glacier in Ecuador)	Monitoring this metric provides an indication of how much water will be available in the future. Water is critical to human survival and food production.

Land-Surface Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Productivity of cropland	Yields of irrigated crops and dryland crops (parsed out separately) through time Water, fertilizer, pesticide, and labor inputs through time	Globally, but with focus on major agricultural regions (e.g., North India, East China, South Africa, United States)	This metric provides an indication of how much and how fast yields can continue to be improved. High yields are needed to feed populations without major expansion of croplands.
Livestock populations	Density of livestock (animal heads per square km) Counts of different types of livestock (cattle, sheep, goats)	Sub-Saharan Africa South America	Livestock is a critical source of food and livelihoods, especially as a way to manage risk and utilize relatively unproductive lands in poor regions. In the regions (e.g., Sub-Saharan Africa, South America) indicated, the populations of livestock are indicators of the condition of the rangeland. The rangelands in these cases are neither irrigated nor fertilized and are strongly coupled to the weather conditions. Because herds build slowly but can drop abruptly and because the populace is often financially strapped, drops in cattle numbers is potentially catastrophic.
Metrics that quantify the state of ecosystems			
Biodiversity change related to temperature	Physiology of animals in relation to biophysical models and associated indicators Components of the Penman-Monteith equation (daily mean temperature, wind speed, relative humidity, and solar radiation to predict net evapotranspiration)	Tropical lowlands	As plantations such as for bananas are abandoned, secondary forests are expanding. Will these form refuges for organisms displaced by conversion of primary forests, thus sustaining biodiversity?

Land-Surface Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Shifting agricultural practices	Time of crop planting and harvest Presence/absence of crop residues on soils after harvest Number of crop harvests per year Type of crop being grown	Globally, but with focus on major agricultural regions (e.g., North India, East China, South Africa, United States, Southeast Asia)	Changes in planting date and residue management are two of the main proposed adaptation strategies for agriculture. Adoption of no-till is one of the key proposed areas to mitigate climate change impacts via agriculture, by storing more carbon in soil.
Ecosystem health/habitat degradation	Ecosystem mortality Temporal trends in leaf area, water stress, and mortality of plants Measurements of vegetation, crops and other land use (via "enriched," sub-pixel civilian satellite archive)	Global coverage implied Focus on areas of population growth and urban expansion	Human well-being and biodiversity depend on ecosystems services (MEA, 2005).
Land cover and land use (focus on change into and out of agriculture)	Change in land cover type Measurements of vegetation, crops and other land use (via "enriched," sub-pixel civilian satellite archive)	Global coverage implied Identification of "Hot Spots" or specific areas could be identified (e.g., South Asia urbanization, South America forest conversion)	Societies depend on goods and services derived from various land uses. Shifting agricultural practices are important to monitor because of the emphasis on local sustainability and the strong traditional basis for the practice. The changes in these cropping systems under stress (either from increased populations or environmentally induced shortfalls) could potentially serve as a barometer for the more complex, technologically dynamic agricultural systems. Separating climatic influences from other societal trends is an issue. This should be helped by the global nature of the measurement.

CRYOSPHERE

The Cryosphere Panel emphasized indicators that are highly integrated in regard to the human dimension of climate change in contrast to the sparse populations present within the cryosphere (Table 3-3). For example, the panel proposed the extent of terrestrial permafrost and the overlying active layer as a metric. Changes in permafrost have implications for flora and fauna, as well as for human populations. Permafrost dictates the character of flora and fauna. Roots cannot penetrate beyond the active layer, but as thawing has become more widespread, cases of "drunken forests" (wherein trees whose roots had been supported by the rigidity of the underlying soils fall over in haphazard disarray) and northward migration of deeper rooted plants have become more common. Likewise, a deeper active layer allows burrowing animals to migrate northward. Thawing also results in the degradation of human infrastructure, for example, creeping of railroad beds and collapse of habitable buildings.

The panel also sought to provide metrics that capture the forcings and feedbacks among components of the climate system, for example, sea ice volume. Absorbed solar radiation over bright ice versus dark ocean varies a full order of magnitude, driving one of the most powerful positive feedback effects of Earth's climate. Loss of sea ice exposes darker radiation-absorbing surfaces, which tends to warm the ocean surface layers further, leading to more ice loss, exposure of more dark ocean, and so forth. This loss of sea ice will adversely affect the polar societies that are strongly dependent on marine ecosystems for food and livelihood. Furthermore, a reduction in sea ice will impact surface shipping routes, which will have economic, political, and environmental ramifications, both favorable and unfavorable.

The panel recognized that there is some overlap with the other panels' metrics. These important metrics shed light on linkages within the human-environment system. For example, the Ocean Panel proposed an ice shelf metric and the Cryosphere Panel proposed a continental ice volume metric. It has been suggested that the loss of ice shelves because of excessive heat content in ocean currents lead to more rapid decay of continental ice and consequent increases in sea level.

The panel was cognizant of the observational capabilities of the report's primary audience, which led it to deemphasize those metrics that, although very important in global climate interactions, require comprehensive observations on a very large scale. These types of metrics are published along with a more complete description of measurement parameters in the Integrated Global Observing Strategy-Cryosphere Theme Report.[12]

The cryosphere metrics listed in the following table are coarsely prioritized with primary consideration given to their relevance to direct human impacts and their suitability to quantification by the report's primary audience. Secondary consideration was given to characteristics of record longevity and significance to global climate interactions.

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[12] See *http://cryos.ssec.wisc.edu/docs/cryos_theme_report.pdf*.

TABLE 3-3 Key Metrics: Cryosphere

Cryosphere Metric	**Measurements**	**Illustrative Locations for Measurements**	**Why This Metric Is an Indicator of Environmental Sustainability**
Condition and extent of terrestrial and sub-aqueous permafrost, including the overlying active layer	Active layer depth Vertical temperature profile of permafrost Ice volume fraction Surface snow cover, vegetation, and temperature Surface elevation change Ground morphology and vegetation type Ground creep	Continuation of existing permafrost monitoring sites (see Circumpolar Active Layer Monitoring [CALM] website and map at *http://www.udel.edu/Geography/calm/about/map.html*) Possible new set of North-South transects (5-6 sites per transect) at 4 longitudinal locations (e.g., Alaska, Siberia, Scandinavia, Canada) These locations might be able to draw on either traditional knowledge or local governments for sites where change most strongly affect environmental sustainability factors.	Change causes destruction of infrastructure or directly affects environmental sustainability factors, such as water availability (through altered drainage patterns) or water quality (through release of organics and pollutants). Large investment in altered infrastructure may become necessary, including oil and gas engineering and migration of northern populations. Release of greenhouse gases from thawing permafrost contributes to climate change.
Mass of small, high-altitude glaciers	Glacier extent in summer and winter Surface elevation in summer and winter	Selected high-altitude glaciers (smaller is better) Those with longest records contained within the World Glacier Monitoring Service, especially in Asia and South America, where glacier runoff is a critical water resource	Loss of these glaciers would remove a critical water source (especially in summer) for many high-elevation populations.

Cryosphere Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Land ice dynamics	Changes in velocity of outlet glaciers (with InSAR, GPS geodesy, or optical imagery) Meltwater lake coverage and drainage in ablation zones Extent, magnitude, and timing of surface ablation Subglacial hydrology (storage and transfer) and basal boundary condition (wet vs. frozen, permittivity) Grounding line location	Major outlet glaciers and ablation zones of the ice sheets (especially areas of known large changes) Selected smaller glaciers and ice cap outlets (e.g., Greenland: Jackobshavns, Helheim, Peterman, Kangerlussuag; Antarctica: Pine Island, Thwaites, Smith, Kohler, Mertz, Totten, Jutelstraumen, Lambert Glaciers and Foundation, Whillans and Kamb Ice Streams)	Higher sea level amplifies coastal erosion, storm damage, permanent flooding, and land inundation. Rising sea level leads to significant property loss, leading to costly mitigation/adaptation, migration of human and animal populations, and consequent potential for conflicts. Reliable forecasting of sea level rise and assessment of impacts can significantly mitigate adverse impacts.
Temporal viability of sea ice	Melt pond extent and size distribution Albedo Surface relief (all tracked through the melt season)	Selected areas (10 km x 10 km, minimum) in the perennial and seasonal ice zone (e.g., the locations of the 6 fiducial sites in the Arctic Fram, Canada, E. Siberian, Chukchi, Beaufort, and Barrow [NRC, 2009a]) Current technical limits on spatial resolution vs. coverage prevent comprehensive coverage	Lower albedo leads to increased solar radiation absorption, thinner sea ice through increased melt, warmer upper ocean, decreased viability of sea ice in subsequent years, reinforcing regional and global climate warming.

Cryosphere Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Seasonal snow cover and snow water equivalent, and their seasonal progression (see Hydrology table)	Fractional snow-covered area (the fraction of each grid cell covered by snow; heterogeneity and pattern) Snow wetness (liquid water in the snowpack)Rain-snow transition during storms Runoff and its timing relative to demand Snow albedo, subdivided into visible vs. near-infrared wavelengths, to estimate change by grain growth and absorbing impurities Snow water equivalent (can remotely sense in lowlands with passive microwave, but cannot remotely sense in the mountains)	Continental scale (e.g., Arctic Canada, Arctic Eurasia, Tibetan Plateau) Mountain scale (e.g., western North America, Andes, Greater Himalaya, including Karakorum, Hindu Kush, and High Asia Alps)	About one-sixth of Earth's population depends on end-of-season snowpack. Snow also affects ecosystems. The measurements provided here would tease out effects of precipitation, temperature, and albedo, helping to validate and improve regional climate models. Snow is a significant component of available water supply and a critical factor in regional and local water management (e.g., U.S. west). Surface transportation (especially rail and truck) is sensitive to the presence and evolution of snow.

Cryosphere Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Lake, river, and reservoir ice cover (see Hydrology table)	Freeze-up and breakup dates of lake and river ice Extent and thickness of ice	Continue sites with longest records (e.g., Great Lakes Environmental Research Lab, *http://www.glerl.noaa.gov/data/pgs/ice.html*) Possibly a few north-south transects (on different continents) Sample moderate-size lakes in north temperate and tropical region	Presence of lake and river ice affects transportation industry and population mobility. Timing and intensity of spring melt/breakup is factored into flood plain management. Lake ice duration is strongly connected to regional warming Lake ice controls suitability of lakes for cold and cool water fishes; eutrophication causes anoxic bottomwaters and fish kills. Lake ice duration is strongly connected to water quality for human health because chlorination of high dissolved organic carbon water creates harmful byproducts, which are regulated in the United States and Europe. Images showing patterns of lake ice formation and breakup will be useful in developing predictive linking of ice-cover duration to climate models.
Sea ice volume (thickness and extent)	Sea ice extent and ice type Freeboard height Snow thickness Ice motion	Entire Arctic and southern oceans	Polar societies are strongly dependent on marine ecosystems for food and livelihood; shrinking sea ice will adversely affect these subsistence societies. Surface shipping routes (e.g., through northeast and northwest passages) will be revised with reduction in Arctic ice pack, with economic, political, and environmental ramifications.

Cryosphere Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Land ice mass balance (see Hydrology, Oceans, and Natural Disasters tables)	Surface elevation change (via altimetry) Mass change (via satellite gravity) Ice speed at grounding line (ice sheet) Surface accumulation Melt extent, intensity, timing (including equilibrium line position) and surface temperature Glacier area change Post-glacial rebound	Entire Greenland and Antarctic ice sheets Glaciers with longest observational records (see World Glacier Monitoring Service)	Higher sea level amplifies coastal erosion, storm damage, permanent flooding, and land inundation. Rising sea level leads to significant property loss, leading to costly mitigation/adaptation, migration of human and animal populations, and consequent potential for conflicts. Reliable forecasting of sea level rise and assessment of impacts can significantly mitigate adverse impacts.

ATMOSPHERE

The Atmosphere Panel divided metrics of global climate change and environmental sustainability into three categories: (1) climatic trends (rates of change) for parameters that measure climate sensitivity, characterize global climate state, and define major drivers for climate change; (2) measurements of state changes that represent key feedbacks with current high uncertainty and possible high impact on future climate; and (3) trends with direct implications for vulnerability or sustainability of ecosystems, human systems, and health (Table 3-4). There is overlap among these categories. For example, the monitoring of major urban/industrial regions for energy use and greenhouse gas emissions cannot be separated from the monitoring of local emission of atmospheric toxics. Also, changes in clouds and aerosols are often coupled, and therefore their measurement should be coupled.

The panel's choice of metrics is meant to span the range from cause to impact, effectively integrating the causality chain from humans through the physical climate and back to societal impacts. For example, the requirement to monitor the column and boundary layer abundances of the long-lived greenhouse gases is for attribution (i.e., sources of emissions) as well as for climate impacts. The measurements of urban heat and aerosol and effective ozone emissions, however, also relate to impacts. Obviously, some of these atmospheric metrics need to be linked with the land-surface or ocean in order to address changes in ecosystems, agriculture, and human health.

Given the rapid and often chaotic variability of the atmosphere, measurements should be made with the goal of defining a scenario, describing environmental conditions, or establishing a statistical base for climate change. The panel did not delve into the requirements to achieve these specific goals, because that would require much greater detail than the panel could provide about the timing, location, and precision of the measurements. Thus, the atmosphere metrics will need to be re-examined and tailored over the long-term to the specific capabilities of the instruments that will be used for measurement, in the context of the overall observing system.

TABLE 3-4 Key Metrics: Atmosphere

Atmosphere Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Climatic trends (rates of change) for parameters that measure climate sensitivity and characterize global climate state, and that define major drivers for climate change			
Changes in the frequency and intensity of precipitation, increased height of the freezing level	Precipitation amount (surface) Hydrometer size and phase Lightning flash rate Changes in snowpack	Monsoon regions Mediterranean regions Mountain ranges that supply major rivers (e.g., Himalaya, Andes, Sierra) Highly populated river basins and coastal zones subject to flooding	Changes in the manner of precipitation and not just the total amount are expected with climate change. Regional adaptation plans must be able to anticipate such shifts in order to plan for public safety and welfare, including water supply, irrigation of farmland, and ecosystem shifts.
Temperature climate normals	Surface temperature statistics (surface and satellite) Changes from the past 30-year statistics for seasonal duration and for extreme events such as heat waves and cold spells	Major agricultural and natural ecosystems (e.g., boreal) to detect shifts in phenology Metropolitan areas for heat stress Ice sheets and mountain glaciers (measures altitude of <T>=0)	Shifts are predicted as part of a warming world. The changes of temperature normals coupled with seasons, heat waves, and ice sheet melt are clear measures of regional climate change in a warming world with direct connections to health, agriculture, and water resources policies.
Greenhouse gas (GHG) emissions	Abundances of individual gases: CO_2, CH_4, N_2O, CFCs, SF_6, NF_3 (total column and planetary boundary layer)	Major industrial, urban, and fossil-fuel producing regions (e.g., Beijing, Tokyo, New York City, Hamburg) Permafrost areas (e.g., Siberia and Alaska) Wetlands (e.g., Southeast Asia) Biomass burning (e.g., Boreal Canada, Sub-Saharan Africa) Agricultural regions	Monitoring this metric could indicate compliance with mitigation targets (e.g., see NRC, 2010b).
Measurements of state of changes that represent key feedbacks with current high uncertainty and possible high impact on future climate			

Atmosphere Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Upper tropospheric water vapor	Relative humidity Specific humidity	Global with cirrus cloud data measured by satellites	Increases in water vapor and in cirrus are a potential large positive natural feedback in a warming world, and associated uncertainties are a major factor in the climate debate. Cirrus enhancement by aviation, a possible climate forcing, is an environmental sustainability issue.
Atmospheric stability, lapse rate, and convective available potential energy (CAPE)	Temperature profiles Specific humidity	Tropical convergence regions (e.g., western Pacific, Amazonia) Mid-latitude storm tracks Tornado alley in the United States	The potential for climate change to intensify regions of strong storms is a risk that is very uncertain and can best be tracked by monitoring the potential energy that drives such events.
Marine stratus clouds	Cloud extent Liquid water path Mean radius	Marine stratus decks in key regions (e.g., Chile, California, Africa)	Marine stratus clouds are a major uncertainty in climate feedbacks and would be a key indicator of climate response and magnitude. Coastal climates are directly affected.
Aerosols (dust outbreaks; smoke; deposition onto snow/ice; industrial/agricultural aerosol; volcanic aerosols)	Optical properties (visibility, optical depth, albedo, cloud condensation nuclei) Speciation: dust, sulfate (volcanic, biogenic, anthropogenic), nitrates, organic carbon, soot	Asian (e.g., Gobi desert) and Sahara dust-forming regions Tropical forest-burning areas (e.g., Amazon) Glaciers and ice sheets (e.g., Greenland) China/India areas of industrialization (e.g., Himalaya, North Indian Ocean) Super-metropolitan (e.g., Japan, Southern California, Mexico City, Sao Paulo, South China, India industrial centers)	Aerosol effects are another major uncertainty in climate projections, affecting surface climate and regional precipitation, as well as human health. Changes in desertification, industrial activity, wildfire occurrence, and direct and indirect aerosol radiative forcing are all potentially important drivers for which the indicator data will directly inform public policy and the fields that study climate change. Urban heat island effects and flooding (e.g., in Sao Paulo) are directly linked to environmental sustainability.

Atmosphere Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Radiative flux and frequency (clouds)	Liquid/ice water content and distribution Shortwave and longwave	Global satellite data Marine stratus decks such as coastal Chile Cirrus clouds, especially over subtropical oceans Areas prone to severe weather	Cloud radiative forcing and feedbacks are the greatest uncertainty in the climate change field. This indicator establishes what trends, if any, are taking place.
Trends with direct implications for vulnerability or sustainability of ecosystems, human systems, and health			
Statistics of tropical and extra-tropical cyclones (see Natural Disasters table)	Lifecycle of the very strong cyclones, integrating energy and potential damage quotients (wind, storm surge)	The tropical cyclone basins (e.g., Gulf of Mexico, Pacific cyclone regions) and the severe storm tracks in winter	The question of whether a warming world generates more frequent cyclones is not resolved. Such measurements may discern a trend that is needed for adaptation in major populated regions, island nations, etc.
Aerosol affects on regional climate and human health: smoke, deposition onto farmland and forests near cities, and industrial/agricultural aerosol (see Human Health and Dimensions table)	Optical properties (visibility, optical depth, albedo, cloud condensation nuclei) Speciation: dust, nitrates, organic carbon, soot	Areas of industrialization (e.g., Himalaya and north Indian Ocean) Super-metropolitan areas (e.g., Japan, United Kingdom, Southern California, Dhaka Mexico City, Sao Paulo, Beijing, India industrial centers)	Aerosols are important drivers for human health effects of fossil fuel use and for the urban heat island. Aerosols in major cities (e.g., Sao Paulo) may engender flooding and are therefore directly linked to environmental sustainability.
Emissions and power/energy use in major metropolitan areas	Column abundance of major individual GHGs and air-quality emissions Heat output Electrical power use Regional climate patterns	Select optimal targets from developing and developed world (e.g., Los Angeles, New York City, Mumbai, Lagos, Sao Paulo)	This is an indicator of the impact of major population centers on GHGs, air quality, and energy use. Monitoring this metric could indicate compliance with mitigation targets (NRC, 2010b).

Atmosphere Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Emissions and stress factors in major agricultural areas	Column abundance of CO_2, CH_4, N_2O Flux of smoke aerosols, water vapor, and volatile organic compounds Key growing season parameters (e.g., heat stress, albedo, precipitation, and soil moisture)	Select optimal targets, primarily from developing world (vulnerability) and developed world (GHGs): Sub-Saharan Africa, Eastern Europe, Midwest United States	This metric could be used as an indicator of food crop loss in developing countries. This is also a measure of the agricultural sector on GHGs and air quality.
Air quality and toxics (see Human Health and Dimensions table)	Boundary layer abundances of ozone and aerosols upwind, downwind, and within major population areas Characterization of stagnation events that combine heat and pollution	Areas of industrialization (e.g., Himalaya and north Indian Ocean) Super-metropolitan areas (e.g., Japan, United Kingdom, Southern California, Dhaka Mexico City, Sao Paulo, Beijing, India industrial centers) East Asian Outflow (Japan)	Monitoring this metric could help identify roles of climate change vs. global pollution vs. local emissions in controlling peak pollution episodes. Human health depends on air quality. Levels of respiratory disease affect population resilience and viability and the ability of a society to respond to climate and other stressors. Respiratory diseases are related to air quality, which will change along with changes in temperatures, hydrology, atmospheric chemistry, and rates of pollution/industrialization/development.

HYDROLOGY

Water is essential for human sustenance and Earth-surface processes. It changes Earth's surface and shapes where and how we live. Water and its components change and are changed by chemical, biological, and physical processes (Dozier et al., 2009). Furthermore, humans add engineered and social systems to control, manage, utilize, and alter our water environment for a variety of uses and through a variety of organizational and individual decisions. Humans use water in many ways: consumption and washing, agriculture, industrial processes, transportation, and recreation. The stresses resulting from a lack of water, poor quality water, or too much water in a short time can make societies potentially unsustainable. In the long term, the major land-surface water fluxes—rainfall and snowfall, snowmelt, runoff, evapotranspiration, and groundwater recharge and withdrawal—must be in balance. However, this balance can change over time, and changes in any of the terms may indicate changes in the water cycle that affect the coupled human-environment system.

The Hydrology Panel's metrics are highly integrated with the human dimension of climate change (Table 3-5). One can view the water cycle as a system of reservoirs and fluxes (NRC, 1991), and the metric of highest priority—the amounts of water stored in parts of the terrestrial system—addresses the need to better know where and how much water is stored. Precipitation, both rain and snow, is the main driver of the land-surface water cycle, and our ability to measure snowfall and snowmelt remains primitive, even though more than 1 billion people depend on snowmelt for their water resources (Barnett et al., 2005). Therefore the seasonal progression of snow water equivalent is second in priority. The third-priority metric addresses fluxes between the places where water is stored. Streamflow is the residual of two large fluxes—precipitation and changes in evaporation of precipitation amplify changes in streamflow. Streamflow is therefore an obvious indicator of alteration to the land-surface water cycle (which can occur due to climate change, land-cover change, or changes in water management). Sustainability of surface water resources is often a direct reflection of changes in streamflow. Consider the Aral Sea, where changes in its volume and extent are a direct consequence of reduction in the major inflow of the Syr Darya River because of irrigation diversions.

Terrestrial water storage also plays a critical role in the global water balance. Land and ocean systems exchange water mass through the precipitation, evaporation, and discharge components of the global hydrologic cycle. The annual amplitude of the land and ocean mass variations may well be a metric of water cycle acceleration. Moreover, water management practices that affect terrestrial water storage, particularly groundwater withdrawal, likely contribute to current rates of sea level rise. Local sea level rise can result from local depression of the land-surface caused by subsidence owing to groundwater withdrawal.

Finally, the panel proposes metrics that emphasize water quality and its relation to environmental sustainability. As *The Economist* (2010) notes in a recent special issue about water, "Enough is not enough. It must also be clean."

TABLE 3-5 Key Metrics: Hydrology

Hydrology Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Volume (or mass) of water stored in parts of the terrestrial system	Groundwater balance (recharge, pumping, irrigation)	Developing nations and places where surface water resources are contaminated or in decline Agricultural regions where groundwater mining is active (e.g., Sahel region of Africa, Ganges-Brahmaputra plain, Yellow River)	Recharge vs. withdrawal is a key indicator of sustainable use, but data about withdrawal are hard to find. Provides an indication of how much water will be available in the future. Water is critical to human survival and food production Tracking groundwater (possible via gravity measurements) would provide information about large regions.
	Lake and reservoir heights, volumes, and surface area Volume-area relationships (via altimetry and in situ)	World's major reservoirs and lakes (e.g., Lake Mead, Lake Powell) High latitudes where lakes may be disappearing (e.g., Siberia)	Reservoir sizes and changes in volume indicate resilience of water systems. Some basins have reservoirs equivalent to several years' runoff, whereas others have limited storage that can provide water only through a year of drought.
	Soil moisture (via in situ and microwave remote sensing) Plant productivity Decomposition rate Soil formation rate (see Land-Surface table)	Agricultural regions worldwide Severe weather regions Areas where monitoring recharge is important (see above)	Soil moisture is driven by precipitation and climate and feedbacks to atmosphere. Changes in soil moisture will impact groundwater recharge, agriculture, floods, and drought. This metric has important links to ecology and biogeochemistry.
	Extent of mid- and low-latitude glaciers	Greater Himalaya, including Karakorum and Hindu Kush Andes Cascades	Glaciers respond to multiple stressors and are important sources of water availability and streamflow for humans and ecosystems. Regional climate feedbacks and loss of the glaciers contribute to sea level rise.

Hydrology Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
	Inundated area and dates of inundation of wetlands Elevation of water surface in flooded areas	Low-elevation basins of large rivers, especially Amazon, Indus, Ganges-Brahmaputra, and north-flowing Eurasian rivers	Wetland loss directly impacts biodiversity and key water related to ecosystem services. Shallow anoxic water bodies contribute to atmospheric methane.
Seasonal snow cover and snow water equivalent, and their seasonal progression (see Cryosphere table)	Fractional snow-covered area (the fraction of each grid cell covered by snow; heterogeneity and pattern) Snow wetness (liquid water in the snowpack) Rain-snow transition during storms Runoff and its timing relative to demand Snow albedo, subdivided into visible vs. near-infrared wavelengths, to estimate change by grain growth and absorbing impurities Snow water equivalent (can remotely sense in lowlands with passive microwave, but cannot remotely sense in the mountains)	Continental scale (e.g., Arctic Canada, Arctic Eurasia, Tibetan Platea) Mountain scale (e.g., western North America, Andes, Greater Himalaya, including Karakorum, Hindu Kush, and High Asia Alps)	About one-sixth of Earth's population depends on end-of-season snowpack. Snow also affects ecosystems. The measurements provided here would tease out effects of precipitation, temperature, and albedo, helping to validate and improve regional climate models. Snow is a significant component of available water supply and a critical factor in regional and local water management (e.g., U.S. west). Surface transportation (especially rail and truck) is sensitive to the presence and evolution of snow.

Hydrology Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Fluxes of water through the land-water system	Precipitation Runoff (streamflow) Evapotranspiration Withdrawals and inter-basin transfer Information about water usage (industrial, residential, agricultural)	For streamflow: start with mouths of major rivers globally and work upstream (e.g., Indus, Ganges-Brahmaputra, Salween, Mekong, Yangzte, Yellow River, Niger, Nile) For precipitation: measure globally, with attention to particular complications of (a) orographic effects and (b) difficulties in measuring solid vs. liquid precipitation.	Streamflow is the most obvious indicator of alteration of the land-surface water cycle (which can occur due either to climate change, land cover change, or water management). Sustainability of surface water resources is generally a direct reflection of changes in streamflow. Information about usage of water indicates which sections of the society are most vulnerable.
Water quality	Water color (proxy for dissolved organic carbon concentrations) of lakes, reservoirs, rivers, and streams	Large lakes (e.g., Lake Baikal, Lake Superior) Major rivers Reservoirs, location to be determined based on inventory of existing fine-resolution imagery Lakes and rivers that drain into wetlands in tropical regions	Dissolved organic carbon (DOC) has second order feedbacks on carbon cycle because of large CO_2 and CH_4 fluxes from lakes and streams DOC has major environmental sustainability consequences for water quality for human use and for promoting harmful algal blooms in coastal regions.
	Temperature of lakes, reservoirs, rivers, and streams	Regions with water supply constraints mainly in southwestern United States and Africa Mountain streams and lakes influenced by earlier snowmelt (e.g., North America, Appalachia, and Andes)	Lake and stream temperatures are directly connected to climate drivers and integrate second order effects on hydrology. Temperatures are relevant to sustainability of freshwater ecosystem goods and services.

Hydrology Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
	Seasonal changes in chlorophyll content and nutrient concentration in lakes, reservoirs, rivers, and streams	Temperate lakes in lake districts Small representative reservoirs for water supply Large lakes (e.g., Lake Baikal, Lake Victoria) Major rivers draining into coastal systems Rivers draining wetlands in arctic and tropical regions	This metric integrates across changes in climate and human-environmental systems. Water quality strongly influences sustainability of water resources and aquatic habitats.
	Groundwater quality (pathogens, nutrients, pollutants)	Areas where groundwater quality is affected by wastewater, agriculture, and industry	Much of humanity depends on groundwater of uncertain quality.
Lake, river, and reservoir ice cover (see Cryosphere table)	Freeze-up and breakup dates of lake and river ice Extent and thickness of ice	Continue sites with longest records (e.g., Great Lakes Environmental Research Lab, *http://www.glerl.noaa.gov/data/pgs/ice.html)* Possibly a few north-south transects (on different continents) Sample moderate-size lakes in north temperate and tropical region	Presence of lake and river ice affects the transportation industry and population mobility. Timing and intensity of spring melt/break-up is factored into flood plain management. Lake ice duration is strongly connected to regional warming. Lake ice controls suitability of lakes for cold and cool water fishes; eutrophication causes anoxic bottomwaters and fish kills. Lake ice duration is strongly connected to water quality for human health because chlorination of high dissolved organic carbon water creates harmful byproducts, which are regulated in the United States and Europe. Images showing pattern of lake ice formation and break-up will be useful in developing predictive linking of ice cover duration to climate models.

Hydrology Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Contribution to sea level rise from land water storage (see Cryosphere, Hydrology, and Natural Disasters tables)	Changes in storage of water in the forms that are susceptible to change, including: Glaciers Groundwater Reservoirs Lakes Wetlands Soil moisture (especially in irrigated areas)	Combination of measurements and locations higher in table: Glacier extent and volume in Greater Himalaya Groundwater volume and recharge/ withdrawal (e.g., Sahel, Ganges-Brahmaputra plain, Yellow River) Surface area and height of reservoirs, lakes, and wetlands	Changes in sea level will impact coastal processes, including inundation and sea water intrusion into coastal aquifers. Sea level rise represents a key indicator of global water balance (when ocean storage increases, land storage decreases).

NATURAL DISASTERS

When extreme events such as hurricanes, coastal storms, floods, and droughts occur, the consequences of gradual, scarcely perceptible global change can become evident. Hurricane storm surge events, for example, may penetrate inland to greater distances than previously measured because of a rise in sea level. When extreme events occur at the interface between Earth and human systems, they can wreak disaster on elements that are vulnerable to these events.

The ability of populations and Earth systems to sustain themselves in locations prone to extreme weather- and climate-related events (e.g., hurricanes, floods, droughts) may be one of the most visible and most easily measured of all environmental sustainability indicators. Monitoring the ability of such populations to rebuild and maintain municipal services and quality of life, or for such Earth systems to maintain diversity, health, and areal extent, despite repeatedly being affected by weather- and climate-related natural disasters should provide graphic indication and warning of the changing, possibly increasing impacts of climate change. As climate change progresses, weather- and climate-related extremes may increase in their strength, intensity, and destructive impact and may change in their frequency or geographic pattern of occurrence.[13]

After some future natural disaster or a succession of these events, especially in places where environmental sustainability is marginal, the cost, time, and effort to restore or rebuild public services and facilities will exceed the available financial resources and technical abilities. As this "point of no return" approaches, an increasing number of residents will leave and not return, key facilities will not be restored, etc. The near loss of New Orleans, Louisiana a U.S. Gulf Coast city that successfully weathered centuries of hurricanes, to Hurricane Katrina in 2005 has already prompted concern, for example, that intensifying hurricane activity in the Atlantic will make many U.S. Gulf Coast communities unsustainable. On August 29, 2005, the center of Hurricane Katrina passed just east of the city of New Orleans. The levee network protecting the city failed during the storm; by August 31, 80 percent of New Orleans was flooded, with some parts under 4.5 m of water. Following the disaster a debate began regarding whether to rebuild and restore the city. The debate about whether to rebuild in areas so vulnerable to future storms is ongoing. Similar changes may be seen in Earth systems that are becoming increasingly affected by extreme natural events: the number and diversity of inhabiting species will decrease; the overall health of the system will degrade; and the areal extent of the system will decrease. The barrier islands of Louisiana, for example, are eroding at

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[13] Climate change, for example, is expected to affect tropical cyclone intensity by increasing sea surface temperatures, a key factor that influences cyclone formation and behavior (Emanuel, 2005). Tropical sea surface temperatures increased by approximately 0.5° C between 1970 and 2004 (Agudelo and Curry, 2004). There is observational evidence for a sustained increase during the same 30 years in the proportion of category 4 and 5 hurricanes worldwide (Webster et al., 2005). There is a statistically significant increase in the frequency and duration of hurricanes in the North Atlantic since 1970, but in other ocean basins the trend is not statistically different from zero.

an extreme rate, primarily during hurricane events.[14] Many communities on the western coast of Louisiana were destroyed by Hurricane Rita in 2005. The 140 km of shoreline that was affected sustained -23.3 ± 30.1 m of erosion on average. The affected coastline was completely inundated by the hurricane's storm surge, which locally reached 3.5 m (Sallenger et al., 2009). Although there is little habitation on these islands, their erosion may have a severe impact on the environment landward of the barriers. The vast system of sheltered wetlands along Louisiana's delta plain is becoming increasingly exposed to open Gulf conditions as the barrier islands continue to disintegrate. This disintegration of barrier islands is a result of increasing wave attack, salinity intrusion, storm surge, tidal range, and sediment transport, which may significantly accelerate the damage to wetlands that have already experienced the greatest areal losses in the United States (USGS, 2004).

The tables that follow address climate change and environmental sustainability in two ways. Table 3-6, Environmental Sustainability Indicators for Natural Disaster-Prone Populations and Earth Systems, addresses the ability of populations and Earth systems to sustain themselves in locations prone to climate-related disasters. Table 3-7, Weather- and Climate-Related Natural Disaster Agents, addresses the climate-related natural processes that can cause natural disasters, processes that are impacted and changed (e.g., frequency of occurrence, intensity, areal extent) by climate change. The sustainability table (Table 3-6) is ordered by the ability to observe a given metric, with the easiest to observe appearing first. The weather and climate table (Table 3-7) is ordered in a very coarse approximation of human consequences, with the metrics that lead to the greatest human consequences appearing first.

[14] With the establishment of a levee system along the lower Mississippi River in the 1800s, sediment deposition by the river's meandering delta, ended. Longshore sediment redistribution, primarily in hurricane storm events, is catastrophically eroding the Louisiana coastline. Historical maps (Williams et al., 1992), for example, indicate that the shoreline at Bayou Lafourche, Louisiana, has eroded back about 3 km since 1887.

TABLE 3-6 Key Metrics: Environmental Sustainability Indicators for Natural Disaster-Prone Populations and Earth Systems

Natural Disasters Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Population change in response to extreme weather- and climate-related natural disasters	Changes in population in urban and rural areas correlated with local weather- and climate-related extreme events (hurricanes, severe storms) Population density (remote sensing of housing and development; Earth's city lights, urbanization—people per road mile; available road transport) Migration (related to natural disasters; incursion onto and from coastlines; e.g., see Bhaduri et al., 2002)	Areas attractive to population growth that are at risk for extreme events: 1) Coastlines prone to recurring severe tropical storm landfall: Gulf of Mexico (e.g., New Orleans, Galveston, Tampa); eastern Atlantic (e.g., Miami, Charleston) 2) River systems prone to recurring flooding: Mississippi , Chang Jiang (Yangtze), Huang Ho (Yellow), Ganges-Brahmaputra Rivers	Populations may begin to permanently leave disaster-prone areas as the cost/benefit of remaining changes adversely.
Disaster loss vs. cost to rebuild	Actual total loss caused by a weather- and climate-related natural disaster (determined from insurance estimates, federal, state, and local emergency offices) Cost to rebuild (determined from insurance adjustors, contractors, federal, state, and local offices)		When the cost to rebuild exceeds actual disaster loss, the "tipping point" of disaster financial sustainability is exceeded. Further financial investment becomes unrecoverable. Communities facing costs to rebuild that exceed actual disaster losses may be able to sustain themselves by using special sources provided by insurance policies, special appropriations, etc. When the costs to rebuild exceed even these special sources, the communities can no longer be maintained.

Natural Disasters Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Change in Earth system diversity in response to extreme weather- and climate-related events	Species types and number (determined from surveys made annually by federal agencies), correlated with local climate-related extreme events	Areas at risk to recurring weather- and climate-related natural disasters: 1) Coastlines prone to recurring severe tropical storm landfall: Gulf of Mexico, eastern Atlantic 2) River systems prone to recurring flooding: Mississippi, Chang Jiang (Yangtze), Huang Ho (Yellow)	Earth systems that become unsustainable in the face or recurring natural-disaster attack will display changes in species health (e.g., disease, mortality, pests), reductions in historic environmental system diversity, and changes in the geographic size of habitats. There may also be replacement of species with others that are being displaced geographically.
Change in Earth system health	Plant and animal health (mortality change compared with extreme event occurrence, changes in types and extent of pests and diseases, changes in species distribution) Geographic extent (habitat geographic size in response to extreme events)		

TABLE 3-7 Key Metrics: Weather- and Climate-related Natural Disaster Agents

Natural Disasters Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Shorter duration events			
Severe storms (see Atmosphere table)	**Tropical storms:** NOAA Accumulated Cyclone Energy Index (based on maximum wind speeds measured at 6-hr intervals); annual tropical storm number; maximum wind speed; maximum storm-surge height; geographic storm tracks; precipitation; frequency	Tropical oceans (e.g., Atlantic, Pacific, Indian)	Changes in severe storm intensity and occurrence may be indicators of global climate change.
	Non-tropical storms (continental): Lightning: Schumann Resonances (extremely low frequency incidence of global lightning activity) Annual storm number Maximum wind speeds (straight-line) Hail events (number, hail size) Tornadoes (number, maximum wind speed) Geographic storm tracks Precipitation Flash floods	Global extremely low frequency lightning activity—measurable equally anywhere on Earth Other severe storm parameters would be measured in continental interiors (e.g., Americas, Europe, Asia, Africa, Australia)	

Natural Disasters Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Landscape and biomass fires	Fire incidence, fire apparent radiated thermal energy (kW/sr), fire temperature, area burned (via satellite) Fire incidence, acres burned, biomass burned, fire emissions (CO, CO_2) (via in situ)	Global land masses (all areas without ice) Southeast Asia, Amazon, Sub-Saharan Africa, western United States, and Canada	Global climate change may increase fire incidence, severity, and geographic pattern. Fire greenhouse gas emissions (CO, CO_2), smoke, and soot may, in reverse, contribute directly to climate change through greenhouse warming, increases in atmospheric albedo, etc.
Large volcanic eruptions	USGS Volcanic Explosivity Index (volume of volcanic products, eruption cloud height, etc.) Aerosol, dust measurements Airborne gas sampling (particulates, aerosols SO_4, etc.) Post-eruption changes in atmosphere, agriculture, landcover	The Earth's recently-active volcanoes. (Large volcanic eruptions occur infrequently, at different locations on the Earth.)	Large volcanic eruptions have global atmospheric impacts (some volcanic eruptions can propel large volumes of volcanic ash and aerosols to great heights in the atmosphere, circling the Earth for weeks to months before they precipitate). Volcanic ash and aerosols in atmosphere can reduce global temperature by increasing atmospheric albedo. (The albedo of an aerosol layer is dependent on its optical depth. Increases in the planetary albedo decrease the amount of radiation absorbed, which results in decreasing the Earth's temperature (Sigurdsson et al. 2000).
Longer duration events			

Natural Disasters Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Global sea level (see Oceans, Cryosphere, and Hydrology tables)	Persistent changes in sea level measured at sites not affected by tectonic movement Associated changes in near-shore groundwater-table height, salinity, other water chemistry Secondary changes in river gradients caused by sea level rise	Low-lying oceanic island groups and Arctic coasts (e.g., Maldives) Micronesian Islands Deltaic coasts (e.g., Bangladesh) Large coastal ports (e.g., New Orleans, Columbia River, Houston, Los Angeles) Coastal urban centers (e.g., Venice, New York)	Sea level rise is a consequence of oceanic volume increase. Global melting of alpine and continental glaciers and ice sheets, together with warming of sea water is producing a global rise in sea level. Higher sea level amplifies coastal erosion, storm damage, permanent flooding, and land inundation.
Riverine floods	Annual country-wide numbers of flood events, their extent, depth, duration Causal storm extent, intensity (rainfall) Resulting landcover, land-use changes (deforestation, levees, dams), and changes in water quality	Major river systems of the world (e.g., Nile, Amazon, Mississippi, Yangtze, Ob, Yellow, Yenisei, Paraná, Irtish, Congo)	Changes in flood frequency, severity, and occurrence may be indictors of global climate change.
Drought	U.S. Drought Monitor: integrates drought-severity and percent of U.S. lands under each drought category Long-term decreases in precipitation; surface-water changes (e.g., rivers, lakes)—depth, areal extent, volume, quality Groundwater depth and groundwater quality in drought areas; associated changes in landcover, land use.	Arid areas of the world (e.g., Africa Sahel, Australia, western United States)	Changes in flood frequency, severity and occurrence may be indictors of global climate change.

Natural Disasters Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Epidemic disease (see Human Health and Dimensions table)	Number of epidemics Type Impacts (number hospitalized, casualties, fatalities) Historic recurrence Area affected	Worldwide, with emphasis on areas where epidemics may be related to environmental vectors such as Bay of Bengal	Global changes in wind patterns, sea level rise, etc., can transport disease vectors. Epidemics and pandemics affect population resilience and viability and the ability of a society to respond to climate and other stressors Outbreaks of these pathogens are often linked with climatic variability and thus can be indicative of changes in the climate system.
Insect infestations	Number of insect infestations, insect type, landcover, and crop impacts (area, species affected) Historic recurrence	Worldwide, with emphasis on areas where insect infestations may be related to environmental vectors such as African Sahel	Global changes in wind patterns and sea level rise can provoke insect population changes and catastrophic increases in insect number; environmental vectors can transport insects great distances into areas traditionally not impacted by the pests.

HUMAN HEALTH AND OTHER DIMENSIONS

Some climate changes that manifest initially as a physical impact will eventually have a human impact when viewed through the lens of environmental sustainability. Human health and dimensions metrics differ from other more traditional metrics (oceans, cryosphere, land-surface, atmosphere, and hydrology) because they deal primarily with the human consequences of climate change.

Human metrics, as presented in Table 3-8, represent measurements of environmental threat with respect to vulnerability. For example, an earthquake itself represents a serious threat but it is the population density, building code and structures built according to that code, and other such factors that are the indicators for the human dimension. Such measurements must be made over time if both trends and variability are to be determined. Thus, the metrics taken alone cannot represent the overall effect but can do so in the aggregate, with regional differences taken into account.

Many of the human health metrics and measurements are drawn from English et al., 2009. As the Human Health Panel developed examples of locations around the globe that are suitable for gathering the underlying observations, the panel also selected candidate sentinel cities/regions (in bold, italic text in Table 3-8). These sentinel sites would be important for monitoring the metrics listed in the table, providing a cross-section of human health and dimensions indicators for a representative set of cities/regions. The cities/regions provide a coarse listing, which can be refined to a more specific scheme in the future, and individual metrics can be included at additional locations.

The table comprises three general categories: Human Health, Other Human Dimensions, and Climate Change, with human health metrics being more specific than the other human dimensions metrics. For example, climate change impact on human diseases such as malaria, dengue, and viral encephalitis can be highly specific in terms of rate, intensity, geographical distribution, and timeline of an outbreak or epidemic. Thus, measurements of human health are typically more specific, and impacts on health outcomes can often be defined in greater detail. Where climate conditions can be evidenced more severely, such as flooding in Bangladesh, the human health impact can be dramatic and devastating. Underlying problems of malnutrition, along with vulnerability to natural disaster, such as an earthquake zone, will compound the human impact. Human dimensions include many sectors such as crime and violence, and their metrics, therefore, are intentionally broad. These metrics do not capture correlation or causation; rather, they are a set of observables describing outcomes relative to human systems and health. Overall, each of the climate change metrics can be interpreted as having implications for both human health and other human dimensions.

TABLE 3-8 Key Metrics: Human Health and Dimensions

Human Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Human Health			
Epidemics/Pandemics 1) Disease transmission—climate sensitive 2) Climate stress related (see Natural Disasters table)	Morbidity and mortality data (including Department of Defense records) Disability-adjusted life years (e.g., childhood mortality, maternal mortality) Human cases of environmental infectious disease/positive test results in reservoirs/sentinels/vectors Records of legal and illegal transport of domestic and feral animals; animal husbandry/factory farm practices (use of antibiotics, types of feedstocks/offal, housing conditions); consumption of bush meat	United States and where military records are available Global with emphasis on areas where epidemics may be related to environmental vectors ***Bogota, Shanghai, Mexico City, Athens, Lagos, Tokyo, Jakarta, New Orleans, South Asia (India/Bangladesh), Luanda Arabian Peninsula, Cairo, Delhi, Asmara, Eritrea, Hyderabad***	Human health is the ultimate integrator of environmental and resource conditions. Human health depends on disease ecology and transmission dynamics. Epidemics and pandemics affect population resilience and viability and the ability of a society to respond to climate and other stressors. Outbreaks of these pathogens are often linked with climatic variability and thus can be indicative of changes in the climate system.

Human Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Incidence of respiratory disease (see Atmosphere table)	Air pollutants (particulates, ozone) Air pollutant origins (local vs. remote, e.g.., 44 pm ozone in Los Angeles vs. advection of the Asian brown cloud across the Pacific) Respiratory/allergic disease and mortality related to increased air pollution and pollens General morbidity and mortality data (including Department of Defense records) Disability-adjusted life years (childhood mortality, maternal mortality) Frequency of temperature inversions, blocking highs (i.e., weather patterns conducive to trapping of pollutants near surface) Deforestation Levels of exercise and fitness in urban environment (including rates of bicycle usage, public transport, car) Cancer rates	Areas of industrialization (e.g., Himalaya and North Indian Ocean) Super-metropolitan areas (e.g., Japan, United Kingdom, Southern California, Dhaka Mexico City, Sao Paulo, Beijing, India industrial centers) ***Bogota, Shanghai, Mexico City, Athens, Lagos, Tokyo, Jakarta, New Orleans, South Asia (India/Bangladesh), Luanda Arabian Peninsula, Cairo, Delhi, Asmara, Eritrea, Hyderabad***	Human health depends on air quality. Levels of respiratory disease affect population resilience and viability and the ability of a society to respond to climate and other stressors. Respiratory diseases are related to air quality, which will change with change in temperature, hydrology, atmospheric chemistry, and rate of pollution, industrialization, and development.

Human Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Waterborne diseases	Surface and ground water amounts and distribution (i.e., drought index estimates, surface water levels, precipitation and evaporation rates, soil moisture, and hydrology model estimates) Water- use practices after disasters (e.g., floods, earthquakes) including changes in access to potable water and wastewater management infrastructure and their utilization. Surface water measures of enteric pathogens and other markers of human and animal waste both before and after a disaster. Frequency and amount of extreme rainfall, wastewater/sewer system overflow Population migration (e.g., see Bhaduri et al.., 2002), population distribution and density in urban, peri-urban, and rural regions Municipal water treatment practices (e.g. available waste treatment processes, and percentages of households and industries using each process), and community water supply system functional integrity, distribution and amount of water impervious surfaces (paved), urban/peri-urban runoff control Medical and Public Health Infrastructure (determinants of preparedness and vulnerability such as per capita hospital beds, doctors, nurses, triage centers, air conditioned safe havens; blood, water, food, and drug stocks; municipal warning systems)	Middle East Asia ***Bogota, Shanghai, Mexico City, Athens, Lagos, Tokyo, Jakarta, New Orleans, South Asia (India/Bangladesh), Luanda Arabian Peninsula, Cairo, Delhi, Asmara, Eritrea, Hyderabad***	Human health depends on water quality and infrastructure (see Hydrology table). The rate of waterborne disease affects the ability of a society to respond to stressors, and it in part is affected by temperature and hydrologic changes.

Human Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Environmental health	Greenhouse gas emissions (e.g., see EPA, 2009) Droughts: Standardized Precipitation Index (SPI), Surface Water Supply Index (SWSI) Maximum and minimum temperatures, heat index Stagnation air mass events O_3 estimates due to climate change Increase in heat alerts/warnings Pollen counts, ragweed presence Frequency, severity, distribution, and duration of wildfires Harmful Algal Blooms (HAB): human shellfish poisonings, HAB outbreak monitoring in freshwater and ocean waters (see Hydrology and Oceans tables)	***Bogota, Shanghai, Mexico City, Athens, Lagos, Tokyo, Jakarta, New Orleans, South Asia (India/Bangladesh), Luanda Arabian Peninsula, Cairo, Delhi, Asmara, Eritrea, Hyderabad***	Measurements of events in the extreme are useful metrics of human resilience.
Other Human Dimensions			
Resource demands	Measures of resource size and imputed demand, including rate of consumption Balance of water, timber, and other resource withdrawals relative to renewals Ratio of national debt to gross domestic product Unemployment rate Percentage of homeless as a result of flooding, wildfires, etc. Trends in gross domestic product per capita Trends in labor productivity (product divided by employment) Inflation level and rate of change Percentage of population below poverty level (e.g., see NRC, 1999)	Global Africa ***Bogota, Shanghai, Mexico City, Athens, Lagos, Tokyo, Jakarta, New Orleans, South Asia (India/Bangladesh), Luanda Arabian Peninsula, Cairo, Delhi, Asmara, Eritrea, Hyderabad***	This metric measures the fragility of a society and its vulnerability to additional stress from climate change and variability. Changes in resource demands may reflect responses to the changing climate. Water is vital and is an example of a resource that is climate-sensitive (see Hydrology table).

Human Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
Population distribution and vulnerabilities (see Natural Disasters table)	Population density (remote sensing of housing and development; Earth's city lights, urbanization—people per road mile; available road transport) Population living in vulnerable areas: sea level rise and flooding Migration (related to natural disasters; incursion onto and from coastlines; e.g., see Bhaduri et al., 2002) Elderly living alone, poverty status, children, infants, and individuals with disabilities Infant mortality Travel time to cities greater than 50,000 people Gross domestic product	Global Outer Banks, Congo, densely populated Asian megadeltas, polar regions, U.S. Gulf Coast, southeastern United States ***Bogota, Shanghai, Mexico City, Athens, Lagos, Tokyo, Jakarta, New Orleans, South Asia (India/Bangladesh), Luanda Arabian Peninsula, Cairo, Delhi, Asmara, Eritrea, Hyderabad***	Monitoring this metric provides an indication of where people are impacting the environment and how they are responding to that environment. It is important to look at populations that are in areas that are vulnerable to sea level rise and other natural disasters to gauge their level of resilience.
Food security and agriculture	Land-use trends (satellite Imaps, land fertilization rates, deforestation, rate of conversion of croplands to other uses) Agriculture practices (crop type, crop rotation systems, number of plantings per year) Irrigation (type, ratio of renewable water supply to withdrawals, aquifer load/reserve, fraction of agricultural land irrigated, river diversions, damming practices); and monitor tradeoffs of irrigation (change in the incidence of vectorborne diseases linked to irrigation) Precipitation, snowpack, snowmelt, river discharge rates, soil moisture Soil erosion rates Percentage of population chronically underfed Temperature	Global Southeast Asia (Tibetan Plateau, Indus, Ganges, Brahmaputra, Salween, Mekong, Yangzte, Yellow Rivers) Africa North China Plain ***Bogota, Shanghai, Mexico City, Athens, Lagos, Tokyo, Jakarta, New Orleans, South Asia (India/Bangladesh), Luanda Arabian Peninsula, Cairo, Delhi, Asmara, Eritrea, Hyderabad***	Food/agriculture is vital and is an example of a resource that is climate-sensitive. To measure environmental sustainability that reflects economic, political, social, and environmental drivers, one must consider supply and demand of a given resource.

Human Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
State/Societal stability	Regime type (democracy, autocracy, etc.), infant mortality, conflict in neighboring states, and political/economical discrimination (e.g., see Goldstone et al., 2010) Incidence of violence Governance (changes through time to rule of law, constitutions, type of governance, territorial extent of government control, and anti-government groups) Crime rates Illegal deforestations and other land uses Population migration (e.g., see Bhaduri et al., 2002) Aspects of urban design (risk of urban heat island effect and/or stormwater runoff)	Global Africa Middle East ***Bogota, Shanghai, Mexico City, Athens, Lagos, Tokyo, Jakarta, New Orleans, South Asia (India/Bangladesh), Luanda Arabian Peninsula, Cairo, Delhi, Asmara, Eritrea, Hyderabad***	Political stability affects population vulnerability.
Climate Change			
Climate change mitigation	Greenhouse gas emissions by nations, especially compared with voluntary commitments in support of international policy agreements Levels and trends in energy and carbon prices Trends in the use of non carbon-emitting energy technologies Effects on disadvantaged populations of mitigation policies	***Bogota, Shanghai, Mexico City, Athens, Lagos, Tokyo, Jakarta, New Orleans, South Asia (India/Bangladesh), Luanda Arabian Peninsula, Cairo, Delhi, Asmara, Eritrea, Hyderabad***	Climate change policies related to energy efficiency and renewable energy are often economically beneficial, improve energy security, and reduce local pollutant emissions. Other energy supply mitigation

Human Metric	Measurements	Illustrative Locations for Measurements	Why This Metric Is an Indicator of Environmental Sustainability
	Implications for human health (as one illustrative sector): Health co-benefits of carbon emission reduction, notably from improved air quality and greater opportunities for "active transport," and thus improved fitness Changes in land use with health implications Changes in occupational mixes with health implications (reductions in coal mining)		options can be designed to achieve sustainable development benefits such as avoiding displacement of local populations, job creation, and health benefits.
Climate change adaptation	Number of adaptation projects receiving assistance from international adaptation funds Changes in infrastructure and settlement patterns in especially vulnerable areas Number of climate change vulnerability assessments completed for regions and localities Number of climate change adaptation plans developed and implemented by governments and private-sector parties at all scales Number of national and international agreements, policies, and regulations that include climate change adaptation objectives	***Bogota, Shanghai, Mexico City, Athens, Lagos, Tokyo, Jakarta, New Orleans, South Asia (India/Bangladesh), Luanda Arabian Peninsula, Cairo, Delhi, Asmara, Eritrea, Hyderabad***	Many of the health effects of climate change are those that we are already dealing with and therefore already have existing tools for prevention.
	Implications for human health (as one illustrative sector): Access to cooling centers Number of heat wave early warning systems Number of municipal heat island mitigation plans Number of health surveillance systems related to climate change Public health workforce available/trained in climate change research/surveillance/adaptation		

4

Final Thoughts

Climate change is a complex and increasingly important environmental stressor, with implications for Earth and human systems. There are many observing systems currently available that capture elements of how climate is changing, for example, direct measurements of atmosphere and ocean temperature. The purpose of this report is to look beyond the existing observing approaches that focus primarily on physical attributes (even as these remain important) to provide more information about the human dimensions and impacts of climate change.

This report is not an exhaustive analysis of all the human-environment interactions that will be stressed by a changing climate, but instead it attempts to provide representative lists of metrics that appear likely to be affected by foreseeable disruptions over the next 20-25 years. The committee's challenge was to sort through the many possible metrics and identify some subset within key sectors where observations over time could help project climate-related changes in the human-environment system and their impacts.

As the committee deliberated and examined potentially useful metrics, it became apparent that key indicators of environmental sustainability, in a climate change context, are found at the intersection of how the climate is changing and how those changes will affect the five domains of human vulnerability: food, water, energy, shelter, and health. It will be a challenge to advance the understanding and ability to observe and analyze these points of intersection. It is understood that the Earth is a complex system. As public policy in response to climate change evolves, it will be increasingly important to think with a systems perspective in order to understand the components and their interconnections.

The committee finds that observations of global-scale processes are especially valuable from an indicators perspective. They reflect both the impacts of climate change as well as the feedbacks and forcings that change the directions, scale, or timeframe of impacts. An emphasis on global-scale processes provides insights on linkages within the Earth system because these linkages extend from the cryosphere to the hydrosphere, from the atmosphere to the oceans, and include the land-surface and natural disasters.

Several metrics appear in multiple tables, such as sea level rise, seasonal snow cover, and air quality. In part, this is simply a result of the fundamental linkages across the components of the Earth system. Sea level rise is a function of oceanic, land ice, and hydrological processes, but it also acts as an "amplifier" for natural disasters such as tropical cyclones by increasing the risk of harm. For example, subsidence in the Gulf Coast increased the damage from Hurricane Katrina, which serves as an example of the intersection of Earth and human systems in the context of climate change. Thus the metrics of climate change presented in this report cross many disciplines.

Identifying metrics of climate change that intersect with human systems is a difficult but important task. Clearly, there is a sense of urgency behind this task. The climate is changing simultaneously with an increase in the global human population, which in turn makes humans more vulnerable to environmental stresses and disasters. More than ever before, it is critical to think about metrics of climate change through an environmental sustainability lens, and identify those indicators that will provide human society sufficient time to act.

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Appendix A

Statement of Task

The National Academy of Sciences (NAS), through its National Research Council (NRC), is facilitating the increased involvement of scientists in answering questions related to climate and environmental change, energy, natural disasters, and national security. The goal is both to advance scientific understanding of global climate and other environmental and disaster-related phenomena, and consider the implications for both fundamental scientific understanding and national security.

As part of a broader suite of activities, the Committee on Indicators for Understanding Global Climate Change was asked to develop a document that proposes an illustrative suite of indicators, measurements (including locations around the globe), and metrics that are most important for understanding global climate change and provide insights on environmental sustainability issues. This information could be useful in consideration of a coordinated climate observing strategy.

Appendix B

Working Document
Topical Panel Breakouts

Climate, Energy, and National Security: Topical Panels
May 20-21 and June 24-25, 2009
San Francisco, CA

Please note that the format of the tables and definitions evolved over time as the committee did its work

PURPOSE

The goal of the first meetings of the Topical Panels is to develop a preliminary list of indicators of environmental sustainability, in each of the eight Topical areas covered by the Panels. The first day of each meeting will include invited presentations to discuss these concepts in detail and prepare the members of the Panels for the breakout sessions, where they will generate preliminary lists and supporting information. This working document will assist the Panels in completing the breakout task.

A brief summary of definitions is followed by a table to be completed during the breakout sessions. When completed, this table will contain a list of indicators for monitoring environmental sustainability in a given Panel's Topical area and supporting information. For each indicator proposed, completing the table requires providing information in six categories (columns):

- Working title for the proposed indicator
- The relevant environmental system
- The measurements required to construct the indicator
- Application to monitoring changes in the environmental system
- Why is the indicator a good indicator of sustainability?
- Priority locations for component measurements

The second row of the table provides key questions that the Panels should consider in completing the supporting information for a given indicator.

After completing the table, the Panel is to enter a concise (one-page) summary describing how the proposed indicators are relevant to the subject of monitoring environmental sustainability in the Panel's Topical area. This description should reflect that the proposed list of indicators represents a step beyond previous efforts to develop lists of measurements for monitoring changes in the physical climate system.

Using the information entered into this working document during the breakout sessions, the Topical Panel Leads will author a report on the subject of indicators of environmental sustainability. This document will take the form of a consensus NRC report and be produced via standard NRC procedures for report review and publication. The document will offer the proposed environmental sustainability indicators in the context of measurements that should be given priority in consideration of a coordinated climate observing strategy.

WORKING DEFINITIONS

The following definitions are offered to facilitate the work of the Topical Panels during the breakout sessions. These definitions are neither comprehensive nor exhaustive. Many of these terms will be discussed in greater detail during the meeting plenary, which includes invited presentations by experts in the development and application of these terms.

Sustainability: The ability of a coupled human-environment system to function effectively without major disruption for a period of time. *Source: Presentation by Pam Matson and Tom Parris*

Environmental Sustainability (in the context of a changing climate): The ability of an environmental system to maintain processes, functions, biodiversity, and productivity in a changing climate and under additional influences resulting from the possible implementation of strategies to mitigate and/or adapt to climate change. *Source: ongoing discussions with President of the NAS*

Climate Change Indicator: Earth processes related to regimes requiring long-term monitoring to assess trends that are related to changes in the normal distribution of climate patterns. *Source: Scitor report*

Environmental Indicator:
A parameter, or a value derived from parameters, which points to, provides information about, describes the state of a phenomenon/environment/area, with a significance extending beyond that directly associated from a parameter value. *Source: Organization for Economic Cooperation and Development*

An environmental indicator is a numerical value that helps provide insight into the state of the environment or human health. Indicators are developed based on quantitative measurements or statistics of environmental conditions that are tracked over time.

Environmental indicators can be developed and used at a wide variety of geographic scales, from local to regional to national levels. *Source:U.S. Environmental Protection Agency.*

Measurement: The physical parameters that are the essential elements of information needed to construct an indicator via physical, empirical, or stochastic models. *Source: Scitor report*

Observation: The physical properties detected by an instrument that are used to calculate point-in-time estimates of a given measurement via physical, empirical or stochastic models. *Source: Scitor report.*

WORKING TABLE FOR COMPLETION DURING TOPICAL PANEL BREAKOUT SESSIONS

Indicator	Environmental System[a]	Measurements	Monitoring Changes in Environmental System	Why Is This Indicator a Good indicator of Sustainability?	Priority Locations for Component Measurements
Working title for an indicator of environmental sustainability	About which environmental systems will the proposed indicator provide information? Environmental systems include but are not limited to the components of the physical earth system.	List the individual variables that must be measured or inferred from observations to construct the indicator. NOT the "engineering quantities" or the signal directly detected by an instrument or sensor.	Will the indicator provide information relevant to monitoring changes in the environmental system? What changes? Changes may or may not be caused by human activities.	Why is this indicator a good indicator of sustainability?	Key locations around the globe for making the measurements necessary to construct indicator. Include locations for "taking the pulse" of the planet to ascertain environmental sustainability.

[a]The term "environmental system" is used here to reflect the use of the term "environmental sustainability," which for this purpose refers to the environmental component of the broader concept of sustainability. Broadly speaking, sustainability includes Human-Environment Systems (HES) and the interfaces among the components of HES. An environmental system may consist of one of the components of the earth system reflected in the topical panel areas, subcomponents of those areas, and interfaces among them.

SUMMARY THOUGHTS

Please provide a brief (one-page) synopsis of your panel's thoughts, including why the proposed list of indicators is sufficient for assessing and monitoring environmental sustainability in your topical area. The synopsis should speak to how the proposed indicators represent a step beyond previous efforts to develop indicators that are limited to monitoring climate change and explain how the indicators facilitate monitoring the sustainability of environmental systems.

Appendix C

Committee and Staff Biosketches

COMMITTEE ON INDICATORS FOR UNDERSTANDING GLOBAL CLIMATE CHANGE

Mark R. Abbott (Chair)
Oregon State University

Mark R. Abbott is dean of the College of Oceanic and Atmospheric Sciences at Oregon State University. In addition to his scientific and academic administration expertise, Dr. Abbott brings to the committee relevant appreciation of how the study topics relate to the programs of the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and NASA. His research focuses on the interaction of biological and physical processes in the upper ocean and relies on both remote-sensing and field observations. He deployed the first array of bio-optical moorings in the Southern Ocean as part of the U.S. Joint Global Ocean Flux Study (JGOFS). He is a member of the National Science Board, and he is a member of the Committee on Earth Studies. He also served on the Committee on NOAA NESDIS Transition from Research to Operations and the Panel on Land-use Change, Ecosystem Dynamics and Biodiversity of the National Research Council (NRC) Decadal Survey on Earth Science and Applications from Space.

Robert A. Bindschadler (Vice-Chair)
NASA Goddard Space Flight Center

Dr. Robert Bindschadler has been an active Antarctic field researcher for the past 25 years. He has led 15 field expeditions to Antarctica and has participated in many other expeditions to glaciers and ice caps around the world. He maintains an active interest in the dynamics of glaciers and ice sheets, primarily on Earth, investigating how remote sensing can be used to improve understanding of the role of ice in the Earth's climate. Applications developed by Dr. Bindschadler include those for measuring ice velocity and elevation using both visible and radar imagery, monitoring melt of and snowfall on ice sheets by microwave emissions, and detecting changes in ice-sheet volume by repeat space-borne radar altimetry. He has advised the U.S. Congress and the vice president on the stability of ice sheets and ice shelves and has served on many scientific commissions and study groups as an expert in glaciology and remote sensing of ice. Some of the more significant awards he has received are: Fellow of the American Geophysical Union (2001), Goddard Senior Fellow (2000), Excellence in Federal Career (1989), the Antarctic Service Medal (1984), and the NASA Exceptional Scientific Achievement

Medal (1994). He has published more than 130 scientific papers and numerous review articles and has appeared on television and been heard on radio, commenting on glaciological impacts of the climate on the world's ice sheets and glaciers. He currently is the immediate past president of the International Glaciological Society, chairs the West Antarctic Ice Sheet Initiative, sits on both the U.S. and international planning groups for the International Polar Year, and is an editor for the *Journal of Glaciology*.

Rita Colwell
University of Maryland

Rita R. Colwell (NAS) received her Ph.D. in oceanography at the University of Washington. Dr. Colwell is senior advisor and chairman emeritus to Canon U.S. Life Sciences, Inc., president and chairman of CosmosID, Inc., and distinguished university professor at the University of Maryland, College Park, and at the Johns Hopkins University Bloomberg School of Public Health. Dr. Colwell was the first woman to be named director of the National Science Foundation NSF), where she served with distinction from 1998 to 2004. In her capacity as the NSF director, she served as co-chair of the Committee on Science of the National Science and Technology Council. Dr. Colwell has held many advisory positions in the U.S. government, nonprofit science policy organizations, and private foundations, as well as in the international scientific research community, and she is a member of the Royal Academy of Science, Stockholm, American Philosophical Society, American Academy of Arts and Sciences, and National Academy of Sciences. Dr. Colwell has authored or co-authored over 750 refereed publications and 16 books and has been elected to honorary membership of microbiological societies of several countries. She is a recipient of the National Medal of Science and the Stockholm Water Prize. Dr. Colwell received the Order of the Rising Sun, Gold and Silver Star, from the Emperor of Japan.

Jeff Dozier
University of California, Santa Barbara

Jeff Dozier is a professor in the Bren School of Environmental Science & Management at the University of California, Santa Barbara, where he has taught since 1974 after earning his Ph.D. from the University of Michigan. He founded the Bren School and served as its first dean for 6 years. His research interests are in the fields of snow hydrology, Earth system science, remote sensing, and information systems. He has led interdisciplinary studies in two areas: one addresses hydrologic science, environmental engineering, and social science in the water environment; the other addresses the integration of environmental science and remote sensing with computer science and technology. From 1990 to 1992, he was the senior project scientist for NASA's Earth Observing System when the configuration for the system was established. Professor Dozier has chaired or served on numerous NRC committees concerned with data for science, and he is currently a member of the Board on Earth Sciences and Resources. He is a fellow of the American Geophysical Union and the American Association for the Advancement of Science, an honorary professor of the Academia Sinica, a recipient of both the NASA/Department of Interior William T. Pecora Award and the NASA Public Service

Medal, and the winner of the 2009 Jim Gray Award from Microsoft for his achievements in data-intensive science.

Darrell G. Herd
Defense Intelligence Agency

Dr. Darrell Herd is a senior research scientist (Defense Intelligence Senior Level, DISL) in the Defense Intelligence Agency (DIA). Dr. Herd was appointed as DIA's chief research scientist in October 2005. He is spearheading defense efforts to secure U.S. intelligence, surveillance, and reconnaissance advantage for the 21st century. Dr. Herd was awarded a B.A. with high distinction and departmental honors in geology and anthropology by Indiana University in 1971. He received an M.S. (1972) and a Ph.D. (1974), both in geology, from the University of Washington. From 2000 to 2003, Dr. Herd served as the deputy director for national support for the Central MASINT Organization, DIA. In 2000, Dr. Herd launched a major reassessment of key North Korean command and control facilities and their vulnerabilities to attack. In 2001 Dr. Herd founded a special exploitation cell for the Office of the Secretary of Defense, to provide perishable, time-sensitive, all-source intelligence to Special Operations teams pursuing fleeting targets. Between 2001 and 2003, Dr. Herd pioneered innovative use of several nontraditional collection capabilities, securing unique intelligence sources at minimal cost. Dr. Herd is the first author and architect of the U.S. Intelligence Community's exploitation of overhead classified remote-sensing collection systems to warn, detect, and respond to natural disasters. His successful, nontraditional use of classified collection systems in response to a succession of disasters (e.g., Spitak, Armenia, earthquake, 1988; Pinatubo volcano, the Philippines, 1991; Hurricane Andrew, Florida, 1992; Northridge, California, earthquake, 1994) prompted the founding of dedicated disaster-response teams at the Central Intelligence Agency (National Photographic Interpretation Center) and at U.S. Pacific Command, Hawaii (the Pacific Disaster Center).

William H. Hooke
American Meteorological Society

William H. Hooke is a senior policy fellow and the director of the Atmospheric Policy Program at the American Meteorological Society (AMS) in Washington, DC. Prior to arriving at AMS in 2000, he worked for the National Oceanic and Atmospheric Administration (NOAA) and antecedent agencies for 33 years. After 6 years of research with NOAA he moved into a series of management positions of increasing scope and responsibility including chief of the Wave Propagation Laboratory Atmospheric Studies Branch, director of NOAA's Environmental Sciences Group (now the Forecast Systems Lab), deputy chief scientist, and acting chief scientist of NOAA. Between 1993 and 2000, he held two national responsibilities: director of the U.S. Weather Research Program Office and chair of the interagency Subcommittee for Natural Disaster Reduction of the National Science and Technology Council Committee on Environment and Natural Resources. Dr. Hooke was a faculty member at the University of Colorado from 1969 to 1987, and he served as a fellow of two NOAA Joint Institutes (CIRES, 1971-1977; CIRA

1987-2000). The author of more than 50 refereed publications and co-author of 1 book, Dr. Hooke holds a B.S. (physics honors) from Swarthmore College (1964) and an S.M. (1966) and a Ph.D. (1967) from the University of Chicago. Dr. Hooke chaired the Disasters Roundtable of the National Academy of Sciences (NAS)/NRC from 2002-2009, and he chairs the newly formed NAS/NRC Committee on Private-Public Sector Collaboration to Enhance Community Disaster Resilience. He was named an NRC National Associate in 2008. He was elected to membership in the American Philosophical Society in 2006.

John A. Orcutt
Scripps Institution of Oceanography

John A. Orcutt is a distinguished professor of geophysics at the University of California, San Diego. Dr. Orcutt earned a B.S. in mathematics and physics from the U.S. Naval Academy, an M.Sc. in physical chemistry as a Fulbright Scholar from the University of Liverpool, and a Ph.D. in geophysics from the University of California, San Diego, Scripps Institution of Oceanography. His research focuses on cyberinfrastructure and geophysical applications; geophysical studies of ocean seismo-acoustics including rough seafloor scattering, acoustic-elastic interactions, and the use of small arrays; structure of the elastic earth using seismology, synthetic seismograms, and geophysical inverse theory; internal structure of ocean spreading centers; genesis of the oceanic lithosphere; and nuclear test-ban verification methods. Dr. Orcutt is a past president of the American Geophysical Union and a secretary of the Navy/Chief of Naval Operations Oceanography Chair. He is a member of the American Philosophical Society and served briefly as interim president of the Ocean Drilling Program in 2000. Dr. Orcutt is a charter member of the Ocean Studies Board (OSB) and has served on numerous NRC committees, including the OSB's Committee on Exploration of the Seas.

Herman H. Shugart
University of Virginia

Herman Shugart is the W.W. Corcoran Professor in the Department of Environmental Sciences, with a joint appointment in the Biology Department, and directs the Global Environmental Change Program at the University of Virginia (UVA). His primary research interests focus on the simulation modeling of forest ecosystems. He has developed and tested models of biogeochemical cycles, energy flow, and secondary succession. In his most recent work, he uses computer models to simulate the growth, birth, and death of each tree on small forest plots. The simulations describe changes in forest structure and composition over time, in response to both internal and external sources of perturbation. The models are applied at spatial scales ranging in size from small forest gaps to entire landscapes and at temporal scales of years to millennia.

Steven Wofsy
Harvard University

Steven Wofsy is currently Abbott Lawrence Rotch Professor of Atmospheric and Environmental Chemistry at Harvard University, Division of Engineering and Applied Science and Department of Earth and Planetary Sciences. He studied chemical physics at the University of Chicago (B.S., 1966) and Harvard University (Ph.D., 1971), shifting to atmospheric chemistry in 1971. His work has focused on changes in the composition of the stratosphere and troposphere, at first in theory and modeling and later in field and laboratory studies. His current research emphasizes the effects of terrestrial ecosystems on the global carbon cycle, aircraft measurements of greenhouse gases in the atmosphere, and the impacts of climate change and land use on ecosystems and atmospheric composition. Several projects focus on quantitative measurements of ecosystem carbon fluxes, for timescales spanning from instantaneous to decadal and spatial scales from meters to thousands of kilometers, combining physical, chemical, and biological methods. His awards include American Geophysical Union's McIlwane prize and NASA's Distinguished Public Service Medal.

Staff

Chris Elfring is the director of the Board on Atmospheric Sciences and Climate as well as the Polar Research Board. She is responsible for all aspects of the Boards' work, including strategic planning, project development and oversight, financial management, and personnel. She joined The National Academies in 1988 as a study director for the Water Science and Technology Board. Before going to The National Academies, Ms. Elfring was a policy analyst at Congress's Office of Technology Assessment, where she focused on agriculture, water use, and natural resource management. She went to Washington in 1979 as an American Association for the Advancement of Science Congressional Fellow from the University of Wisconsin-Madison, where she earned her M.S. in science communications. She has a long-standing interest in the policy dimensions of science and communicating science to non-scientists.

Curtis H. Marshall was a senior program officer with the Board on Atmospheric Sciences and Climate (BASC) until October 2009. He received his B.S. (1995) and M.S. (1998) in meteorology from the University of Oklahoma and his Ph.D. (2004) in atmospheric science from Colorado State University. His doctoral research, which examined the impact of anthropogenic land-use change on the mesoscale climate of the Florida peninsula, was featured in *Nature* and the *New York Times*. Prior to joining the staff of BASC in 2006, he was employed as a research scientist at the National Oceanic and Atmospheric Administration. While on the staff of BASC, he directed peer reviews for the U.S. Climate Change Science Program and staffed studies on mesoscale meteorological observing systems, weather radar, the NPOESS spacecraft, and the impacts of climate change on human health.

Katie Weller is an associate program officer for the Board on Atmospheric Sciences and Climate and a report review associate for the Division of Earth and Life Studies. She has worked on National Research Council studies that produced the reports *Earth Observations from Space: The First 50 Years of Scientific Achievements*, *Evaluation of the Multifunction Phased Array Radar Planning Process*, and *Scientific Value of Arctic Sea Ice Imagery Derived Products*, among others. In 2009, Ms. Weller received her M.S. in environmental science and policy at Johns Hopkins University.

Ricardo Payne is a senior program assistant for the Board on Atmospheric Sciences and Climate. He has contributed administrative and research support to several National Research Council studies and is currently engaged in the *America's Climate Choices* suite of activities. Mr. Payne earned B.S. degrees in geography and urban studies and documentary film from Temple University in 2007. Mr. Payne is interested in the film medium's potential as a communicative tool within environmental policy and further understanding climate change from geospatial, ecological, and socio-economic perspectives.