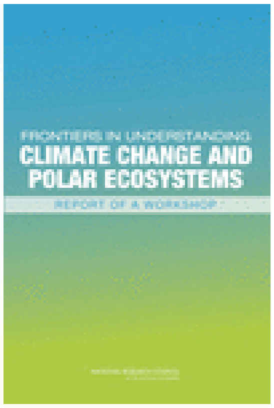

Frontiers in Understanding Climate Change and Polar Ecosystems: Summary of a Workshop

Committee for the Workshop on Frontiers in Understanding Climate Change and Polar Ecosystems; National Research Council

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FRONTIERS IN UNDERSTANDING
CLIMATE CHANGE AND POLAR ECOSYSTEMS

REPORT OF A WORKSHOP

Committee for the Workshop on Frontiers in Understanding
Climate Change and Polar Ecosystems

Polar Research Board

Division of Earth and Life Studies

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

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Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the views of the workshop participants, nor did they see the final draft of the report before its release. The review of this report was overseen by A. David McGuire,

University of Alaska, Fairbanks. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

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APPENDIXES

Summary

The polar regions are experiencing rapid changes in climate. These changes are causing observable ecological impacts of various types and degrees of severity at all ecosystem levels, including society. Even larger changes and more significant impacts are anticipated. As species respond to changing environments over time, their interactions with the physical world and other organisms can also change. This chain of interactions can trigger cascades of impacts throughout entire ecosystems. Evaluating the interrelated physical, chemical, biological, and societal components of polar ecosystems is essential to understanding their vulnerability and resilience to climate forcing.

Although climate change is occurring on a global scale, ecological impacts are often specific, local, and vary from region to region. Because impacts in high latitude ecosystems are already evident and are expected to be even more pronounced in the future, polar regions offer novel opportunities to begin exploring interdisciplinary questions such as: How are marine and terrestrial species currently responding to the changing climate and can we explain and predict future changes and responses? How clearly can we attribute particular ecological impacts (e.g., species movement or changes in biogeochemical cycles) to particular climate forcings? Do we understand the role of various ecosystem feedbacks well enough to anticipate the extent of impacts? What do we know about the nature and probability of reaching certain thresholds or triggers where impacts change rapidly in scope or nature? What is the importance of change in remote polar ecosystems for the global environment and society at large?

The Polar Research Board (PRB) of the National Research Council organized a workshop to address these issues on August 24-25, 2010, in Cambridge, Maryland. Experts gathered from a variety of disciplines with knowledge of both the Arctic and Antarctic regions. The workshop sought to bring together different people and perspectives and to use existing information to illustrate the nature of multidisciplinary linkages among ecosystem components under a changing climate regime. It also sought to generate conversation about how to better study and understand these changes in the future.

Participants were challenged to consider what is currently known about climate change and polar ecosystems and to identify the next big questions in the field. A set of interdisciplinary "frontier questions" (discussed in more detail in Chapter 2) emerged from the workshop discussions as important topics to be addressed in the coming decades:

- Will a rapidly shrinking cryosphere tip polar ecosystems into new states?
- What are the key polar ecosystem processes that will be the "first responders" to climate forcing?
- What are the bi-directional gateways and feedbacks between the poles and the global climate system?
- How is climate change altering biodiversity in polar regions and what will be the regional and global impacts?
- How will increases in human activities intensify ecosystem impacts in the polar regions?

The first frontier question concerns the need to identify the impacts of the rapidly disappearing cryosphere on polar ecosystems. Workshop participants noted that the continued loss of cryosphere will be a major driver of change in polar ecosystems and will play a role in amplification of climate change and its teleconnections with lower latitudes. The topic of tipping elements and thresholds is a key issue for polar ecosystems as well. In some instances, critical thresholds may have already been reached or may soon be reached that could bring ecosystems to a new state or level of activity or behavior. If potential tipping points are known or can be anticipated, then responses to the changes may be identified.

The second frontier question addresses the important processes that still need to be included in regional to global system models in order to characterize the response of polar ecosystems to climate forcing. Without these key elements the models cannot reliably predict future change. The third frontier question seeks to identify the key polar gateways (connections and feedbacks) to the global climate system, a considerable challenge due to the vast complexities of the Earth's climate and its interactions with natural ecosystems. Many workshop participants emphasized that improved understanding of such gateways will require collaborations between scientists with a broad range of expertise in many aspects of natural systems. The fourth frontier question examines the various elements of biodiversity (genetic, taxonomic, and functional) and the effects of recent biodiversity loss in the polar regions resulting from anthropogenic changes in the environment and the climate system, as well as changes in human development. Finally, the fifth frontier question aims to determine the increasing ecosystem impacts and responses to human activities (e.g., fishing, tourism, and resource extraction) in the polar regions.

To begin to address these questions, workshop participants discussed the need for a holistic, interdisciplinary systems approach to understanding polar ecosystem responses to climate change. As an outcome of the workshop, participants brainstormed methods and technologies (see Chapter 3) that are crucial to advance the understanding of polar ecosystems and to promote the next generation of polar research. These include new and emerging technologies, sustained long-term observations, data synthesis and management, and data dissemination and outreach.

1

Introduction

The Earth's polar regions (see Figure 1.1) are ecologically, economically, and, increasingly, geopolitically important; they are particularly vulnerable to the speed and magnitude of climate change and have significant potential to influence the global climate system (Oreskes, 2004; IPCC, 2007a; Anderegg et al., 2010). Climate models and observational data have shown that polar regions have warmed at substantially higher rates than the global mean (IPCC, 2007c). A key mechanism driving increased warming in the polar regions is the albedo feedback effect caused by variations in sea-ice cover, snow cover, and in the Arctic (broadly defined herein to include northern treeline boreal vegetation), forest cover. In addition, changing atmospheric and oceanographic circulation patterns also lead to increased regional warming in the Arctic and Antarctic (Vaughan et al., 2003; Maslowski et al., 2007; Deser and Teng, 2008; Steig et al., 2009).

Recent evidence has revealed that climate change is having significant impacts on terrestrial, freshwater, and marine ecosystems in both polar regions (e.g., Juday et al., 2005; Lyons et al., 2006; Montes-Hugo et al., 2007; Grebmeier et al., 2010; Screen and Simmonds, 2010). Impacts in these ecosystems have been predicted to continue and exceed those forecast for lower latitudes, altering biological resources and socio-economic systems and providing important feedbacks to global climate. The complexity of ecological and human systems, and the fact that these systems are subject to multiple stressors, makes future environmental impacts very difficult to predict. Quantifying feedbacks, understanding the implications of sea

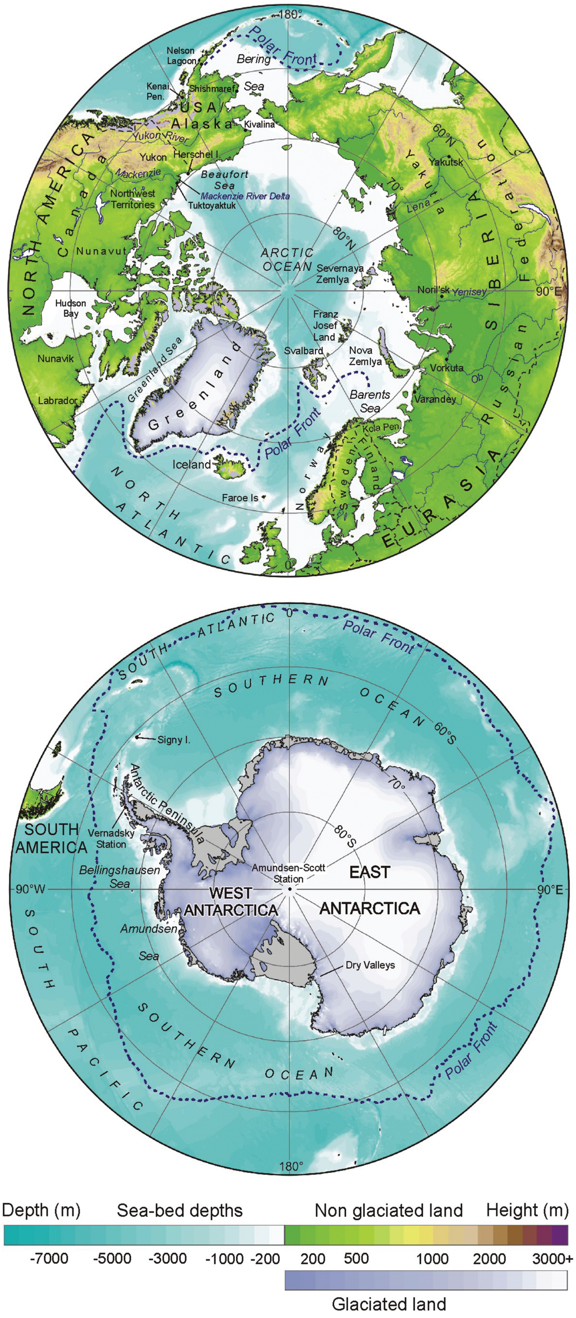

FIGURE 1.1 Map of the Arctic and Antarctic regions. SOURCE: Figure 15.1 in IPCC (2007c).

ice loss to adjacent marine and land areas as well as society, and resolving future predictions of ecosystem alteration or population dynamics all require consideration of complex interactions and interdependent linkages among system components.

The National Research Council, through its Polar Research Board, organized a workshop "Frontiers in Understanding Climate Change and Polar Ecosystems" in what is intended to be the first in a series of periodic workshops addressing "frontiers in polar science." The workshop, held on August 24-25, 2010, in Cambridge, Maryland, consisted of two components: a series of presentations in plenary sessions that introduced examples to highlight known and anticipated impacts of climate change on ecosystems in polar regions and an interactive portion designed to elicit an exchange of information on evolving capabilities to study ecological systems and highlight the next questions or frontiers that stand to be addressed (Chapter 2).

During the workshop, scientists from academic institutions, federal agencies, and other organizations explored emerging interdisciplinary questions and topics with the goal of understanding polar systems in a changing world and identifying new capabilities to study marine and terrestrial ecosystems that might help answer these questions (Chapter 3). Participants were asked to identify (but not prioritize) areas of research and technology advances needed to better understand the changes occurring in polar ecosystems. Participants were invited from a broad range of disciplines across the Arctic and the Antarctic including (but not limited to) expertise in marine and terrestrial ecology and oceanography, geology, human and social sciences, as well as atmospheric, geochemical, and biological sciences. Four plenary speakers (two with an Arctic focus and two with an Antarctic focus) were selected to highlight terrestrial, marine, cryosphere, and paleoclimate perspectives. These talks were intended to set the stage and to provide necessary background information. The topics covered were not intended to be exhaustive and some issues related to adaptation and the social components of climate change were not discussed in great detail. The planning committee is responsible for the overall quality and accuracy of the report as a record of what transpired, and this report summarizes the views expressed by workshop participants.

In accordance with the statement of task, the workshop:

- explored a selected field of science with special polar relevance: climate change and polar ecosystems,
- considered accomplishments in that field to date,
- identified emerging or important new questions,
- identified important unknowns or gaps in understanding, and
- allowed participants to identify what they see as the anticipated

BOX 1.1
Workshop Definitions

Based in part on workshop discussions, the workshop planning committee developed the following definitions of terms used in the three themes and workshop presentations.

Ecosystem connectivity: The distribution of material, energy, and information within and among spatial units of an ecosystem. The structure and function of ecosystems is the result of connectivity and local environmental heterogeneity.

Ecosystem services: The multiple benefits provided by ecosystems to humans. These include supporting, provisioning, regulating, and cultural services (IPCC, 2007c).

Polar amplification: Greater temperature increase at the poles, compared to the rest of Earth, as a result of the collective effect of a multitude of physical drivers and feedbacks.

Regime shift: “A relatively rapid change (occurring within a year or two) from one decadal-scale period of a persistent state (regime) to another decadal-scale period of a persistent state (regime)” (King, 2005).

Resilience: The capacity of an ecosystem to absorb disturbance without shifting to an alternate state and losing function and services.

Threshold (in an ecosystem): A point where environmental forcing results in a sudden, often nonlinear, change in system properties, but the system does not change state qualitatively. For example, high wind may cause large waves on a lake that causes a boat to rock violently, yet the boat remains upright and continues to function as designed.

Tipping element: “Subsystems of the Earth system that are at least subcontinental in scale and can be switched—under certain circumstances—into a qualitatively different state by small perturbations” (Lenton et al., 2008).

Tipping point: An environmental threshold that, when crossed, causes a change between two equilibrium states of an ecosystem, which may be more rapid than the forcing that triggered it. Once under way, the change will proceed at the speed given by the internal ecosystem dynamics, even if the forcing is removed (implies a loss of control). Getting out of the new state may be irreversible. For example, the wind in the example above reaches a point where the boat capsizes and the boat now loses its original function, although potentially functioning subsequently in another capacity.

Vulnerability in an ecosystem: Susceptibility caused by exposure to contingencies and stress, and the difficulty in coping with them. It is “a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity” (NRC, 2007).

frontiers for future research in the field, including challenges and opportunities.

WORKSHOP THEMES

The workshop planning committee (Appendix D) proposed three working themes to the participants in advance of the workshop. They were selected to help guide and focus the workshop discussions and to provide context to the participants as they considered frontiers in climate change and polar ecosystems. The three organizing themes were:

Polar Amplification

Polar regions are warming faster than any other part of the Earth system (Holland and Bitz, 2003; Bekryaev et al., 2010). The effects are manifested as atmospheric warming, decreasing extent and duration of sea ice cover, glacier retreat, permafrost thawing, increasing river discharge, loss of snow cover, and shifting ecosystem structure and function. Some of this polar amplification is caused by the well-studied albedo effect, but other drivers and feedbacks are less well understood. For example, how is the loss of coastal glacial ice mass in Antarctica linked to ozone depletion, changes in the Southern Annular Mode, sea ice feedbacks, or is it responding to an integration of all these? How can the scientific community address uncertainty in assessing the individual roles of snow and ice cover, atmospheric and oceanic circulation, and cloud cover and water vapor in recent observations of warming near-surface air temperatures? What are the contributions of these potential drivers to both Arctic and Antarctic temperature amplifications, and how will they change over the next few decades?

Thresholds and Tipping Points

The identification and prediction of thresholds and tipping points (see Box 1.1) in natural systems likely presents one of the greatest challenges facing those scientists investigating climatic and environmental change since the intrinsic properties can be nonlinear and abrupt. In the polar regions, there is considerable risk of passing thresholds and tipping points caused by the rapid response of the cryosphere system (including the atmosphere, ocean, and biosphere) to increased anthropogenic forcing. This issue is a potential frontier that warrants investigation to identify current and future early warning signals that will allow the world to prepare for future conditions and allow societies the opportunity to adapt.

Ecosystem Connectivity, Vulnerability, and Resilience including Human Dimensions

Polar ecosystems are intimately connected to sea ice extent in the marine realm, and snow levels and the production of liquid water in the terrestrial realm. These parameters are directly related to seawater and land temperatures that influence food sources, organismal growth, reproduction, and biogeochemical cycles. The connectivity between fine and broad-scale properties is increasingly recognized as key to understanding ecosystem dynamics, particularly as global temperatures increase over time. Recent environmental changes are having broad-scale ecosystem impacts at lower trophic levels that have the capability to cascade to higher trophic organisms and the effects of changes in the cryosphere will likely cascade throughout the entire ecosystem (Wassmann, 2008). Therefore, evaluating status and trends in the biological components of key polar ecosystems is necessary to identify vulnerable trophic components and important linkages.

Climate change in polar ecosystems has the potential to amplify connectivity among landscape units (Schofield et al., 2010) leading to enhanced coupling of nutrient cycles across landscapes, and altered biodiversity and productivity within the ecosystem. To understand current and future ecosystem responses to variable climate forcing, it is critical to understand both the vulnerability and resilience of the ecosystem components including local communities and populations, particularly in the Arctic where life is largely subsistence-based and linked inherently to these ecological issues. The ability to predict ecosystem responses to polar climate change will require the development of ecological, hydrological, climatological, and sociological models that are tightly integrated with one another.

The workshop addressed the three themes in the context of climate change and ecosystem interactions that unfold through diverse processes with nonlinearities across a range of time and space scales (see Figure 1.2). Workshop participants emphasized that while there exists some understanding of a variety of the mechanisms involved, many uncertainties remain. The uncertainties became particularly clear during discussions of biome shifts occurring in the boreal region, where impacts accumulate and expand in scope, extent, and intensity. One impact can lead to a cascade of thresholds that may eventually reach a tipping point, which can play a role in mass extinction (e.g., Hoegh-Guldberg and Bruno, 2010).

Participants stressed that the earth, oceans, atmosphere, and human actions be considered as a single, interconnected system in order to achieve a more complete understanding of climate and ecosystem responses as illustrated in Figure 1.3. In this system, responses are often nonlinear and

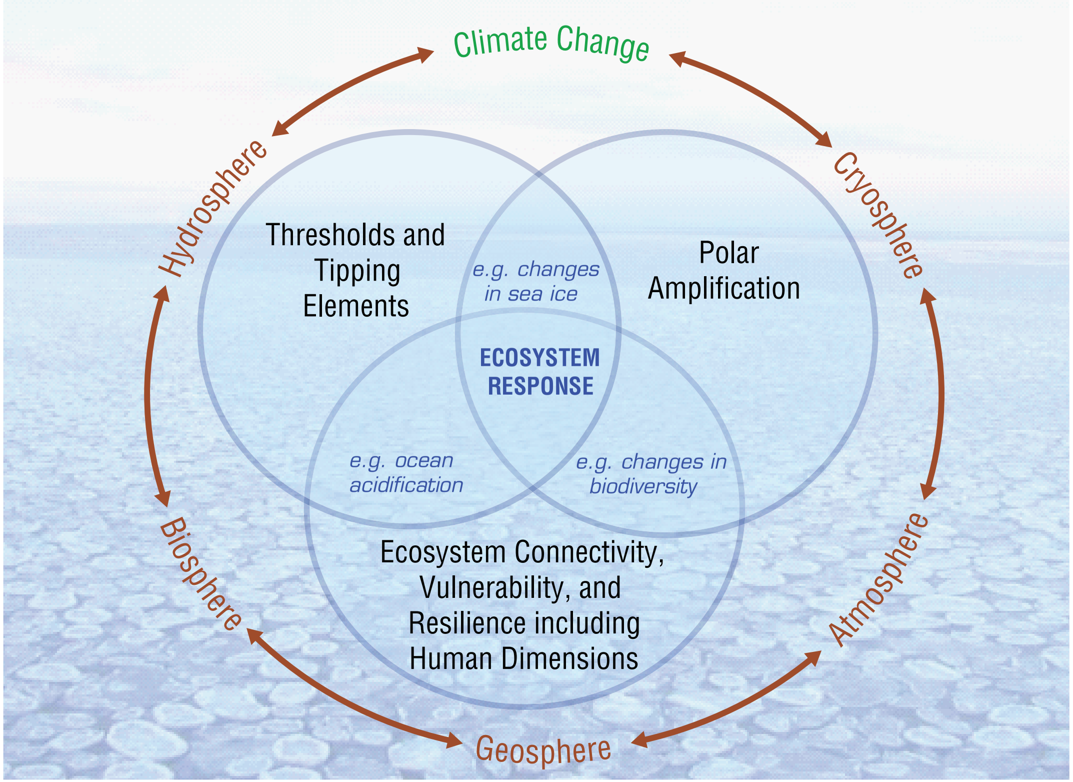

FIGURE 1.2 Schematic illustrating the connectivity among the earth system components and climate change in the context of the three workshop themes, including examples of changes that could drive an ecosystem response.

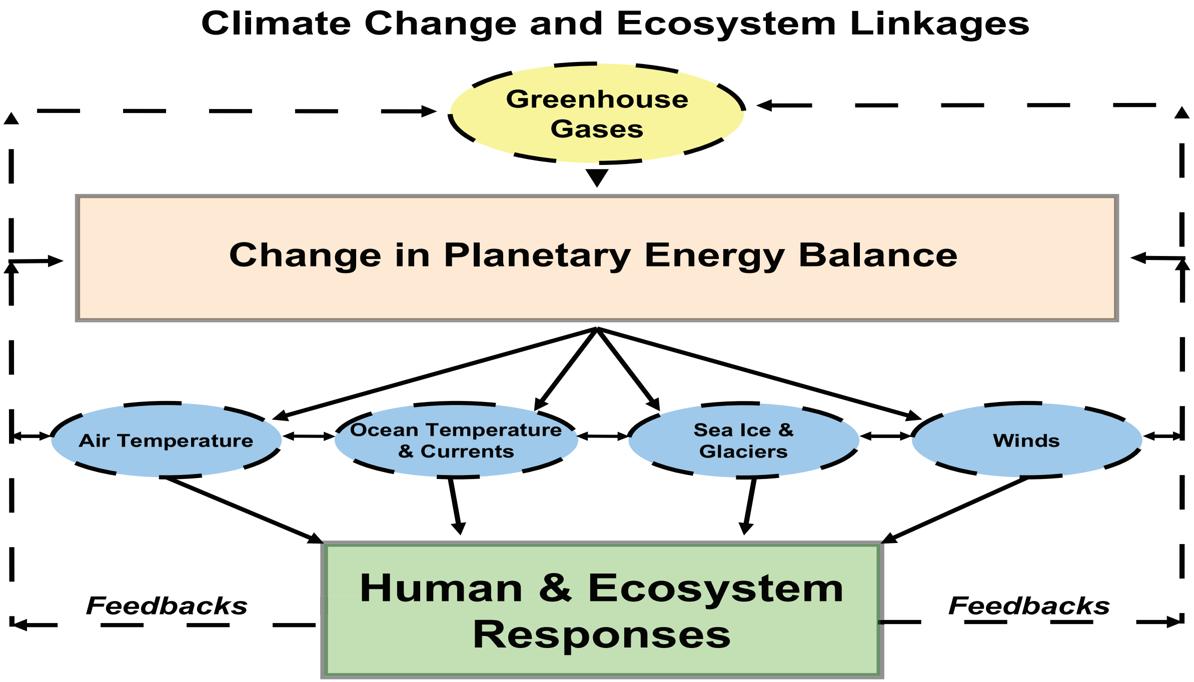

FIGURE 1.3 This diagram represents the connections between climate change and human and ecosystems responses. It illustrates how changes in greenhouse gases lead to changes in the planetary energy balance (changing latitudinal gradients and heat retained near the surface), which has further impacts on air temperature, ocean temperature and currents, sea ice and glaciers, and winds. These impacts will affect humans and ecosystems and, in turn, the human and ecosystem responses will feed back into the components of the system.

can have different threshold and tipping point characteristics. Understanding these thresholds and tipping points, and the mechanisms controlling them, is among the most important challenges in Earth system science (NRC, 2007).

There is a great deal of complexity in Earth system science. The principal components of the Earth system may be defined and bounded differently, depending on the object of study (e.g., the climate system, biogeochemical cycles, ecosystems, and local to global-scale economies). Some Earth system components are defined more clearly than others; for example, ocean and atmospheric circulation is a relatively well-known system, whereas the climate system is a less-well-understood example. Additionally, system components interact according to rules that may or may not be able to be defined adequately. A principal property of systems is feedback, in which reciprocal interaction of components may be self-limiting (negative feedback) or reinforcing (positive feedback).

A principal tool for studying systems in general and the Earth system in particular is numerical simulation modeling. Models may focus on any particular subcomponent, for example, a polar coastal system including subsistence-based human communities, the Northern or Southern Annular Modes, and the Greenland or West Antarctic Ice Sheets. At higher levels of organization, a reduced-complexity model might include simplified parameterizations of each of these subcomponents in a model of the "full" Polar System. There are many different approaches to simulation modeling involving different strategies for defining parameters and interactions, but in general they all follow the systems concept, concentrating on defined systems of interacting components.

PLENARY PRESENTATIONS: INSIGHTS IN POLAR ECOSYSTEM SCIENCE

The following sections summarize plenary presentations from the workshop; these presentations were designed to set the stage for what is already known about climate change and polar ecosystems (see Appendix A for the agenda and Appendix B for plenary speakers and abstracts). Illustrative examples from both the Arctic and Antarctic terrestrial and marine ecosystems highlight climate change impacts currently observed in these regions. This is not intended to be an exhaustive list of impacts in the polar regions, but it is representative of the issues and climate-related changes discussed by workshop participants and speakers.

During the opening presentation of the workshop, Dr. Jeffrey Severinghaus addressed some of the differences between Arctic and Antarctic ecosystems based on current evidence of polar climate changes and atmospheric composition from ice core records. These records reveal that ecosystems in the Arctic have been subjected to numerous abrupt climate changes in the past, whereas Antarctic ecosystems have not experienced these abrupt changes. Antarctic records are characterized by gradual and relatively small changes and the rapid warming currently observed is atypical for that environment. Because of this long-term stability, Antarctic biota may be less resilient to warming than Arctic biota that can potentially adapt to environmental change and the anticipated warming of the next few centuries. Following these initial remarks, additional plenary speakers discussed terrestrial and marine ecosystems as well as the feedbacks and sensitivities in regions of rapid sea ice decline.

Observed Changes in Polar Terrestrial Ecosystems

In the past two decades, Arctic ambient temperatures have increased at twice the rate of the rest of the world (Parkinson and Butler, 2005). Higher than usual temperatures are becoming more common in autumn and winter and daily temperature fluctuations have become more extreme (ACIA, 2005). The Arctic is experiencing thawing permafrost, changes in precipitation, storm surges, flooding, erosion, and increased weather variability (ACIA, 2004; Warren et al., 2005). The effects of these changes include the northward range expansion of flora and fauna, introduction of non-native species, decreases and changes in traditional food sources, disappearance of permafrost food storage in Arctic villages, and wide-scale coastal erosion.

The Antarctic region is an important regulator of global climate and the Southern Ocean is a significant sink for both heat and carbon dioxide, acting as a buffer against human-induced climate change. Terrestrially-based environmental change is most apparent in the Antarctic Peninsula, where climate change has been the most dramatic. Variations in ice cover, glacier retreat, and the collapse of ice shelves are examples of the changes that have occurred, resulting in further shifts to the physical environment of the region.

The examples below offer illustrations of the changes in both the Arctic (the biome shift in the boreal region and subsistence impacts) and the Antarctic (climate change in the McMurdo Dry Valleys ecosystem) terrestrial ecosystems.

Arctic Example: The Biome Shift Occurring in the Boreal Region

During a plenary session of the workshop, Dr. Glenn Juday addressed the shifts occurring in the boreal forests of Alaska. The pronounced and rapid climatic shift in the Arctic, resulting in large part from anthropogenic forcing as well as polar amplification, is already having profound impacts there (Barber et al., 2009). Recent investigations have revealed that most populations of Alaska's interior boreal forests, including the dominant tree species white spruce (*Picea glauca*), Alaska birch (*Betula neoalaskana*), and black spruce (*Picea mariana*), are now experiencing severe drought stress and accelerated disturbance (e.g., fires, insect-caused tree death) associated with climate change (Juday et al., 2005).

Combined temperature and precipitation conditions in interior Alaska (as measured by the ~100 year instrument-based climate record for the Fairbanks station) appear to have now approached or exceeded the lethal limit for white spruce and other major tree species. Trees at many high elevations and formerly cold sites in the interior, as well as other regions of Alaska, are suffering adverse effects of temperature increases and this has major implications for the generation of dendroclimatic reconstructions and potentially for the global carbon cycle. In addition, outbreaks of spruce budworm have developed in Alaska as well as some northern Canadian forests. Alaskan birch have been stressed to near lethal levels across lowland interior regions twice in the last decade from acute drought injury and aspen leaf miner is causing widespread tree death and dieback.

The current wildland fire and insect outbreak regimes, both directly temperature related, are disturbing the forest at a rate that will not allow the recent age structure of forests to appear again as long as the new disturbance rate is maintained. Landscape-scale tundra fire is a reality on the Alaska North Slope, initiating the process of mobilizing one of the Earth's great pools of sequestered carbon into the atmosphere (see Figure 1.4). The accelerated disturbance is significantly reducing available habitat for a set of specialized older forest organisms. Conversely, the length of the growing season for Fairbanks has increased by 50 percent over the past century and doubled at other locations, and recent temperature increases have improved climate suitability for black and white spruce in far western Alaska (where moisture stress is less acute), and possibly in the far northern tundra as well. However, these latter areas generally have sparse tree populations, which may or may not represent the best-adapted genotypes to these new conditions, and practical challenges to migration may require a significant amount of time to be overcome by exclusively natural processes. The boreal forests are a sizeable component of the globe's carbon sink. Estimates indicate that boreal forests store nearly twice as much carbon as tropical forests per hectare. The Canadian Boreal Initiative report, for example, cites that the boreal forests store 22 percent of all carbon on the earth's land surface (Carlson et al., 2009), and thus the changes in growth currently under way may potentially feed back into further climatic change. This synoptic picture is consistent with a biome shift, in which the interior boreal forest is being severely altered

FIGURE 1.4 This is an image of a fire caused by lightning in the summer of 2007 on the North Slope of Alaska. Tundra fires release sequestered carbon into the atmosphere. SOURCE: Bureau of Land Management.

and eliminated from many landscape positions, and opportunities for migration upward in mountains or coastward represent the best survival prospect for elements of the boreal forest.

Arctic Example: Subsistence Impacts

In Arctic subsistence communities, a host of changes related to climate have been noted over the last decade. For example, higher than usual air temperatures and extreme weather events are becoming more common. Weather conditions that might be seen as negative in urban communities are often seen as favorable in subsistence communities. These conditions include, for example, rains that enhance land-based food production and freezing temperatures that result in improved conditions for winter travel. Conversely, these weather events can also erode coastlines, wash out roads, and make travel difficult in certain areas. A 2004 Government Accountability Office report (GAO, 2004) found that almost 90 percent of Alaska's 213 predominantly Native villages in every region of the state are affected negatively by floods or erosion. Communities are increasingly vulnerable as winter freeze-up occurs later in the season. The lack of early autumn sea ice places many villages in great danger of storm impacts as the ice helps to control wave action along the coastlines. Storm impacts can endanger human life, damage infrastructure, and result in erosion.

Hunting on ice is dangerous or impossible when early breakup and late freeze-up create poor ice conditions. Access can be restricted to subsistence resources and there is increased risk and reduced efficiency to hunting. Many traditional hunters have also had difficulty gaining access to land mammals (e.g., caribou) because lack of sufficient snow prevents effective use of snow machines (Callaway et al., 1999). At the same time, the composition, distribution, and density of subsistence species are changing and these changes directly affect the subsistence species available for harvest.

Thawing of permafrost results in habitat changes, sinking buildings, and melting ice cellars, making long term storage of traditional foods more difficult especially in areas of discontinuous permafrost (see Figure 1.5). It also sets up the land for greater impacts from storm surges along

FIGURE 1.5 This photograph is of a cellar in Barrow, Alaska during January 2010. Thawing permafrost can cause damage to infrastructure including ice cellars, which are used in long term storage of traditional foods. Melting can occur during the winter months as well as summer. SOURCE: Michael Brubaker, Alaska Native Tribal Health Consortium.

the coast. In addition to all of these physical impacts, there are potential social implications to climate change. One example involves the sharing of local and traditional knowledge, which is generally passed from elders to younger generations. This critical information, such as ice thickness or the timing or sites of marine mammal haulouts, may become less reliable as climate change impacts result in increased local environmental variability, potentially destabilizing these important social relationships.

Antarctic Example: Climate Change in the McMurdo Dry Valleys Ecosystem

On the Antarctic continent, warming is also occurring faster than expected in certain areas; the Antarctic Peninsula has warmed five times faster than the global average, and the warming of the southern ocean and associated loss of sea ice has resulted in a shift in penguin species and their food sources (McClintock et al., 2008; Montes-Hugo et al., 2009). In contrast to the changes in the Antarctic Peninsula, temperatures in the vast interior of the Antarctic continent have remained stable or cooled over the past few decades (see Box 1.2).

The underlying cause of warming in the peninsula region versus cooling elsewhere, particularly in the McMurdo Dry Valleys and western Ross Sea regions, has been attributed to intensification of the Southern Annular Mode (SAM) caused by human-induced ozone depletion over the continent (Kindem and Christiansen, 2001; Thompson and Solomon, 2002) and greenhouse gas increases (e.g., Mayewski et al., 2009). As the ozone hole diminishes, temperatures have been predicted to increase gradually throughout the continental interior and in the McMurdo Dry Valleys (Chapman and Walsh, 2007; Walsh, 2009), though it is unclear how increasing greenhouse gases may, or may not, affect ozone hole recovery or the current regional warming and cooling trends.

Based on recent data obtained by the McMurdo Long Term Ecological Research (LTER) project, the lakes in this continental ecosystem have started to gain heat over the past four to five years (John Priscu, personal communication, March 10, 2011[1]), indicating that the predicted warming trend may have begun. This warming trend may be responsible for the recent increased summer pulses of liquid water to the ecosystem, which are amplifying connectivity among landscape units, leading to enhanced coupling of nutrient cycles and increased biological functioning within and between trophic levels. There is an immediate and definite need to better understand the role of greenhouse gases in continent-wide temperature change if scientists are to understand related ecosystem changes.

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[1] For raw data, see McMurdo Dry Valleys LTER, Website: *http://www.mcmlter.org* (accessed March 28, 2011).

BOX 1.2
Case Study: Impacts of Climate Variability in the McMurdo Dry Valleys

Climate variability is best understood by monitoring over time. Spatial analysis of meteorological data showed that the McMurdo Dry Valleys, the site of a National Science Foundation (NSF) funded LTER program now in its 18th year of data collection, cooled by about 0.7° C per decade between 1986 and 2000 (Doran et al., 2002). Most of this change occurred during summer and was significantly correlated with decreased winds and increased clear-sky conditions over the period of record. Summer cooling is particularly important to the McMurdo Dry Valley ecosystem because temperatures are poised near the melting point at this time and slight temperature changes can melt glacier ice and provide liquid runoff to surrounding soil, stream, and lake ecosystems.

The discharge from principal streams in the dry valleys decreased nonlinearly over this time period causing lake levels to recede and the permanent lake ice to thicken. The thicker lake ice reduced underwater irradiance during the summer, which in turn decreased the rate of phytoplankton primary productivity in certain lakes by almost 10 percent per year (Doran et al., 2002). The reduction in primary production caused by this cooling trend can eventually produce a situation where the lake becomes depleted in carbon stores. This same cooling trend resulted in changes in diversity and abundance of soil tardigrades and nematodes. These data show that summer temperatures are the critical driver of Antarctic terrestrial ecosystems and highlight the cascade of ecological consequences that can result when seasonal temperature trends change.

Perennially ice-covered Lake Bonney at the foot of the Taylor Glacier. Lakes like Bonney are a major component of the McMurdo Dry Valley landscape. The McMurdo Dry Valleys are poised at the melting point during the summer months, making them highly sensitive to climate change. SOURCE: John Priscu.

Observed Changes in Polar Marine Ecosystems

Polar marine ecosystems are also experiencing significant climate-related changes. Arctic and Antarctic marine ecosystems are characterized by microbial, plant, and animal populations with life cycles and physiological requirements closely tied to the annual cycle of ice advance, duration, and retreat and available sunlight. Notable examples include sea ice microbial communities that support overwintering zooplankton. The early ice edge bloom of algae is critical to support underlying benthic communities often initiating reproductive processes in the spring. Sea ice also provides an important habitat for birds and mammals (e.g., penguins, polar bears, walrus, and seals) that use the ice as a foraging platform or breeding habitat.

Arctic and Antarctic polar marine ecosystems are vulnerable to climate warming and sea ice reduction at all trophic levels from microorganisms to top predators. Many workshop participants indicated that a major research and forecasting challenge is to understand the ecological, biogeochemical, and socioeconomic implications and impacts of these changes and predict their future courses as warming and sea ice loss proceed over the next few decades.

The well-studied examples below reveal the extent of changes that have already occurred, the direction of future changes, and mechanisms driving ecosystem alterations in both the Arctic (northern Bering and Chukchi Seas) and the Antarctic (western Antarctic peninsula).

Arctic Example: Northern Bering and Chukchi Seas

During a plenary session of the workshop, Dr. Patricia Yager discussed productivity, food web dynamics, and benthic-pelagic coupling. The shallow northern Bering and southern Chukchi Sea shelf ecosystem is characterized by high, diatom-based primary production in the water column and efficient export from the surface layer to the shallow sediments, feeding a large and diverse benthic community that is critical for benthic-feeding marine mammals and seabirds. Seasonal ice coverage and cold waters have typically limited pelagic fish predation, allowing diving seabirds, bearded seals, walrus, and gray whales to harvest the high benthic production. With recent warming and sea ice loss, declines in clam populations coincident with dramatic declines in diving sea ducks have occurred, large vertebrate predators, such as walrus and gray whales, have migrated farther north, and pelagic fish are expanding their ranges northwards (see citations in Moore and Huntington, 2008; Grebmeier et al., 2010). In recent years the rapid loss of sea ice has resulted in the relocation of thousands of walruses from ice to land in both Russia and Alaska (see Box 1.3).

BOX 1.3
Case Study: Arctic Sea Ice Retreat and Walrus Relocation

Marine walrus (*Odobenus rosmarus divergens*) populations are responding to reduced seasonal sea ice coverage in the Chukchi continental shelf off Alaska and Russia (Douglas, 2010). The majority of walruses use floating sea ice as habitat over the continental shelf waters between the United States and the Russian Far East where, in the summer, a vast majority of female walruses and young forage on the high biomass of animals living in the underlying sediments. However, recent studies by the United States Geological Survey (USGS) and Russian scientists have observed tens of thousands of Pacific walruses coming ashore in Alaska (Fischbach et al., 2009) and Russia in response to significant sea ice retreat in the Chukchi Sea. These USGS studies suggest that Pacific walruses will have a progressively harder time finding sea ice as a resting platform for access to offshore benthic prey fields (clams and worms in the sediments). Reduced summer sea ice is anticipated to negatively impact their populations, although outright extinction is not projected.[a]

Most walruses use floating sea ice as habitat (left; taken in 2006); however, scientists have recently observed many coming ashore in Alaska and Russia due to sea ice retreat (right; taken in 2010). SOURCE: Karen Frey (left) and USGS (right).

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[a] See *http://alaska.usgs.gov/science/biology/walrus/index.html* for further information (accessed March 28, 2011.).

The ecosystem structure changes are influencing food web dynamics as well as affecting traditional native subsistence hunting communities that must now travel longer distances in open water to hunt. For example, model projections reveal that phytoplankton primary production will increase in response to greater light availability caused by reduction in sea ice cover (Arrigo et al., 2008), although nutrient limitation could ultimately limit the magnitude of this increase (Grebmeier et al., 2010). A shift to smaller algal species sizes has already occurred due to freshening in the western Arctic Ocean (Li et al., 2009), providing another example of potential changes in food web structure and carbon cycling with continued warming. In addition, increases in ocean acidification and sea ice melt contribute to undersaturation of calcium carbonate with serious impacts for biota in the Arctic Ocean as well as the Arctic ecosystem in general (Yamamoto-Kawai et al., 2009).

Antarctic Example: Changes in the Western Antarctic Peninsula

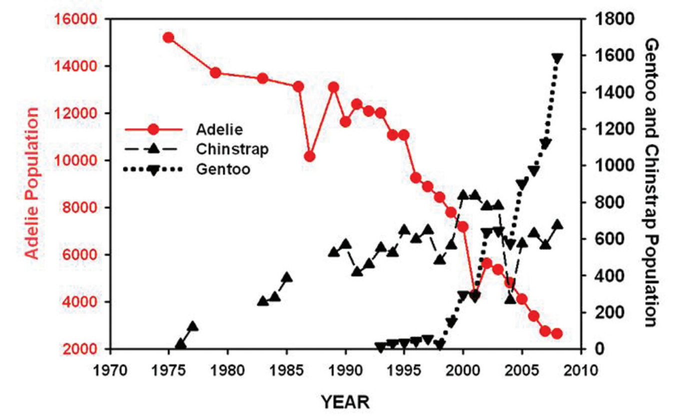
Dr. Sharon Stammerjohn addressed many of the seasonal sensitivities and changes in regions of rapid sea ice decline, including changes occurring in the Western Antarctic Peninsula, during a plenary session at the workshop. The Western Antarctic Peninsula region has warmed in winter by +6°C since 1950 (Vaughan et al., 2003), and sea ice duration has declined by about 80 days since satellite detection started in 1978 (Stammerjohn et al., 2008). In addition to these changes, the continental shelves, extending from about 120° west latitude to the western peninsular region, are the only areas where the Antarctic Circumpolar Current impinges directly on the continental shelf system (Orsi et al., 1995; Martinson et al., 2008) and thus delivers warm Circumpolar Deep Water to these shelves systems. Increases in the latter have been implicated in the accelerated ice mass losses from the West Antarctic Ice Sheet at its coastal margins (Rignot et al., 2008). As in the Arctic, water column warming and increased freshwater input from melting glaciers are forcing changes throughout the ecosystem (e.g., McClintock et al., 2008). Phytoplankton stocks, as detected by satellite ocean color sensors since 1978, have declined by over 80 percent in the northern region of the Peninsula, as sea ice loss has reduced the meltwater-induced water column stratification that fosters plant growth (Montes-Hugo et al., 2008). Farther south, phytoplankton are increasing as new ice-free areas open up. Antarctic krill stocks have declined by an order of magnitude in the Atlantic sector since 1950. In response to sea ice loss, reduction in krill availability, and increases in late spring snowfalls, populations of Adélie penguins have declined by 80 percent in the Palmer Station region (see Box 1.4). Local populations of Crabeater seals are also in decline and ice-avoiding or ice-tolerant populations of Gentoo penguins and fur seals are migrating into the region and establishing new breeding colonies.

Increased primary production at higher latitudes is likely, as loss of sea ice leads to an open water column year-round, limited only by nutrient supply and perhaps light if the mixed layer depth is depressed too deep in the water column seasonally. Phytoplankton species may also shift to forms less palatable to crustacean herbivores that serve as

BOX 1.4
Case Study: Responses of Penguin Populations to Climate Change Along the West Antarctic Peninsula

Apex predators including seabirds, such as Adélie penguins and Crabeater seals, require sea ice as a platform for foraging, breeding, and other activities to successfully complete their life cycles. The pack ice seals, crabeater (*Lobodon carcinophagus*), Weddell (*Leptonychotes weddellii*), leopard (*Hydrurga leptonyx*), and Ross (*Ommatophoca rossii*) all breed within the ice pack. Adélie penguins (*Pygoscelis adéliae*) are also ice-obligate, requiring winter sea ice (Ribic et al., 2008) to afford optimal access the foraging areas, but they breed on land in the Austral summer. Each of these species presents interesting contrasts that illuminate the understanding of how polar species are responding to regional climate change.

The local Adélie penguin rookeries near Palmer Station on southwest Anvers Island have declined in size by almost 80 percent since modern observations started in 1975. At the same time, two congeneric, but subantarctic, ice-tolerant or ice-avoiding species, the Gentoo (*Pygoscelis papua*) and Chinstrap penguins (*Pygoscelis antarctica*) have immigrated into the region, in many cases establishing nesting sites in areas formerly occupied by Adélie pairs. Gentoos and Chinstraps now make up about half the total penguin population in the region. Anomalously low sea ice extent in 1989-90 following the 1988-89 La Nina event may have signaled a tipping point from which the system has not been able to recover. The case of Adélie penguins is valuable because these ocean-foraging, land-breeding birds appear to be responding to both marine and terrestrial forcings. Their decline has roughly paralleled the regional decline in sea ice extent and duration, and also declines in favored prey species including the Antarctic krill (*Euphausia superba*) and the Antarctic silverfish (*Pleurogramma antarctica*).



This figure illustrates changes in penguin breeding pairs near Palmer Station, Antarctica. SOURCE: Adapted from Figure 18 in Ducklow et al. (2007).

preferred prey for the familiar polar faunas; and ice-avoiding gelatinous zooplankton may replace krill. Ocean acidification will reach a threshold where it will impact carbonate-forming phytoplankton, zooplankton, and benthic species in both polar regions (Fabry et al., 2009), further complicating the effects of warming and ice loss on marine ecosystem structure.

2

Frontier Questions in Climate Change and Polar Ecosystems

The goal of the Polar Research Board's workshop was to bring together a diverse group of scientists to identify key research frontiers at the intersection of polar ecosystems and global climate change. "Frontiers" in this context signifies those cutting edge ideas and research needs that will take the science forward into the coming decades. Workshop participants were asked to consider: Where does the science need to go next? What has been accomplished and what are the future questions to be answered? What are the next big innovative topics in this area of scientific research?

Through presentations and discussions, the workshop participants identified five key questions that represent forward-looking opportunities:

- Will a rapidly shrinking cryosphere tip polar ecosystems into new states?
- What are the key polar ecosystem processes that will be the "first responders" to climate forcing?
- What are the bi-directional gateways and feedbacks between the poles and the global climate system?
- How is climate change altering biodiversity in polar regions and what will be the regional and global impacts?
- How will increases in human activities intensify ecosystem impacts in the polar regions?

The list is not intended to be unique or exhaustive and, indeed, relevant work is already occurring within the science community, as described in the examples and case studies in Chapter 1.

WILL A RAPIDLY SHRINKING CRYOSPHERE TIP POLAR ECOSYSTEMS INTO NEW STATES?

Many of the workshop participants emphasized the need to quantify both the vulnerability and resilience of the polar ecosystems, including local communities and populations, in response to the rapidly shrinking cryosphere, and to understand the connectivity between the cryosphere and the global system. Changes in air temperature and precipitation patterns are altering the structure of the cryosphere, the hydrological cycle, fire regimes, and permafrost melting in the terrestrial system. Warming atmospheric and seawater temperatures over the western Arctic (Chukchi Sea and Canada Basin) and the western Antarctic Peninsula have dramatically reduced sea ice cover, changing air-sea interactions regionally and their connectivity to the global system.

The polar regions are poised to lose biodiversity as the result of air, sea, and land temperature changes and seasonal-to-total melting of sea ice, glaciers, and permafrost. Changes in biodiversity can be expected to result in altered biogeochemical processes, which can affect the overall production of the system. For example, a shift in dominance from krill-eating Adelie penguins to fish-eating seals can alter the net efficiency of biogeochemical processing. If the dominant higher trophic animal is eating higher on the food chain (fish-eating seals) versus feeding lower on the food chain (krill-eating penguins), the system is less efficient as more total energy is used to get the same base level of food to the top predator, requiring more food at the base of the food chain.

Other impacts of a shrinking cryosphere include changes to subsistence life styles, resource exploration, and tourism. Coastal erosion is increasing as sea ice retreats and open water can degrade coastal regions and negatively impact human habitation. Increased potential for resource access and extraction may be realized as the open water season increases in length (Arctic Council, 2009). Traditional hunting methods and sites are changing with changes in weather, the landscape, and resource availability (e.g., Ford et al., 2008). Understanding ecosystem changes with climate forcing, their complexities, vulnerabilities, and feedbacks are considered important research frontiers in a world that continues to warm. Workshop participants stressed the important goal of coupling climate models with biogeochemical models in order to identify potential tipping points and associated tipping elements, transformational processes, and thresholds within polar regions to ultimately develop strategies to minimize and/or adapt to the impact of climate change on ecosystem services and processes.

A tipping point describes a critical threshold reached in a nonlinear system, where a small perturbation to the system can cause a shift from one stable state to another (see Box 1.1). The global climate system is a nonlinear system and there are several possible tipping points that could potentially be reached this century as a result of human-induced activities. These have been referred to as "policy-relevant" tipping points (Lenton et al., 2008; see Figure 2.1 for examples). Abrupt climate change can be considered a sub-type of tipping point, where a climate system response is faster than the cause itself (NRC, 2002). Lenton et al. (2008) describes "tipping elements" as large-scale components of the Earth system (at least subcontinental in scale) that may pass a tipping point. The transition of the tipping element in response to forcing can be faster, slower, or no different in rate than the cause, and can be either reversible or irreversible. Although variable in nature, the inherent common property of these tipping elements is that they exhibit "threshold-type behavior in response to anthropogenic climate forcing, where a small perturbation at a critical point qualitatively alters the future fate of the system" (Lenton et al., 2008). A large proportion of defined tipping elements have direct relevance to polar regions, not only because these areas are warming more rapidly than any other place on Earth, but also because these tipping elements typically involve amplifying ice-albedo and greenhouse gas feedbacks that are specific to high-latitude regions.

Declining seasonal sea ice and the disappearance of the Arctic perennial sea ice pack, as well as the shrinking Greenland and West Antarctic ice sheets are processes of particular concern to the workshop participants because of their inevitability and/or severity of impacts and the potential for tipping points to be reached. Additional processes with potential tipping points of concern include dieback of the boreal forest, a northward shifting treeline into tundra regions, CO_2 and CH_4 release from carbon-rich permafrost soils, and release of marine methane hydrates from sub-sea permafrost. Recent work has been put forth advancing the ability to anticipate and forecast an approaching tipping point in the Earth's climate system, where an initial slowing down in response to a perturbation is commonly experienced (e.g., Dakos et al., 2008). Advances in modeling and forecasting an approaching tipping element may enable us to further understand whether these critical thresholds and their repercussions can be avoided (i.e., mitigation) and/or whether they can be tolerated (i.e., adaptation).

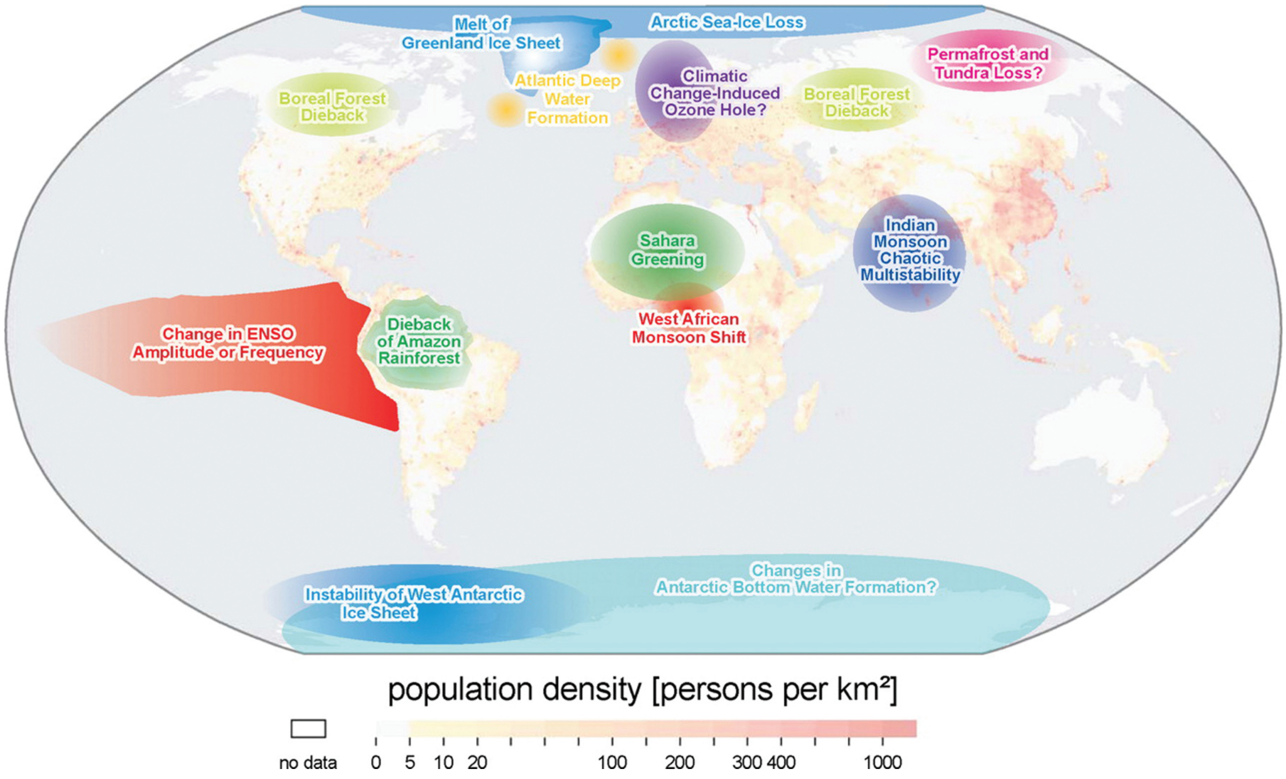


FIGURE 2.1 Potential policy-relevant tipping elements in the climate system. Subsystems indicated could exhibit threshold-type behavior in response to anthropogenic climate forcing, where a small perturbation at a critical point qualitatively alters the future fate of the system. SOURCE: Lenton et al. (2008; Copyright 2008, National Academy of Sciences, U.S.A.).

WHAT ARE THE KEY POLAR ECOSYSTEM PROCESSES THAT WILL BE THE "FIRST RESPONDERS" TO CLIMATE FORCING?

Workshop participants discussed the role of Arctic and Antarctic polar regions in highly coupled systems, with strong links between land, ocean, ice, atmosphere, and humans. These individual components cannot be fully understood independently of one another, as a perturbation to one system component will likely cause cascading effects throughout the entire polar system. For example, current regional and global models have not been able to accurately capture patterns of recent Arctic change (e.g., sea ice decline) and pathways for model improvements are currently sought. Some of the workshop participants emphasized the importance of understanding and quantifying the system *interactions* (rather than simply the isolated components) to accurately predict polar ecosystem response to climate forcing. Models that address the complex interactions between living organisms and their environment (i.e., a focus on "biocomplexity") are critical to understanding how climate change influences ecosystem processes. Developing these models in concert with observational studies is essential to developing predictive tools that are useful to policymakers and have benefits for society. As such, these models can be used to support judgments to create adaptive systems of decision making.

Terrestrial

In the terrestrial realm, major uncertainties in current modeling capabilities include the ability to quantify shifts and feedbacks associated with ecosystem disturbances (e.g., fires, logging, insect infestation), migrations of flora and fauna, coastal erosion, and hydrological and carbon-related impacts of warming and permafrost degradation. Major ice-albedo and greenhouse gas feedbacks may be associated with these changes as well. These feedbacks have the potential to drastically alter predicted outcomes if they are not modeled properly. For example, it is estimated that ~1024 Pg C is currently locked away in the top 0–3 meters of permafrost soils (which amounts to twice the current atmospheric carbon pool) (Schuur et al., 2008). However, with warming and permafrost thaw, this pool of carbon may be reintroduced to the contemporary carbon cycle through release of significant CO_2 and CH_4 to the atmosphere through decomposition and methanogenesis of organic carbon. Major uncertainties surrounding the *rates of change* in these scenarios of permafrost thaw, the magnitude of released CO_2 and CH_4 to the atmosphere, as well as whether climate forcing will result in wetter or drier landscapes, need to be resolved if the overall impact and the direction of feedbacks to the polar and global climate system is to be assessed critically. Improved modeling capabilities and understanding of system interactions are not only essential to improve the ability to predict polar ecosystems responses to climate, but, because of globally significant feedbacks, are also essential to improve knowledge of the overall polar and global climate system as well.

The ice-free continental ecosystems of the Antarctic are microbially dominated and are driven to a large extent by the summer production of liquid water and the distribution of biotic and abiotic matter by wind. To accurately predict ecosystem responses to warming in both the Antarctic and Arctic, models need to include coupled information on surface energy balance, hydrology, and biological/biogeochemistry. Accurate models should also emphasize connectivity among the components and utilize (i) high resolution digital elevation data (e.g., from LIDAR) so that the spatial reference of each modeled segment is properly connected to the others, (ii) high resolution remote sensing (Quickbird and Worldview) data to classify the status of every control volume, (iii) data from field observations/experiments to determine biogeochemical cycling rates and food web/populations dynamics, (iv) stoichiometry of material and energy transformation within each control volume, and (v) matter and energy transfer at the surface via aeolian or water transport. High resolution meteorological and stream hydrology records can provide direct input to the latter components. These spatially explicit process-based models can further include the presence of particular genes, microbes, or nutrients at any point in the landscape, which will allow prediction of the role of wind versus water in promoting growth and movement of biological components of the ecosystem.

Marine

The strong dependence of Arctic and Antarctic polar marine organisms on seasonal sea ice provides the principal connection between ecosystems and climate in these regions. Better understanding of how polar marine ecosystems respond to climate change requires improved models of coupled atmosphere-ocean-ecosystem dynamics at local, regional, and global scales, informed and driven by new observations. Better prediction of polar ecosystem changes requires new models of coupled global-scale atmosphere-ocean circulation that simulates the teleconnections between lower-latitude climate variability and high latitude responses of atmospheric pressure and wind fields, ocean circulation, and sea ice. A good example is the sea ice of the southwest Pacific Ocean/Bellingshausen Sea sector of the Southern Ocean, which exhibits strong covariability with the El Niño-Southern Oscillation (ENSO). Annual advance and retreat of sea ice and the resulting duration and extent are strongly modulated by the interactions of ENSO with the Annular Modes that modify wind speed and direction in spring and fall. Forcing of the Southern Annular Mode by the combined and interacting anthropogenic effects of the ozone hole and greenhouse warming also indicate how better understanding and improved predictive capabilities rest on comprehensive coupled modeling tools.

In general, current models do a poor job simulating high latitude sea ice variability and these shortcomings hamper realistic simulations of atmospheric and oceanic circulation. In addition, deep water formation will be strongly affected by accurate representations of areas of new sea ice formation, which in turn are affected by ice shelf-ocean and continental shelf-ocean interactions, all of which are poorly resolved (or coarsely parameterized). Circumpolar sea ice extent can be reasonably reproduced, but resolving regional and seasonal sea ice variability is still a challenge. Sea ice and snow thickness, rafting/ridging, snow-ice flooding, and melt-ponding are all a challenge even for higher-resolution regional sea ice models, largely because of the lack of data, both for evaluation purposes and for forcing the sea ice models (e.g., accurate regional resolution of winds and upper ocean data). Accurately simulating open water areas (leads, polynyas) is another challenge, which will ultimately affect the prediction of ocean-atmosphere heat fluxes and the consequent strong positive feedbacks. Lack of skill in representation of sea ice dynamics also affects modeling of ocean vertical mixing processes that are critical to plankton dynamics. New observations of these sea ice properties and ocean dynamics at all scales are critical to improved model development and understanding.

Marine ecosystem models have reasonable utility in representing bulk phytoplankton distributions (chlorophyll), for which remotely-sensed data are available, and for which we have reasonably good understanding of the fundamental biophysics underlying the ecology. Even so, detailed modeling of community dynamics like the observed transition from diatom-dominated to cryptophyte-dominated communities along the Western Antarctic Peninsula is still a frontier area. Modeling the potential impacts of lower trophic level species changes on marine carbon cycling, such as the impact of a shift to smaller phytoplankton species production observed in the Western Amerasian Arctic with increased freshwater content (Li et al., 2009), is critical to forecasting potential large-scale ecosystem response to climate forcing. Until the details of lower trophic level community response to climate change are better understood, mechanistic modeling of the upper trophic levels cannot progress. Further up the foodchain, the behavior of individual predators becomes paramount and modeling of functional groups as chemical reactors (as with bulk chlorophyll) is inadequate, instead requiring more detailed information on lower trophic species composition. The divergence of characteristic time and space scales between the base and apex of foodwebs from days and meters to decades and ocean basins also remains a large challenge facing climate-ecosystem models.

WHAT ARE THE BI-DIRECTIONAL GATEWAYS AND FEEDBACKS BETWEEN THE POLES AND THE GLOBAL CLIMATE SYSTEM?

Workshop participants emphasized that polar regions and lower latitude ecosystems are parts of a coupled Earth system. For many ecosystem processes, changes in one component elicit responses from other components, which can further alter other system components. This cascade of bi-directional connectivity makes atmosphere-ecosystem interactions among the most complex in the natural world (NRC, 2007). These responses and interactions become even more complex with the involvement of human actions as broad ecosystem drivers. Given the complexity of these interactions and the feedbacks involved, participants stressed that breakthroughs will require effective collaboration among a wide range of sciences and long-term ecosystem monitoring, as well as involvement of multiple funding agencies.

Studies to date have shown unequivocally that climate change has produced many direct regional impacts at the poles (IPCC, 2007b). Polar regions are expected to be primary drivers of the global climate system because of the strong modification of the surface-energy budget through snow and ice cover, which is tightly coupled to the global circulation of the atmosphere and the ocean. The global implications and associated feedbacks of these polar impacts are difficult to define, and require long-term on-site monitoring and experimentation, in concert with coupled modeling efforts, to resolve. Participants noted that such efforts should focus on the construction of scenarios that cross many scales, a dynamic that we currently have little quantitative knowledge of.

Workshop participants discussed a number of processes and phenomena (including those identified in Anisimov et al. [2007]) that may have bi-directional feedbacks on the global system:

- **Atmospheric variation:** Changes in the polar energy sink region exert a strong influence on the mid- and high-latitude climate by modulating the strength of the sub-polar westerlies and storm tracks (Dethloff et al., 2009). Disturbances in the wintertime Arctic sea-ice and snow cover may induce perturbations in the zonal and meridional planetary wave-train from the tropics over the mid-latitudes into the Arctic. Consequently, Arctic processes can feed back on the global climate system via an atmospheric wave bridge between the energy source in the tropics and the energy sink in the polar regions.

- **Sea level rise:** Of the many potential processes that influence sea level, melting of polar glaciers and ice sheets is perhaps the most tightly linked to atmosphere. Melting and direct ice discharge of the Greenland and Antarctic ice sheets would produce about 7 and 61 meters of sea-level rise, respectively (IPCC, 2001). The collapse of the grounded interior reservoir of the West Antarctic Ice Sheet would also contribute significantly to sea level. Rising sea levels would cascade through the world's tightly connected economic and political systems producing catastrophic global impacts.
- **Ocean circulation:** The increase in freshwater input to the sea could influence ocean circulation producing wide spread global impacts (Lemke et al., 2007). Models have indicated that arctic polar warming and moistening are important on a global scale because associated enhancement of sea-ice melting and freshwater inflow to the Arctic Ocean plays a critical role in controlling the deep convection and ocean meridional circulation, which in turn affects global climate (Kug et al., 2010). In addition to tidal processes and melting of Antarctic glacial ice, changes in atmospheric circulation patterns have also been attributed to the increased upwelling of Circumpolar Deep Water on continental shelves bordering the West Antarctic Ice Sheet (WAIS) (e.g., Thoma et al., 2008). In turn, these atmosphere-ocean and related sea changes have been implicated in amplifying the warming trend over the WAIS (Steig et al., 2009). Unfortunately, details of the actual mechanisms are lacking, emphasizing the need to better resolve ocean processes in particular, and pointing to a need for increased ocean observations.
- **Albedo:** Surface albedo has long been recognized as one of the key surface parameters in climate models through its direct effect on the energy balance (Dethloff et al., 2006). Observed changes in snow, ice, and vegetation cover are all producing changes in surface albedo. Holland and Bitz (2003) have suggested that the rapid loss of snow and sea-ice in certain areas of the Arctic can produce feedbacks that can affect climate change over larger scales.
- **Arctic terrestrial carbon flux:** Some models indicate that, in the next century, terrestrial ecosystems will act as a carbon sink (Stephens et al., 2007; Baker, 2007). However, there are large uncertainties due to the complexity of the processes and it is also possible that melting permafrost and the associated increased carbon emissions will lead to positive climate forcing (Sitch et al., 2007).
- **Biome shifts and migration patterns:** Species that migrate between low and high latitudes may be significantly influenced by changing polar ecosystem dynamics (Alerstam et al., 2007; Wilcove and Wikelski, 2008). The rapid climate warming occurring in Alaska

has led to drastic changes in forest ecosystems. Such changes can lead to potential shifts in bird and large mammal migration patterns. Likewise, changes in ocean pH, temperature, and circulation patterns can reach thresholds that will eventually alter plankton distribution and the migration patterns of marine fish and mammal populations. Once these thresholds are reached, biodiversity at the species and genetic levels will almost certainly be altered.

- **Methane hydrates:** Methane hydrates are known to be abundant in marine sediments, particularly those associated with the continental shelves of the Arctic (Kvenvolden, 1988). As ocean temperatures warm, either directly or as the consequence of altered circulation patterns, the hydrates can become unstable and release significant amounts of methane, a potent green house gas, to the atmosphere (Sloan, 2003; Maslin, 2004). This marine efflux of methane can exacerbate warming at the global scale. For example, Shakhova et al. (2010) have recently suggested that atmospheric release of a small amount of methane from the East Siberian Arctic Shelf could lead to abrupt warming.
- **Southern Ocean biological production:** Regional and global models indicate that heat transport and associated stratification of the Southern Ocean will change in response to climate forcing (Ganachaud and Wunsch, 2000; Boning et al., 2008). In concert with the prediction of amplified ocean acidification in south polar waters, it can be expected that these changes in the physical environment will influence the species composition and rate of primary production in the Southern Ocean. Such changes may alter the production of methane sulfonic acid, a potent cloud nucleator, to the atmosphere, and change the sequestration of atmospheric carbon dioxide and transport to the deep ocean. Such physical and biochemical processes influencing changes in biological production are also being studied regionally in the Arctic Ocean.

HOW IS CLIMATE CHANGE ALTERING BIODIVERSITY IN POLAR REGIONS AND WHAT WILL BE THE REGIONAL AND GLOBAL IMPACTS?

Terrestrial

The rapid warming of the Arctic is potentially leading to rapid shifts in productivity, habitat, and biodiversity that are likely to have profound implications for northern ecosystems and for the globe. Macroecology, the subfield that deals with the study of relationships between organisms and their environments at large spatial scales to characterize and explain patterns of abundance, distribution, and diversity (Brown and Maurer, 1989), will likely bring an important perspective to understanding regional and global impacts. Understanding pattern and process in macroecology presents a considerable methodological challenge, as the scales of interest are simply too large for the traditional ecological approach of experimental manipulation to be possible or ethical (Blackburn and Gaston, 2003; Blackburn, 2004).

Alaska populations of boreal plants and animals contain mixtures of Eurasian species and genes, making Alaska a center of boreal biodiversity from the global perspective. The boreal forest is distinctive in being dominated by conifers from the large landscape perspective. Most of the boreal conifer tree species can attain long life spans, and if they survive to old age, they become a specialized habitat for a set of highly adapted plant (e.g., arboreal lichens, mosses) and animal (e.g., woodpeckers, cavity-nesting bird) species. Human inhabitants are also dependent on a number of critical forest resources in the Arctic (e.g., Usher et al., 2005 and references therein).

Boreal conifers play a key role in enabling fire to propagate across landscapes. In the past, warm temperature anomalies that trigger or promote boreal forest disturbance events, such as fire and tree-killing insect outbreaks, were infrequent. However, in the warmer climate of recent decades disturbances triggered by warm temperatures have occurred so frequently and severely that a substantial reduction in older forest has occurred already (ACIA, 2005). An inescapable consequence of the recent rapid warming and other anthropogenic changes (e.g., increased trade and travel) in the far north is the introduction of an increasing number of species from the south (or from the southeast in the case of Alaska), where species richness is greater (ACIA, 2004). In addition, a principal risk for boreal forest is that climate change appears to be happening so rapidly that a continued shift in the location of areas with a climate optimum for forest growth could outpace tree migration rates (Davis and Shaw, 2001). If so, tree dispersal rates and habitat availability as controls over forest migration will not have sufficient time to operate for the successful movement of all gene types and species. Consequently, these forests may be among the Earth's most susceptible ecosystems with respect to the loss of genetic and species diversity due to climatic change. Thus, a challenge for science and resource management is to identify the diversity of adaptive genetic types present in key boreal species. If genetic biodiversity diminishes, future human uses and opportunities in the boreal forest are likely to be reduced, and ecosystem services, including sequestration of carbon, are likely to be less effective.

Marine

As in the terrestrial case, there is an increase in subarctic species moving northward into the Arctic, with the potential for increased species competition and major ecosystem reorganization. The biodiversity of polar oceans is structured to a large extent by cold temperatures. The Antarctic Ocean has had low, stable temperatures for at least 8 million years, whereas the Arctic Ocean has been cold for only the last ~2.5 million years. In response, organisms in Antarctic waters appear to have lost much of their physiological ability to adjust to increased temperatures (Peck, 2005) compared to Arctic species. For example, the Antarctic notothenoid fishes, which are the most stenothermal animals known, die of heat death at temperatures above 4 °C (Somero and DeVries, 1967). Consequently, some workshop participants theorized that Antarctic marine species might be more susceptible to the effects of regional and global climate change than Arctic species.

In light of the regional warming trends observed in the polar marine environment, it is important to consider marine biodiversity in the context of long-term evolutionary processes in which the genetics of the organisms is modified in ways that allow them to adapt to the temperature environment and short-term pulsed events. Genomic approaches to identify the types of genetic mechanisms that provide organisms with the abilities to adapt to environmental change and, conversely, to understand what types of genetic limitations exist in stenotolerant organisms that possess very limited abilities to tolerate and acclimate to temperature changes, are needed to fully understand the effects that climate change will have on polar marine biodiversity.

HOW WILL INCREASES IN HUMAN ACTIVITIES INTENSIFY ECOSYSTEM IMPACTS IN THE POLAR REGIONS?

Workshop participants commented on the possibility of increased human activity in the polar regions as a result of greater access and more open water days. Until the recent economic downturn, ecotourism was increasing significantly. Shipping across northern routes has started and is expected to increase as the number of ice-free days increases. Potential impacts from such activities include disturbance to wildlife and cultural resources from tourists, oil spills, discharge of gray and black water (sewage) from cruise ships, as well as the potential for invasive species and diseases into these remote and previously difficult to access regions. Natural resource development in the Arctic is likely to be one of the key drivers of marine activity in the future (Arctic Council, 2009). Approximately 13 percent of the world's undiscovered oil may be found in the Arctic (Gautier et al., 2009) and oil and fuel spills are among the most significant threats in both polar regions. As increased open water allows additional time for transit, the chances of oil and fuel spills increases. Additional risk comes from the unpredictable nature of storms and ice, some of which are large enough to sink or damage ships.

In the Arctic, tourism has occurred since the early 1800s. The earliest Arctic tourists were individuals attracted to abundant fisheries, exotic wildlife species, and remote regions. Today, with improved access and technology allowing more comfortable travel and easier access, these numbers have rapidly increased. In fact, tourism has become the largest human presence in many regions of the Arctic (UNEP, 2007). There are serious concerns that tourism is promoting environmental degradation in the polar regions in both the Arctic and Antarctic by putting extra pressures on land, wildlife, water, transportation, and other basic necessities. There are also cultural and social impacts to consider in the Arctic. Examples include inappropriate visitor behavior that violates traditional customs and disturbance of cultural sites or removal of cultural objects. Conversely, there may be positive local economic impacts from the tourist industry (e.g., job creation and the use of local transport, accommodations, and eating establishments).

In the Antarctic, tourism has grown rapidly in recent years with approximately 45,000 visitors to the region during the 2007-2008 season (IAATO, 2008), up from less than 10,000 per year during the 1990s (IAATO, 1997). Large cruise ship tourism, as well as small boat cruising and landings make up the majority of activities with impacts on the polar regions. These visits occur at the most sensitive time for the region, the polar summer, when resident species are present and tending young, feeding, and fledging. There has also been a recent upswing in the use of Antarctica and the Arctic as sites for "extreme adventure" trips and "climate tourism" (tourists who wish to see a region and its species before potential extinction caused by climate change) often requiring detailed planning and logistical support. Smaller expeditions may not plan adequately and may resort to "humanitarian" requests for aid from shipping or nearby national bases when they encounter problems. There are also impacts incurred by scientific researchers, however, these impacts tend to be more constrained to the areas surrounding the research stations.

3

Methods and Technologies to Address the Frontier Questions

During the workshop, several cross-cutting issues emerged that highlight the research needs and requirements for advancing the understanding of polar ecosystems. Participants noted that a striking characteristic of the workshop was the ease with which these key issues emerged from the discussion. Many participants also emphasized enhancements and intensification of activities that have a presence now rather than new tools or techniques. These enhancements are intended to help scientists answer the frontier questions and address unknowns in the field. It is beyond the scope of this document to present all of these methods and technologies, however, many workshop participants highlighted the importance of a concerted effort to advance the establishment of long-term field and data observatories, synthesis and management centers, and education and outreach tools to improve the connection between polar research and societal needs.

EMERGING TECHNOLOGIES

Genomics

Genomics is "the study of the structure, content, and evolution of genomes," including the "analysis of the expression and function of both gene and proteins" (NRC, 2003). In this context, genomics encompasses functional genomics (gene and protein expression and function), structural genomics (analysis of the three-dimensional structures of proteins), metabolomics (analysis of the metabolites produced and consumed by a population of cells), and many others (e.g., ecogenomics, metagenomics, pharmacogenomics, toxicogenomics). Genome sciences make use of, and are integrated by, the related disciplines of bioinformatics and computational biology. These genomic approaches offer global or near-global overviews of gene lists, and gene and protein expression. Genomic profiles also enable the exploration of the genetic content of organisms that cannot be studied by classical genetic methods.

Genomic studies have been used to show how Antarctic fish species have evolved to their current diversity levels during the evolution of the Antarctic continent and can be used to evaluate diversity changes as polar ocean temperatures warm and acidify (Ritchie et al., 1996; Bargelloni et al., 2000; Verde et al., 2006). Environmental genomics has proved to be particularly important in the study of marine and terrestrial microorganisms, most of which remain uncultured (Kimura, 2006). The application of genome science to study diversity-function relationships in polar systems has been highly productive and questions such as which organisms are present (analogous to the white pages in a phone book) and what metabolic functions are involved in biogeochemical transformations (analogous to the yellow pages in a phone book) can now be addressed at the molecular level. For example, a genomic approach has been used to study the biogeochemical transformations of gases in Antarctic lakes (Priscu et al., 2008), the phylogenetic and metabolic diversity of organisms immured in north and south polar ices (Christner et al., 2006; Miteva et al., 2008), the diets of krill (Martin et al., 2006), and the response of phytoplankton changes in the Arctic Ocean to freshwater input resulting from climate warming (Lovejoy et al., 2007).

New, and relatively inexpensive, pyrosequencing methods are replacing traditional Sanger sequencing, allowing for enormous amounts of information to be generated from the entire genome of environmental samples (metagenomics). New developments in pyrosequencing are expected to double the number of base pairs per read within the next year. The enormous amounts of data produced from these exhaustively sequenced samples will require novel bioinformatic tools to convert the data into a format that can be used by scientists to include in ecosystem models that address evolution, diversity, biogeography, biogeochemistry, and metabolic capacity in response to climate driven environmental change.

Remote Sensing

Workshop participants noted that the ability to understand polar ecosystems and their linkages to the regional and global climate system has been intimately linked to ongoing collections of satellite imagery over the past few decades. For instance, observations of "greening" tundra, "browning" boreal forest, declining Arctic sea ice cover, shrinking ice sheets, and warming ocean waters have been enabled by long-term, large-scale, satellite-based datasets. Many workshop participants stressed that efforts to maintain and improve these long-term, consistent satellite observations are critical to continued understanding of the future fate of polar ecosystems. In some cases, these datasets already have a long-term expected observational record (e.g., with the 32-year ongoing Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave/Imager (SSM/I) based sea ice products from 1978–present). However, other platforms highly utilized in the polar science community have had shorter lifetimes with no immediate plans for continuation (e.g., NASA's QuikSCAT scatterometer for melt detection (among other parameters) operational from 1999–2009), which limits their use for longer-term observational studies. While new platforms take time to implement, additional technologies such as airborne lidar and spaceborne altimetry for various applications (including observations of terrestrial surface water storage changes, e.g., the NASA Surface Water and Ocean Topography (SWOT) mission scheduled for launch in 2020) should also come online in future decades.

Workshop participants also stated that new technological advances and release of previously classified high resolution imagery have the potential to transform the types of polar ecosystem related questions scientists can answer. For example, with Quickbird (61 cm) and WorldView (50 cm) data available to scientists, investigation of features previously unseen by lower spatial resolution satellites (e.g., sea ice melt ponds, glacial streams, individual trees and shrubs, and individual animals such as the Pacific walrus and Adelie penguin) has the potential to revolutionize the ability to detect and understand polar ecosystem change. Participants emphasized the importance of continuing to plan for satellite missions to avoid gaps and to deploy new technologies on these satellites to improve measurements of the polar cryosphere as the climate continues to change.

In situ Instrumentation

Workshop participants pointed out that the development of robust in situ environmental sensor instrumentation for evaluating key processes in polar ecosystems is essential to investigate the causes and consequences of environmental change. Time series observations at critical spatial and temporal scales of the various systems of interest (atmosphere, cryosphere, marine, and terrestrial) are essential to differentiate natural fluctuations from anthropogenic change. Technological advances in biological sensors are needed to approach the current sensor capability for high-resolution physical measurements on land and sea. More sophisticated biological and chemical sensor techniques are needed to track species composition of plankton, pCO_2 and pH, nutrients like silica and ammonium, and acoustic and video capabilities on fixed and floating mooring arrays for observations for marine mammals and benthic species, respectively. Workshop participants discussed the development of smaller sensor packages that can be deployed over larger spatial scales, such as sensors currently attached to fish, seabirds, and seals. Development of systems that can survive in winter, particularly in ice-covered seas, is crucial, given the continuing logistical difficulty of making human-attended observations.

SUSTAINED LONG-TERM OBSERVATIONS

In situ Observations

Because of their remote location and harsh environment, the polar regions lack sufficient observational assets to meet existing needs for research support, forecasting, and modeling, especially in winter. Thus, several participants noted the need for a vastly enhanced, expanded, and better-integrated system of sustained observations to support frontier scientific research in the polar regions. A network of in situ instrumentation and communications is one critical element of the wider system. Currently, sustained observations are mostly limited to atmospheric sampling and relatively few manned and automated, but often widely-spaced weather stations, especially in Antarctica. One example of such a network that is now being implemented is the Arctic Observing Network (AON) under SEARCH (Study of Environmental Arctic Change), consisting of a suite of atmospheric, land, and ocean sensors, ranging from ocean buoys to satellites. Besides weather, observing systems are needed to document and quantify sea ice, glacier, and ice sheet dynamics, fluxes of greenhouse gases, and the distributions and activities of organisms and biogeochemical cycles.

The Southern Ocean Observing System (SOOS; e.g., Schofield et al., 2010) will address several of these needs, but emphasis still centers on geophysical processes (ice dynamics, circulation, and climate) and is limited to the ocean. Better observations of the continental interior remain a barrier to a comprehensive, continental-scale observing and forecasting capability. In situ sensor systems are a challenge in polar regions where extreme weather and ice are constant threats to performance, communication, and survival of assets. Few of the current instrument platforms such as moorings, AUVs, and Gliders cope adequately with such conditions. Thus, an integrated observing network for land, oceans, and atmosphere is not only a prerequisite for frontier research, but also a frontier area in its own right.

Monitoring Impacts on People

Workshop participants noted the importance of monitoring for change that affects humans in polar regions as climate change impacts threaten the health, safety, and cultural preservation of indigenous populations. For much of the year, research in Arctic regions is limited by sea ice and harsh weather that restrict access using traditional methods. This has limited data acquisition in the past and obscured understanding of events, processes, and variability of the environment over much of the region during parts of the year. The majority of workshop discussions on this topic centered on subsistence community impacts in the Arctic. Long-term data on properties and phenomena such as storm surges, sea ice thickness, permafrost melt, and tundra lake extents are critical to understanding the processes themselves, assessing impacts, devising mitigation plans, and modeling future change.

Suggested means of monitoring includes typical weather stations, the establishment of a long-term ecological research (LTER) station in the offshore waters (Chukchi and Beaufort Seas) similar to those already in place in the Antarctic, and other permanent data collection sites, such as the proposed cabled seafloor observatory at Barrow, Alaska (Barrow Cable Observatory). Greater coordination between industry, local, and federal research programs was also discussed. Frequent sampling intervals that support monitoring of this nature are needed. Several workshop participants stressed the need to fund long-term integrative data collection sites to support this objective.

Biological Sentinels/Proxies

An important theme from workshop discussions was the central role of a long-term, large-scale circum-Arctic and Antarctic observation network in detecting change. Some of the goals of long-term ecological monitoring include detection, attribution, and prediction of regional and large-scale climate changes. These changes are more readily identifiable with the inclusion of biological sentinels. For some time now marine mammals have been considered excellent sentinels of ocean conditions (Laidre et al., 2008; Moore and Huntington, 2008) because of their sensitivity to anthropogenic and natural environmental impacts and because they are typically long-lived, with a large insulating layer of blubber that has a tremendous capacity to retain lipophilic (attracted to and easily dissolved in fats) pollutants. Because of difficulties with time, access, and cost, scientists cannot study all species all the time. Workshop participants stressed the importance of identifying the key species that would be proxies to help understand climate impacts. For example, whales could be appropriate sentinels by providing outreach and education opportunities, because these "charismatic megafauna" easily capture the public interest further demonstrating relevance to this research.

Biotic Community Composition

Changing climates are likely to cause major biotic shifts in Arctic and Antarctic biological communities that will ultimately result in altered community compositions. While a great deal of research tends toward understanding ecosystem impacts, there is insufficient information available on community composition to provide adequate understanding of the severity of those potential changes. Because of this data void, workshop participants discussed the importance of understanding and defining the current system in order to better understand how change will affect that system. Additionally, there was discussion about the major difference in adaptability by the Arctic and Antarctic systems. Some scientists suggest that it is likely that the Arctic is much more resilient because of the existence of highly variable conditions that probably developed alternative trajectories for responses by the community's organisms compared to a much less variable Antarctic system.

An area of concern that arose during workshop discussions was that the potential impacts on community composition in the Arctic due to an ice-free or ice-reduced regime, including reductions in permafrost and the arctic ice cap, will allow for profound terrestrial, under-sea, and surface changes that may permanently alter taxonomic composition, as is already being experienced with northerly migrating tree and other plant species, range expansion by species into previously marginal habitat areas, and southerly migration of ice-dependent species in search of food. Another potential negative consequence of climate change is the loss of synchrony between plant and animal species where, for example, a long-distance migratory bird species arrives when adequate food resources are unavailable. Many workshop participants stressed that each of these concerns point ultimately to an important research need to continue to study the diversity of a population, not just the morphological diversity, but at a genetic level.

Marine LTER in the Arctic

Marine ecosystems are complex systems that can potentially adapt to perturbations in ways that purely physical systems cannot. Long-term biological process-level studies are necessary in order to evaluate ecosystem response to both natural and anthropogenic influenced climate forcing. The high value of LTER sites for process-oriented biological studies to understand ecosystem-level complexity was highlighted during the workshop, with participants noting that there are ongoing terrestrial and marine U.S. LTER sites in the Antarctic, but only terrestrial U.S. LTER sites in the Arctic. Thus, workshop participants highlighted the need for a marine LTER site in the U.S. Arctic to evaluate status and trends in ecosystem dynamics in regions of the western Amerasian Arctic off Alaska where sea ice is retreating rapidly and where the productive marine ecosystem is already undergoing change, such as a northward migration of both lower and high trophic organisms. This site would also support critical winter studies for understanding temporal impacts on key species and biogeochemical processes and their role in human sustenance. Whether it be one focused regional site or a latitudinal-based "Distributed Biological Observatory" concept of transect lines in the marine system for key biological and environmental studies (Grebmeier et al., 2010), it is clear a marine LTER would provide critically needed data for understanding status and trends for input not only into marine processes, but also into regional terrestrial system models that evaluate ecosystem responses to climate forcing. Such a site would also play a significant role in understanding how indigenous societies cope with a changing marine environment.

DATA SYNTHESIS AND MANAGEMENT

International Coordinated Efforts

Many workshop participants stated that international coordinated research efforts at both poles are essential to track land and marine ecosystem change on the appropriate time and space scales. Ongoing and developing projects, such as those supported through the International Arctic Science Committee (IASC) and the Scientific Committee on Antarctic Research (SCAR) planning efforts, are facilitating polar and global ecosystem measurements to track the impacts of climate warming. Workshop participants emphasized the valuable discussions encouraged by interactions between scientists from both polar regions. In this vein, the recently supported continuation of the IASC/SCAR sponsored Bipolar Action Group (see *http://www.scar.org/about/partnerships/iasc/bipag.html*) should help facilitate cross-fertilization of ideas and development of research programs investigating scientific questions pertinent to both poles.

Polar Systems Institute

Several workshop participants recognized the need for Arctic and Antarctic scientists (and both marine and terrestrial) to meet together to explore, and in many cases, identify new research challenges with important societal implications. Along with the PRB itself, the LTER Network has pioneered this area of scientific interaction and synthesis, with two Arctic (terrestrial only) and two Antarctic (one marine, one terrestrial) LTER sites, although in general the usual mode is for the two groups to meet separately, for example, in SCAR and IASC. The need for institutional mechanisms to facilitate better interdisciplinary, cross-polar dialog and more formalized synthesis activities was a major theme of workshop discussions. It was further noted that among the several U.S. polar research institutes, either cross-polar or disciplinary breadth is usually weak. Therefore workshop participants suggested that a Polar Synthesis Institute, possibly similar in scope and operation, could help the National Center for Ecological Analysis and Synthesis (NCEAS) to advance toward new frontiers in polar climate change and other areas of cryosphere research.

SCIENCE-TO-SOCIETY INTERFACE: DATA DISSEMINATION AND OUTREACH

Discussions on improved strategies of information dissemination resulted in a recognized need for increased communication of results in political arenas, in order to engage local and federal policymakers. For example, communications between scientists and agency representatives in lay language exchanges could help overcome the fact that scientists are generally not well-versed in "political-speak."

During the workshop, it was noted that outreach requirements are becoming important and essential components in current requests for proposals, a notion widely supported by the group. It is clear that the future of science resides in a holistic approach that integrates science and society. Outreach that is accessible to non-scientists and that is also culturally sensitive is central to publicizing the causes and impacts of global climate change. In the future, the return of results to affected communities is likely to become a requirement, which will enable polar researchers to reach out and connect with societies and residents of these regions. Engaging indigenous residents in all steps of the research process, including identification of research needs, data collection, analysis, and dissemination of findings, provides unique opportunities for scientists to learn from those who live in the polar environment and know it extremely well.

4

Final Thoughts

With the rapid changes occurring in the climate system in polar regions, there is a critical need for the scientific community to evaluate ongoing and potential impacts of polar climate forcing on all the Earth's ecosystems, including the interconnectivity they have with humans. A focus of the workshop was on developing a systems approach that evaluates diverse processes across a range of time and space scales to understand polar ecosystem response to varying forcing factors. Issues of thresholds and tipping points in ecosystem connections, polar amplification, and ecosystem predictability, vulnerability, and resilience in the context of natural and human perturbations, were discussed. Frontiers questions were developed from these discussions that are considered globally significant, relatively unexplored, challenging, urgent, and at the forefront of an expanding field of knowledge. These questions (without priority) are:

- Will a rapidly shrinking cryosphere tip polar ecosystems into new states?
- What are the key polar ecosystem processes that will be the "first responders" to climate forcing?
- What are the bi-directional gateways and feedbacks between the poles and the global climate system?
- How is climate change altering biodiversity in polar regions and what will be the regional and global impacts?

- How will increases in human activities intensify ecosystem impacts in the polar regions?

Workshop participants also emphasized the need for development of emerging methodologies, technologies, and new organizational structures to address the complex system questions associated with understanding climate forcing and polar ecosystem response in a rapidly changing world. The rapid pace of change and its global-scale impacts make polar ecosystems a fundamental concern for science and society.

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Appendix A

Workshop Agenda & Statement of Task

Tuesday, August 24, 2010

8:00 A.M.	***Breakfast***
8:30 A.M.	Welcome Remarks and Workshop Goals Jackie Grebmeier and John Priscu, Co-chairs

MORNING SESSION – Plenary presentations, 40 minute talks followed by 10 minute open discussion

8:50 A.M.	Plenary Talk 1: Jeff Severinghaus, University of California San Diego *Polar climate change: A view from ice core records* *Moderator: John Priscu*
9:40 A.M.	Plenary Talk 2: Sharon Stammerjohn, University of California Santa Cruz *Exploring seasonal sensitivities and feedbacks by comparing ice-atmosphere-ocean changes in regions of rapid sea ice decline* *Moderator: Hugh Ducklow*
10:30 A.M.	***Break***

10:50 A.M. Plenary Talk 3: Glenn Juday, University of Alaska Fairbanks
The biome shift now occurring in the Boreal region: characteristics and a first look at knowledge needs
Moderator: Rosanne D'Arrigo

11:40 A.M. Plenary Talk 4: Patricia Yager, University of Georgia
Climate and the polar marine biosphere—complex responses and emergent feedbacks
Moderator: Craig Fleener

12:30 P.M. ***Working Lunch***

AFTERNOON SESSION – Working Groups and Discussion

1:30 P.M. Working Groups - Divide into 3 groups for discussion. Moderators serve as discussion leaders guiding the group through a set of suggested questions. Each group identify topics that require additional information or elaboration.

Group A	Moderator:	Bob Bindschadler
	Rapporteur:	Jim McClelland
Group B	Moderator:	Jim McClintock
	Rapporteur:	Scott Goetz
Group C	Moderator:	Diana Wall
	Rapporteur:	Colm Sweeney

3:30 P.M. ***Break***

3:45 P.M. Working group rapporteurs present for *10 minutes each*

4:15 P.M. Open Discussion
(points of agreement and disagreement, topics needing further discussion for next day)
Moderator: Cheryl Rosa

5:30 P.M. Notes and Assignments for Next Day
Grebmeier and Priscu

5:40 P.M. ***Adjourn***

6:30 P.M. *Dinner for workshop participants—working groups discuss issues raised in open discussion and prepare for synthesis panel (e.g. identify cross-over topics)*

Wednesday, August 25, 2010

8:00 A.M. ***Breakfast***

8:30 A.M. Synthesis Panel—Moderators and Rapporteur from each working group present 5-10 minutes on cross over topics and priorities for report

Open discussion of key points
Moderator: Karen Frey

10:30 A.M. ***Break***

10:45 A.M. Continued discussion and summary—identifying content for the report
Moderator: Jackie Grebmeier/John Priscu

11:45 a.M. Wrap-up and Final Remarks
Grebmeier and Priscu

12:00 P.M. ***Working Lunch***

1:00 P.M. ***Adjourn***
Committee Members in closed session until 5:00 pm

STATEMENT OF TASK

This workshop will explore what is known about the impacts of climate change on polar ecosystems and identify what gaps or unknowns exist that will be "frontiers" for future science. Using invited presentations and discussion, the workshop will have two components: a presentation portion that uses case examples to highlight known and anticipate impacts of changing climate in polar regions and an interactive portion designed to elicit an exchange of information on our evolving capabilities to study ecological systems and the big "next" questions that stand to be addressed. The workshop will look at examples and research from both terrestrial and marine ecosystems to illustrate impacts such as species movement, changes in seasonality, and feedbacks, and explore how such impacts can or cannot be shown to relate to climate parameters. The workshop will be designed to bring together polar and non-polar scientists to explore whether there are new capabilities available to study ecosystems in different ways that might shed new light on these questions. Participants will seek to identify (but not prioritize) areas of research and technology advances needed to better understand the changes occurring in polar ecosystems. In summary, the workshop will:

- explore a selected field of science with special polar relevance: climate change and polar ecosystems,
- consider accomplishments in that field to date,
- identify emerging or important new questions,
- identify important unknowns or gaps in understanding, and
- allow workshop participants to identify what they see as the anticipated frontiers for future research in the field, including challenges and opportunities.

Appendix B

Plenary Abstracts

Polar Climate Change: A View from Ice Core Records

*Jeff Severinghaus, Scripps Institution of Oceanography,
University of California San Diego*

Ice cores provide unique records of polar climate and atmospheric composition over the past 800,000 years. In particular, ice cores have revealed that abrupt changes in climate, occurring in as little as a decade, have occurred more than 23 times in the last 100,000 years and are very likely a persistent feature of the Pleistocene glaciations. These abrupt changes display a marked hemispheric asymmetry, with large changes in the Arctic of up to 10 degrees C but almost no change in the Antarctic. The Antarctic records, by contrast, are characterized by gradual change of no more than 2 degrees C per thousand years. As such, ecosystems in the Arctic have been subjected to at least 200 and probably >500 abrupt events that must have had profound biological consequences due to the extreme rapidity of the change. It is therefore quite likely that genomes in the Arctic bear witness to this history, with adaptations for resilience to environmental change. The Antarctic, however, is quite a different story. Because of the long-term climate stability of this region, genomes are likely to have shed such resilience genes, because there is a cost to their maintenance. Thus the Antarctic biota may be less resilient to the anticipated warming of the next few centuries than their Arctic counterparts.

The Biome Shift Now Occurring in the Boreal Region: Characteristics and a First Look at Knowledge Needs

*Glenn Patrick Juday, School of Natural Resources and
Agricultural Sciences, University of Alaska Fairbanks*

The northwestern North American Arctic and boreal regions are centers of biodiversity at the species and genetic levels, almost certainly because of the continuous availability of unglaciated refugia during past periods of rapid climate change. Specifically identifying these basic biodiversity resources will need to be a priority if management for their survival during a time of rapidly shifting climate is to be successful. Recent Arctic warming has reversed cooling of 2000+ years duration that was orbitally driven. Several aspects of the altered climate regime are in the process of causing apparently insurmountable challenges to the survival of much of dominant vegetation where it occurs today, while simultaneously creating suitable climatic conditions where some of these species are largely absent today. Alaska has a ~100-year instrument-based climate record. The combination of temperature and precipitation at low elevations in central Interior Alaska in the early 21st century has approached or exceeded lethal limits for the currently dominant tree species. For example, natural distribution limits of white spruce in North America do not include areas with precipitation below about 280 mm, the current 100-year mean at Fairbanks. The combination of increased July temperature and unchanged annual precipitation in central Alaska now exceeds the previous limits that characterized white spruce distribution. Spruce budworm has now developed outbreak potential on Alaska and northern Canadian forests. Alaska birch have been stressed to near lethal levels across lowland Interior regions twice in the last decade from acute drought injury. Aspen leaf miner is causing widespread tree death, and dieback. The current wildland fire and insect outbreak regimes, both directly temperature related, have been disturbing the forest at a rate that will not allow the recent age structure of forests to appear again as long as the new disturbance rate is maintained. The accelerated disturbance is significantly reducing available habitat for a set of specialized older forest organisms. Recent temperature increases have improved climate suitability for black and white spruce in far western Alaska, and possibly in the far northern tundra as well. However, these areas generally have sparse tree populations, which may or may not represent the best-adapted genotypes to these new conditions, and practical challenges to migration may require a significant amount of time to be overcome by exclusively natural processes. Landscape-scale tundra fire is now a reality on the Alaska North Slope, initiating the process of mobilizing one of the Earth’s great pools of sequestered carbon into the atmosphere. The synoptic picture is consistent with a biome shift, in which the interior boreal forest is being severely altered and eliminated from many landscape positions, and opportunities for migration upward in mountains or coastward represent the best survival prospect for elements of the boreal forest.

Exploring Seasonal Sensitivities and Feedbacks in Regions of Rapid Sea Ice Decline

*Sharon Stammerjohn, Ocean Sciences Department,
University of California, Santa Cruz*

Circumpolar averages of sea ice extent show alarming decreases in the Arctic but increases in the Antarctic, presenting a paradoxical picture of polar amplification of climate change. But, changes in *circumpolar* sea ice extent can be misleading in that they mask much greater regional/seasonal sea ice changes, and thus ocean-atmosphere changes that are critically important for assessing high latitude climate sensitivity (and vulnerability) to global climate change. Regionally Antarctic sea ice has decreased quite dramatically in the high latitude Southeast Pacific Ocean (SPO), while the largest Arctic sea ice decreases have been in the Western Arctic Ocean (WAO). Further, by resolving seasonal sea ice changes during sea ice advance and retreat, we find some extraordinary rates of change: (1) sea ice in the WAO (of $\sim 1 \times 10^6$ km^2) is advancing 26 days later and retreating 35 days earlier, resulting in a 59-day shorter ice season duration; and (2) sea ice in the high latitude SPO (of $\sim 0.5 \times 10^6$ km^2) is advancing 48 days later and retreating 35 days earlier, resulting in an 83-day shorter ice season duration. Regionally therefore, sea ice duration is decreasing faster in Antarctica. However, changes are seasonally asymmetric, polar-opposite, but globally similar in timing: fastest during austral autumn sea ice advance and fastest during boreal spring sea ice retreat (both during ~March-June). Given these seasonal asymmetric sea ice changes, we explore how solar ocean warming in spring-summer may be delaying autumn sea ice advance and/or thinning winter sea ice and/or pointing to additional ocean heat sources.

Climate and the Polar Marine Biosphere—Complex Responses and Emergent Feedbacks

Patricia L. Yager, School of Marine Programs, University of Georgia

High-latitude marine ecosystems are changing rapidly in ways that go far beyond “global warming,” reflecting large deviations from normal for many environmental variables across a wide range of spatial and temporal scales. Most stunning is that these reported changes are determined from direct observations. We no longer need to use model projections to argue that the high-latitude ecosystems are highly sensitive to anthropogenic climate forcing. For example, Arctic air temperatures over large regions have risen more than 3°C relative to 1968-1995 averages while some other areas have cooled (Overland et al., 2008). Similarly, some areas of Antarctica are warming faster than 0.1°C per year; other regions are *cooling* at a comparable rate. Sea ice extent in the Northern Hemisphere has decreased by more than 6.4 (±1.4)% per decade (Perovich et al., 2010; NSIDC[1]), while the Southern Hemisphere has increased at a rate of 1 (±0.7)% per decade. At regional and seasonal scales most relevant to marine organisms, some key areas are experiencing extreme change. Faraday (West Antarctic Peninsula; WAP) air temperatures have warmed more than 5°C in the past 50 years (Ducklow et al., 2007). Consequently, the WAP region has lost significant sea ice, while other areas such as the Ross Sea have gained ice. Most critical to marine life is that the ice season duration in these two regions has diverged dramatically (Stammerjohn et al., 2008), with significantly shorter ice seasons in the WAP, Bellingshausen, and Amundsen Sea regions.

The loss of sea ice has a direct impact on marine organisms whose life histories are tightly coupled to that ice. Sea ice itself is critical habitat for hunting, feeding, breeding, and refuge for many higher trophic animals (Gradinger and Bluhm, 2004; Thomas and Dieckmann, 2010). The increased sightings of unattended walrus pups in the Beaufort and Chukchi Seas (Cooper et al., 2006) is a good example of how critical the sea ice can be. Sea ice also serves as critical substrate for microorganisms, including ice algae and other sea ice microbiota (Melnikov, 1997; Junge et al., 2001; Thomas and Dieckmann, 2010) that contribute to polar productivity, microbial food webs, and carbon flux. Microbial production and degradation of climate-active gases such as carbon dioxide, dimethylsulfide, and organohalogens are also tightly coupled to the sea ice.

Changes in air temperature and sea ice cover also have profound effects on the polar ocean. Where summertime sea ice has been lost, ocean surface temperatures have risen by more than 3 degrees in some areas (Proshutinsky et al., 2009) and springtime cloud cover has increased relative to the 1982-2004 average (Schweiger, 2004; Liu et al., 2007). Wind speeds have also varied from the norm (e.g., Francis et al., 2005), with deviations up to 2 m/s. Precipitation increases due to warmer air temperatures over land also impact the marine ecosystem. Annual river discharge to the Arctic, already high relative to the size of the ocean, has

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[1] National Snow and Ice Data Center, Website: *http://nsidc. org/arcticseaicenews/2010/100410. html.*

increased (Peterson et al., 2002; Shiklomanov, 2009). While there are no overland rivers flowing to the Southern Ocean from Antarctica, melting glaciers contribute freshwater to the ocean. This contribution is increasing significantly as some glaciers (e.g., Pine Island, Smith, and Thwaites) are thinning at a rate of more than 9 meters per year (Pritchard et al., 2009). Sea surface temperature and salinity, cloud cover, and wind-driven mixing all contribute to stratification and the availability of light and nutrients in the surface layer, impacting phytoplankton and associated ecosystems.

In the water column, primary productivity depends on the availability of light and nutrients, which is often determined by the presence of a sea ice margin (Sullivan et al., 1988). But ecosystem structure and the fate of a bloom depend on more than just the total quantity of production, however. Phytoplankton community structure varies according to position through the marginal ice zone. Also critical is the timing of the bloom and how it is coupled in time to the life history of higher trophic levels. For regions where we have long-term observations, polar ecosystems are clearly responding to climate changes (Grebmeier et al., 2006; Ducklow et al., 2007). The dramatic changes in WAP sea ice cover have led to significant decreases in chlorophyll in the north and increases to the south (Montes-Hugo et al., 2009). As a result, krill populations are declining over two-fold in some areas and are being replaced by salps (Atkinson et al., 2004). Penguin and marine mammal populations are also changing in response to changes in their prey (Ducklow et al., 2007).

The climate impacts on pelagic productivity are multi-faceted (e.g., Boyd and Doney, 2003) and it seems hard to predict what polar productivity is likely to be in the future. Data sets across larger areas are uncommon, forcing us to generalize from short-term or regional observations. In one large-scale (2-year) study, changes in sea ice cover were linked to increased primary productivity attributed to a longer growing season (Arrigo et al., 2008). Without good measurements of ice algal production from satellites, however, it is difficult to know whether polar productivity is indeed higher than it used to be. The open-water areas that satellites can observe are increasing, and where there is open water, we tend to observe higher productivity. Model results suggest, however, that the increase will be short lived because of nutrient limitation set up by increased stratification (Lavoie et al., 2010; Cai et al., 2010). Shifts in the structure of the bloom and associated herbivore populations, however, may lead to a greater fraction of production being exported (Lavoie et al., 2010).

The shallow shelves of the Arctic have tight benthic-pelagic coupling and an unusually high proportion of pelagic production has historically fueled a substantial benthic food web (Petersen and Curtis, 1980). Changes in the quantity and timing of sea-ice and pelagic primary production are predicted to cause a shift toward the pelagic food web (Bluhm and Gradinger, 2008). Observations supporting this idea are reductions in certain benthic invertebrate fauna (Grebmeier et al., 2006), declining dabbling duck populations (e.g., Lovvorn et al., 2003), increasing planktivorous bowhead whale populations while benthic-feeding gray whales are shifting their feeding grounds (Moore et al., 2002; 2003), and the spread of pelagic-feeding pollock and other fish populations into the Beaufort Sea (Rand and Logerwell, 2010). In addition to the obvious worries about how these shifts will impact ecosystem function, local Alaskan communities are concerned about the predictability of ice conditions and its impact on their subsistence hunting and quality of life.

Climate driven changes to ecosystem structure will no doubt impact biogeochemical fluxes and could very well impact the flux of CO_2 between the oceans and the atmosphere (Sarmiento et al., 2004; Doney et al., 2009) and polar oceans are particularly important because of the close connections between the high-latitude and deep oceans (e.g., Sarmiento and Toggweiler, 1984). Ultimately the air-sea exchange of CO_2 depends on the relative rates of upwelling (of high-CO_2 water) and net community production with an efficient biological pump. While a proposed global biogeography of particle flux is still in its early stages, many suspect that the efficiency of the biological pump is very closely linked to ecosystem structure. The above-described shift from krill to salps in the WAP region, for example, could have a profound impact on the regional carbon flux since salps “package” carbon differently and produce sinking particles much more effectively than krill. A similar situation is observed in the Arctic (Wassman et al., 2008). Yet, the role of physical processes may overwhelm any biological response, as it seems to do in the Antarctic Polar Front region. Here, where upwelling rates are high, CO_2 tends to flux out of the ocean (Takahashi et al., 2009). A key question is which way the balance between upwelling and biological drawdown will shift in the future (Lovenduski et al., 2008; Lovenduski and Ito, 2009; Le Quéré et al., 2007).

Although we can confidently say that marine ecosystems respond to climate drivers, it often seems as though we have very little confidence in our ability to predict future polar marine ecosystems under climate change. We are not in any position yet to put the polar marine biosphere into large-scale climate system models. How then do we move ahead? Since the themes of this workshop are (1) thresholds and tipping points, (2) polar amplification, and (3) ecosystem connectivity and resilience, I conclude my talk by suggesting that we consider whether *Complexity Theory* (e.g., Lewin, 1999) may help guide our thinking or plan our field programs. Complex systems are dynamical (non-steady state), with multiple interacting components and multiple stable states. They typically exhibit rapid phase transitions (“tipping points”), cross-scale effects (connectivity), and cascade behavior. Additional properties of interest are similarity at multiple scales, adaptive behavior, and emergent properties (the whole is greater than the sum of the parts). Feedbacks like "polar amplification" are emergent properties. Studying complex systems requires modeling, which means that field programs need to coordinate with the modelers first to find out what they really need us to measure. And while reductionism may still be a useful approach, it will very likely not be enough to understand complex systems. Field programs, then, must emphasize mechanistic understanding (a good example of this would be to look beyond community structure to actual gene expression). We must try to define and then measure the emergent properties with high spatial and temporal resolution (e.g., Schofield et al., 2010). We should also look for generalizablility across regions. Complex systems can often be described with simple rules; we just need to figure out what those rules are.

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Appendix C

Participants

COMMITTEE MEMBERS

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Appendix D

Biographical Sketches of Committee Members

Jacqueline M. Grebmeier (Co-chair) is a research professor at the Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science. Her research interests include: pelagic-benthic coupling, benthic carbon cycling, and benthic faunal population structure in the marine environment; understanding how water column processes influence biological productivity in Arctic waters and sediments, how materials are exchanged between the sea bed and overlying waters, and documenting longer-term trends in ecosystem health of Arctic continental shelves. Some of her research includes analyses of the importance of benthic organisms to higher levels of the Arctic food web, including walruses, gray whale, and diving sea ducks, and studies of radionuclide distributions of sediments and within the water column in the Arctic as a whole. Dr. Grebmeier earned her Ph.D. in biological oceanography in 1987 from the University of Alaska, Fairbanks. She is the current U.S. Delegate and Vice-President of the International Arctic Science Committee and a past U.S. Presidential appointee to the U.S. Arctic Research Commission.

John C. Priscu (Co-chair) is a professor of ecology at Montana State University at Bozeman. His research interests are microbial biogeochemistry in polar aquatic systems emphasizing the roles of nitrogen and phosphorus in microbial growth, as well as life associated with Antarctic ice and its relationship to global change and astrobiology. He studies the biogeophysics of ice-covered lakes and ice cores in northern and southern polar regions. He is a former U.S. representative to the Scientific Committee on

Antarctic Research (SCAR) and convened the Scientific Research Program on Sub-glacial Antarctic Lake Environments (SALE). Dr. Priscu earned his Ph.D. in microbial ecology in 1982 from the University of California at Davis.

Rosanne D'Arrigo is a Lamont Research Professor at the Tree-Ring Laboratory of the Lamont-Doherty Earth Observatory (LDEO) in Palisades, New York. She is also the Associate Director of the Biology and Paleoenvironment Division at LDEO. Her field of study is dendrochronology, specifically the development and analysis of paleoclimatic reconstructions based on tree-ring data. Her research interests include the generation of large-scale reconstructions of Northern Hemisphere temperatures, analysis of the "divergence problem" in tree-ring records from northern latitudes, and the reconstruction of the climate dynamics of Monsoon Asia. Dr. D'Arrigo received her Ph.D. in Geological Sciences from Columbia University in 1989.

Hugh W. Ducklow is the Director of the Ecosystems Center at the Marine Biological Laboratory. Dr. Ducklow is a biological oceanographer and has been studying the dynamics of plankton foodwebs in estuaries, the coastal ocean, and the open sea since 1980. He and his students have worked principally on microbial foodwebs and the role of heterotrophic bacteria in the marine carbon cycle. Dr. Ducklow has participated in oceanographic cruises in Chesapeake Bay, the western North Atlantic Ocean, the Bermuda and Hawaii Time Series stations, the Black Sea, the Arabian Sea, the Ross Sea, the Southern Ocean, the Equatorial Pacific, and the Great Barrier Reef. Much of the work was done in the decade-long Joint Global Ocean Flux Study (JGOFS), which he led in the late 1990s. He has been working on various projects in Antarctica since 1994. Currently, Dr. Ducklow leads the Palmer Antarctica Long Term Ecological Research Project on the west Antarctic Peninsula, where he is investigating the responses of the marine ecosystem to rapid climate warming. Although his research is primarily experimental and observational, he utilizes mathematical models and collaborates with modelers to gain deeper understanding and derive maximum benefit from the data we collect. Dr. Ducklow received his PhD from Harvard University in 1977.

Craig Fleener is the Director of the Division of Subsistence in the Alaska Department of Fish and Game and a lifelong Alaskan from Fort Yukon. He has worked as an environmental manager, project coordinator, wildlife biologist, natural resources director and Executive Director of the Council of Athabascan Tribal Governments. Fleener has served in the military for more than 21 years and is currently an Intelligence Officer in the Alaska

Air National Guard. He has served on numerous boards and committees, including Gwich'in Council International, the Alaska Native Health Board, and the Eastern Interior Subsistence Federal Regional Advisory Committee. He served as deputy mayor of Fort Yukon, and is a member of the Alaska Board of Game. Fleener holds a Bachelor of Science degree in natural resource management from the University of Alaska Fairbanks, and has completed substantial graduate work in resource management at the University of Calgary. Mr. Fleener recently received an MS from the Resources and Environment Program at the University of Calgary.

Karen Frey is an Assistant Professor in the Graduate School of Geography at Clark University (Worcester, MA). Karen earned a B.A. (1998) in Geological Sciences from Cornell University, as well as an M.A. (2000) and a Ph.D. (2005) from the Department of Geography at the University of California, Los Angeles. Her research interests involve the combined use of field measurements, satellite remote sensing, and GIS to study large-scale linkages between land, atmosphere, ocean, and ice in polar environments. Over the past decade, she has conducted field-based research in West Siberia and East Siberia, as well as in the Bering, Chukchi, and Beaufort Seas. Her most recent work focuses on impacts of permafrost thaw on river biogeochemistry and impacts of sea ice decline on biological productivity in polar shelf environments.

Cheryl Rosa currently serves as Deputy Director and Anchorage-based Alaska Director of the U.S. Arctic Research Commission. In this position, she assists the seven-member, presidentially appointed Commission in its efforts to strengthen Arctic research and ties to the State of Alaska and international partners. Dr. Rosa received a Doctorate in Veterinary Medicine from Tufts University and a Doctorate in Biology from the University of Alaska Fairbanks. She is a Research Biologist and Wildlife Veterinarian for the North Slope Borough (NSB) Department of Wildlife Management in Barrow, Alaska. Her term appointment to the USARC, from the NSB, is through the Intergovernmental Personnel Act Mobility Program. Dr. Rosa has been active on the North Slope in a wide range of studies, including wildlife health and zoonotic disease, marine mammal stranding response, subsistence food safety, and oil spill/offshore discharge research. Her fieldwork includes marine and terrestrial mammal research in both the United States and Russia. Dr. Rosa has been active on many different local, state, and federal committees. She has served as an advisor to the North Slope Borough Fish and Game Management Committee, the Joint Commissions of the Inuvialuit Game Commission and the North Slope Borough, and the Alaska Eskimo Whaling Commission. She is also a member of the International Whaling Commission's Scientific Committee, the Science Advisory Panel of the North Pacific Research Board, and the Polar Bear Technical Committee (past). Dr. Rosa has worked and lived in the Arctic for almost a decade. Her background and experience provide a strong connection between the people of the North and Arctic researchers.