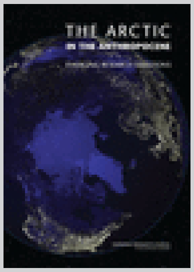

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Committee on Emerging Research Questions in the Arctic
Polar Research Board
Division on Earth and Life Studies

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Preface

This report comes at a unique time in human history—never before has an ocean opened up before our eyes, awakening many to the importance and relevance of the far north. Because of the Arctic's new strategic and economic potential, most of the Arctic countries—the United States, Canada, Norway, Sweden, Denmark/Greenland, Finland, Iceland, and Russia—have produced new or updated national Arctic plans within the past year. These countries include some of the world's largest and strongest economies. Several of the national plans have a development orientation and increased empowerment of northern populations as countries grapple with the prospect of increasingly accessible new mineral and energy resources. Internationally, the opening of the Arctic has raised issues of sovereignty and preparedness and spurred political realignment. Recently, the European Command[1] identified the Arctic as a security concern. The non-Arctic countries of China, India, Italy, Japan, Singapore, and South Korea were accepted as observers by the Arctic Council[2] in 2013, joining France, Spain, Poland, Germany, the Netherlands, and the United Kingdom. The United States will assume chairmanship of the Arctic Council in 2015.

The Arctic itself is unique. The seasonal shifts from icy white in winter to browns, greens, and blues in summer are greater than anywhere else on Earth as the snow melts on land and the sea ice retreats in the ocean. The Arctic Ocean is surrounded by land, with narrow passages allowing interchange between the Pacific and the Atlantic oceans. The terrestrial influence on its hydrology is the strongest of all the oceans, and it receives freshwater from some of the largest rivers on Earth, whose watersheds include much of North America and Asia. Some have called it the estuary for the rest of the world ocean. The nearly encircling, shallow continental shelves are dominated by national Exclusive Economic Zones, which cover a greater proportion of the Arctic than any other ocean. The United States shares international borders with Russia and Canada in the Arctic.

Northern populations are unique in their relationship with the land, having thrived through some of the largest climate variations on Earth ranging from the ice age with mile-thick glaciers and frozen lands, to the warming, thawing, greening, glacial retreat, and urbanization of the Anthropocene. Resilient in the face of past changes, they face a complex suite of disruptions, dislocations, and opportunities in the years to come as all climate models project continued warming and loss of sea ice, on which many of their traditional practices and food sources depend. The need for actionable Arctic science has never been greater than it is today.

This report synthesizes scientific community input on emerging research topics in the Arctic (i.e., those questions that we are only now able to ask or have a realistic prospect for studying). These may be missing from or under-recognized by current research foci. We also outline opportunities and challenges in supporting new and existing research pathways and translating that research into practical information that can help guide management and policy decisions in the United States. The report is directed toward the Interagency Arctic Research Policy Committee (IARPC),[3] which represents 13 federal agencies and organizations with responsibilities in the Arctic.

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[1] http://www.eucom.mil/

[2] http://www.arctic-council.org

[3] IARPC member agencies / organizations include: the National Science Foundation; the Department of Commerce; the Department of Defense; the Department of State; the Department of Health and Human Services; the Department of Homeland Security ; Office of Science and Technology Policy; the Department of Agriculture; the Department of Energy; the Department of the Interior; the Department of Transportation; the

It is designed to address the urgency for understanding the rapidly changing Arctic by connecting the dots among future science opportunities and priorities, infrastructure needs, and collaboration opportunities at local, regional and international levels.

In preparing this analysis, the committee heard from a broad spectrum of the scientific and stakeholder communities and we thank everyone for their thoughts and perspectives (Appendix B). We also thank the over 300 anonymous participants in our community questionnaire (Appendix C). Special thanks to Marc Meloche, David Scott, and Sandy Bianchini of the Canadian Polar Commission for hosting our committee meeting in Ottawa. On behalf of the entire study team, we also thank the sponsors who enabled the undertaking of this important analysis. Finally, this report would not have been possible without the dedication and hard work of the National Research Council staff: Lauren Brown and Maggie Walser. We also thank Elizabeth Finkelman, Shelly Freeland, Rita Gaskins, and Rob Greenway for administrative and logistical support.

Stephanie Pfirman and Henry Huntington, *Co-Chairs*
Committee on Emerging Research Questions in the Arctic

National Aeronautics and Space Administration; the Environmental Protection Agency; the Smithsonian Institution; the National Endowment for the Humanities.

Acknowledgments

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

WALEED ABDALATI, University of Colorado, Boulder
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JULIENNE STROEVE, National Snow and Ice Data Center
ORAN YOUNG, University of California, Santa Barbara
TINGJUN ZHANG, National Snow and Ice Data Center

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions nor did they see the final draft of the report before its release. The review of this report was overseen by John Walsh, University of Alaska Fairbanks, appointed by the Division on Earth and Life Studies, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. The authoring committee also wishes to thank numerous individuals from a broad spectrum of the scientific and stakeholder communities (Appendix B). Responsibility for the final content of this report rests entirely with the authoring committee and the institution.


NORTH PACIFIC OCEAN
Bering Sea
Sea of Okhotsk
50° N
60° N
UNITED STATES (Alaska)
Chukchi Sea
Arctic Circle
Wrangel Island
70° N
CANADA
East Siberian Sea
Beaufort Sea
New Siberian Islands
Banks Island
Laptev Sea
Victoria Island
ARCTIC OCEAN
RUSSIA
Queen Elizabeth Islands
Severnaya Zemlya
North Pole
Ellesmere Island
Kara Sea
80° W
Baffin Island
Baffin Bay
Franz Josef Land
Novaya Zemlya
80° N
Greenland (DENMARK)
Svalbard (NORWAY)
Barents Sea
Greenland Sea
Labrador Sea
Jan Mayen (NORWAY)
70° N
FINLAND
Norwegian Sea
SWEDEN
ICELAND
60° N
Faroe Islands (DENMARK)
NORWAY
EST.
Shetland Islands
LAT.
NORTH ATLANTIC OCEAN
LITH.
BELARUS
North Sea
DENMARK
50° N
UKRAINE
POLAND
UNITED KINGDOM
IRELAND
NETH.
GERMANY
MOL.
CZECH REP.
SLOV.
BEL.
HUN.
ROMANIA
AUS.
FRANCE
0 250 500 mi
0 250 500 km
Scale accurate at 81° N

The Arctic.

Contents

Summary

As rapid change unfolds throughout the Arctic system, the region is taking on an increasingly prominent role in national and international affairs. Because of processes involving ice and snow, climate change here is amplified, thus providing a bellwether for global warming. Yet the "New Arctic," with much reduced ice, challenges existing scientific understanding of how systems behave. The loss of ice also opens doors of opportunity. With an abundance of fossil fuel deposits, minerals, and possible new fisheries, the Arctic attracts attention from industries and nations eager for new frontiers and opportunities for their economies and peoples. Patterns such as these reflect the worldwide trends that have led some scientists and commentators to refer to the current age as the Anthropocene, or epoch of humans.

In response to these changes, the region's indigenous peoples are now exercising greater political power: the Arctic is at the forefront of evolving governance systems and cultural innovations compelled by rapid environmental and social change. Research on the physical, biological, and social Arctic system is a crucial contributor to understanding the rapidly changing Arctic and the effects of those changes on the entire globe. A deeper understanding, together with stronger science-policy connections, can help inform an evolution toward sound policies and management.

The United States has a long history of Arctic research, from the first International Polar Year in 1882, to the establishment of the Naval Arctic Research Laboratory in Barrow, Alaska, in 1947, to the creation of Arctic research programs at the National Science Foundation, the Office of Naval Research, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the Smithsonian Institution, and other agencies. The most recent International Polar Year, in 2007-2009, highlighted the significance of Arctic research globally, and established a benchmark for assessing change and unveiling the future challenges facing the Arctic research community.

In this study, the committee was asked to examine "emerging research questions" in the Arctic (see Statement of Task in Box 1.1). Numerous other studies have identified priority research questions in various fields of Arctic research. Our task was not to duplicate these, but to go beyond them, to identify questions that have arisen as rapid change has pervaded the Arctic system, that have not yet received the attention they likely deserve, and/or that can now be addressed given technological advances. In the words of one scientist, we sought the questions that in five or ten years' time we will kick ourselves for not asking now.

With this mandate in mind, we acknowledge the importance of the high-priority *existing questions* that others have identified. Those questions remain a high priority, and nothing in this report is intended to detract from their urgency or significance. We therefore include examples of the kinds of questions that continue, for good reason, to motivate Arctic research and the funding thereof.

The *emerging questions* that we identify and discuss in detail were selected based on a substantial foundation of information: a review of existing planning and other documents that include key research questions; on a workshop held in Anchorage, Alaska, with over 50 scientists providing ideas from all fields of Arctic research (Appendix B); on more than 300 responses to our community questionnaire of Arctic researchers (Appendix C); and on input from scientists, agency personnel, and diplomats gathered during a committee meeting in Ottawa, Canada, organized by the Canadian Polar Commission on our behalf.

In addition to identifying the emerging research questions, we also assess what is needed to address these questions and to remain able to study emerging topics into the future. Topics here include international and interagency cooperation, investing in and funding Arctic research, long-term observations, managing and sharing information, building operational and human capacity, and acting with knowledge. The report's goal is not to resolve all of these challenges, but rather to identify key gaps that may hinder the ability to address emerging research needs in the Arctic.

RATIONALE FOR CONTINUED ARCTIC RESEARCH

What happens in the Arctic has far-reaching implications around the world; loss of snow and ice exacerbates global climate change including sea level rise, a significant portion of the world's fish catch is from Arctic and subarctic waters, and up to 13 percent of the world's remaining oil is in the Arctic. The iconic cultures and species of the Arctic capture the imagination of millions of people. The geologic history of the Arctic may hold vital clues about past mass extinctions and may offer insight about future ecological concerns. The climate, biology, and society in the Arctic are changing in rapid, complex, and interactive ways, with effects throughout the region and, increasingly, the globe. If we as a global society are to respond effectively to these challenges, understanding the Arctic system has never been more important.

The ability to identify and predict the ways in which loss of sea ice affects climate, biology, and society will help us better prepare and adapt, in the Arctic and beyond. Assessing the impacts of industrial activity will facilitate development of appropriate regulatory strategies that deliver economic benefits while minimizing negative consequences. Studying the ways Arctic peoples respond to social and environmental change will advance our understanding of societal resilience and the conditions that foster it, for the Arctic and for human societies elsewhere.

In its deliberations, the committee considered four categories of information. (1) What we *know*, which forms the foundation for present response and future research efforts. A great deal is known about how the Arctic is changing, along with extensive information about Arctic conditions in various disciplinary fields. (2) What we *know we need to know* includes key questions driving current research, enumerated in many planning documents and other places, and recognizing how much is at stake. (3) What we *think we don't know* (or *what some know that others don't*) is an intriguing category of knowledge that is not widely shared and thus often overlooked, and includes traditional knowledge, proprietary data, and discipline-specific information that has not yet crossed over to inform other fields. (4) Finally, what we *don't know we don't know* is the realm of surprise, which by definition we cannot describe, but to which we need to remain open, as there will undoubtedly be more surprises to come in the Arctic. This scheme allowed us to evaluate whether potential research questions met the criteria to be considered "emerging," pointed us to the need for greater sharing of information to increase the pool of common knowledge, and reminded us to leave room for addressing future surprises.

EMERGING QUESTIONS

We present our *emerging research questions* under five headings: Evolving Arctic, Hidden Arctic, Connected Arctic, Managed Arctic, and Undetermined Arctic. The lists of questions under each heading are not intended to be comprehensive or the final word on the subject, but illuminate what we need to learn about the Arctic based on what we already know. As such, they point the way to future research, but do not imply any limits on what is needed.

Evolving Arctic

The Arctic is rapidly changing. Climate change has received a great deal of attention in recent decades, but many of its implications for the Arctic system have yet to be studied in depth. Arctic societies are also changing rapidly, especially in the political realm as indigenous peoples achieve greater autonomy in some regions. This section highlights six *emerging questions* that span disciplines, fields, and sectors:

Will Arctic communities have greater or lesser influence on their futures?

Many Arctic regions and peoples are experiencing greater political autonomy or influence, but are also increasingly subject to the impacts of global markets and resource demands. How these competing influences will interact with one another is not clear but certainly there will be major impacts on Arctic communities.

Will the land be wetter or drier and what are the associated implications for surface water, energy balances, and ecosystems?

Degrading permafrost and changing precipitation (amount and phase) will alter the hydrologic regime on land, but the direction and timing of change— to say nothing of its implications —is not yet understood and may vary greatly through space and perhaps time.

How much of the variability of the Arctic system is linked to ocean circulation?

There is great variability in the currents and conditions that drive Arctic Ocean circulation, and these are changing rapidly as sea ice retreats and Arctic weather patterns change. The role of Arctic Ocean circulation as a driver of variability throughout the system is poorly understood.

What are the impacts of extreme events in the new ice-reduced system?

The change in average conditions in the Arctic is well documented, but the role of extreme events and sudden shifts or irreversible changes is not well understood. Forest fires, storms, rain-on-snow in winter, and other abrupt but powerful events may have lasting impacts.

How will primary productivity change with decreasing sea ice and snow cover?

Loss of snow and ice means increased sunlight to soils and waters, which should increase primary productivity. The availability of nutrients and, on land, the water content of soils may support more productivity or may offset the advantages of more light. The role of thawing permafrost and increasing active-layer thickness may mediate the trajectory of changes in primary productivity. A more detailed understanding of the processes resulting from snow and ice loss is needed.

How will species distributions and associated ecosystem structure change with the evolving cryosphere?

Changes in the physical environment will affect which species thrive and which fail under new conditions. Changes in abundance and distribution will affect ecosystem structure and could lead to cascading effects on ecosystem processes. The limitations on species adaptations and responses are not yet understood.

Hidden Arctic

Many aspects of the Arctic have been unknowable, in large part because ice cover has blocked access, presenting a major barrier to research. Loss of sea ice, retreat of glaciers, and technological advances now allow research in new fields, new geographical areas, and throughout the year. At the same time, rapid change can lead to the loss of sites, features, and phenomena. This section highlights seven *emerging questions* spanning disciplines, fields, and sectors:

What surprises are hidden within and beneath the ice?

Permafrost holds gas hydrates and preserves organic remains, ice sheets likely hold records of the past not yet assessed, and sea ice conceals crucial oceanographic processes. The opportunity to study all of these holds great promise for new discoveries.

What is being irretrievably lost as the Arctic changes?

Archeological sites are eroding or decomposing as they emerge from permafrost or under ice. Specialized ecosystems are lost due to sudden physical change or the loss of rare habitat. Indigenous languages are in danger. An emerging challenge is how to study that which may soon be gone.

Why does winter matter?

Winter dominates in the Arctic, yet most field campaigns and process studies occur in the brief summer months. Understanding what happens in winter is essential to understanding how changes in physical processes during darkness will affect biota and ecosystems as well as oceanic and atmospheric structure.

What can "break or brake" glaciers and ice sheets?

Glaciers and ice sheets are currently losing mass throughout the Arctic, but positive and negative feedbacks that accelerate or retard ice loss and ice flow over various timescales are not well understood. Some mechanisms appear to accelerate ice loss, but others may limit the rate of change, and changes in these mechanisms vary with season, region, and even along a single glacier. Understanding feedbacks is necessary to project future change, with consequences for sea level rise and more.

How unusual is the current Arctic warmth?

Recent summer sea ice loss in the Arctic has been faster than predicted. Reconstructing the timing and magnitude of past warm events can help identify mechanisms that explain rapid change, and provide insight into the future Arctic state, a major unknown.

What is the role of the Arctic in abrupt change?

Various mechanisms may be responsible for abrupt change, including volcanism, solar variability, and shifts in ocean currents or modes of natural variability. Examining how these have occurred in the past may shed light on what may occur in the near future, with far-reaching implications for humans around the world.

What has been the Cenozoic evolution of the Arctic Ocean Basin?

The geological history of the Arctic Ocean is poorly understood, but may hold clues to major questions, including the geologic processes that led to the onset of Arctic Ocean sea ice or the formation of large igneous provinces, and increase our understanding of ocean circulation changes. The loss of summer sea ice and improvements in seabed drilling technology allow new research to examine these and other key questions.

Connected Arctic

The Arctic system does not exist in isolation, but is connected by air and water currents, by animal migrations, and by societal interactions with the rest of the world. Climatic and meteorological connections in particular may have far-reaching implications globally, for example through rising sea level due to mass loss from land-based Arctic ice, and through weather patterns affected by sea ice loss and disproportionate Arctic warming. The experiences of Arctic cultures can inform and be informed by those of indigenous peoples elsewhere. This section highlights five *emerging questions* spanning disciplines, fields, and sectors:

How will rapid Arctic warming change the jet stream and affect weather patterns in lower latitudes?

The Arctic is warming faster than the rest of the Northern Hemisphere owing to ice and snow loss as well as changes in atmospheric properties. The more rapid Arctic warming relative to mid-latitudes affects atmospheric circulation throughout the hemisphere, including the track of the jet stream and the persistence of weather patterns. These mechanisms have far-reaching effects throughout mid-latitudes and perhaps beyond.

What is the potential for a trajectory of irreversible loss of Arctic land ice and how will its impact vary regionally?

Ice loss from local glaciers and ice caps as well as the Greenland Ice Sheet will cause sea level rise worldwide, but the rate of loss is difficult to predict. Furthermore, the loss of gravitational pull from the ice, the rebound of the land underneath, and shifting ocean currents will affect sea level regionally and globally, but in ways that cannot be predicted with accuracy.

How will climate change affect exchanges between the Arctic Ocean and sub-polar basins?

The formation of relatively fresh seawater in the Arctic, and its export through Fram Strait, affects water circulation in the North Atlantic, particularly the formation of deep water that drives global ocean circulation. Changes in these patterns could have profound impacts around the world, but our current understanding is insufficient to predict what is likely to happen.

How will Arctic change affect the long-range transport and persistence of biota?

As Arctic summers warm and the ice-free season lengthens, boreal and subarctic species may migrate northward. Whether they can survive in Arctic conditions remains to be seen, but changes in distributions of plankton, plants, insects, fishes, birds, mammals, and other life forms are likely to affect many aspects of Arctic ecosystems including interactions with the physical environment. Species will move at different rates so there is the potential for entirely new communities and species interactions. Some species may not survive due to habitat loss in the Arctic.

How will changing societal connections between the Arctic and the rest of the world affect Arctic communities?

Most political and transportation links in the Arctic flow North-South, not East-West. Increasing southern interest in the Arctic will affect Arctic communities through the influx of new people, new cultures, new ideas, and new opportunities. Sharing of experiences among indigenous peoples worldwide may also facilitate sharing of effective adaptations.

Managed Arctic

Humans have lived in the Arctic for millennia, shaping their surroundings and making use of what the Arctic has to offer. In recent decades, the human environment has shifted greatly, including political and economic integration with nation-states and less obvious trends such as urbanization of Arctic peoples. Looking forward, the Arctic is likely to see large-scale human activity and interventions, including increasing interest in resource development and potentially some forms of geoengineering. Whether these changes will lead to conflict or cooperation remains to be seen, but research on these topics is essential to understand the drivers of change and their implications near and far. This section highlights five *emerging questions* spanning disciplines, fields, and sectors:

How will decreasing populations in rural villages and increasing urbanization affect Arctic peoples and societies?

Urbanization is a worldwide trend, but it has been little studied in the Arctic. Towns and cities play increasingly important roles in indigenous intellectual, artistic, economic, and political activity. At the same time, rural villages remain important sites of traditional activities not easily transfered to cities.

Will local, regional, and international relations in the Arctic move toward cooperation or conflict?

Potential resource development, claims on extended continental shelves or shipping routes, and increasing interest from non-Arctic countries all create the potential for conflict. On the other hand, most potential issues are covered by existing international arrangements and the Arctic Council has admitted more observers. The interplay of these trends remains to be seen.

How can twenty-first century development in the Arctic occur without compromising the environment or indigenous cultures while still benefitting global and Arctic inhabitants?

Interest in mineral, petroleum, and other resource development and increasing tourism are likely to grow throughout much of the Arctic in the next few decades. This would provide revenues and other benefits locally and nationally, but also poses environmental and cultural risks. Capitalizing on opportunities while reducing risks is a crucial task at the intersection of science, industry, and governance.

How can we prepare forecasts and scenarios to meet emerging management needs?

The Arctic environment, including its weather, snow conditions, and ice conditions, is changing rapidly. Past observations and experiences are not as reliable in predicting the future as they once were, at a time when there exists an ever greater need for forecasts and scenarios from daily to decadal time frames. Key research topics in this area include probing the limits of predictability and connecting user needs with specific forecast products.

What benefits and risks are presented by geoengineering and other large-scale technological interventions to prevent or reduce climate change and associated impacts in the Arctic?

Global and Arctic-targeted geoengineering in various forms has been suggested as both a short-term and a long-term response to climate change. The societal and environmental implications of various ideas have not been explored in depth, especially in the Arctic, which may experience greater inadvertent effects than in other regions.

Undetermined Arctic

Leaving room for new ideas, and making it possible to identify them when the need arises, requires a combination of research (to better assess new topics), long-term observations (to identify changes and surprises without delay), and flexibility in funding (to be able to move quickly when a significant event occurs). We need to be prepared to look at the Arctic in new ways and to respond accordingly.

MEETING THE CHALLENGES

Identifying research questions is essential, but conducting the actual research and making full use of the results requires more than just the questions. The committee considered various logistical, technological, and other needs that will improve our ability to address emerging questions. In many cases, these apply equally well to existing research questions and thus serve Arctic research in general. We did not assess these topics exhaustively, but we raise them here for further consideration by agencies and others seeking to increase Arctic research capability in ways that effectively address the most pressing questions.

Enhancing Cooperation

No single agency, organization, or even country can take on all research topics in the Arctic. Some research questions are too broad, or involve such extensive field efforts, that they cannot be resolved solely by researchers from a single country or supported by a single funding source. Cooperation is essential: among researchers, between agencies, among nations, across disciplines, between Arctic residents and visiting scientists, and with the private sector. There are good but relatively rare examples of such cooperation in each category, but obstacles often remain high.

Sustaining Long-Term Observations

Long-term observational data are essential for detecting change and for putting research findings into context. There are, however, insufficiently few long-term observation efforts underway and too little coordination among those that do exist. Instead, available records are often a collection of ad hoc efforts conducted with different temporal resolutions, in different areas, and for different purposes. It is thus difficult to distinguish large-scale patterns from localized ones, or to connect findings in one discipline with those from another. A few efforts are underway to remedy these shortcomings, but in many cases, discussions have yet to become routine practice.

Managing and Sharing Information

Data are only meaningful if they can be easily accessed. Our understanding of the Arctic as a system has evolved through the capability to compare data sets from disparate fields and regions, to see connections, commonalities, and systematic differences. But data management to date has often been left to individuals or to separate efforts depending on agency, program, discipline, or other parameters. Data management requirements, too, have often been un- or under-funded, resulting in poor quality metadata, a lack of long-term archiving, and/or other shortcomings that greatly reduce the utility and value of hard-won and expensively produced data. Recently, more attention has been given to data management needs and challenges, so there is progress upon which to build. Researchers and stakeholders would benefit from continuing this effort, along with progress in techniques for using and visualizing data so that they can be used more readily and more often, both by scientists and by others with an interest or a stake in the Arctic.

Maintaining and Building Operational Capacity

New technologies allow new approaches to conduct research in many fields. Among the most promising recent developments is a host of autonomous mobile sensors for the ocean and atmosphere. These can be deployed relatively easily and inexpensively, and thus promise to alleviate the limitations of icebreaker access or aircraft time (though range is still limited for many such devices). New remote sensing capabilities are also being developed to measure features of the Arctic system that required in situ observation in the past. It is also important to sustain the capacity that exists, such as at research stations and by satellites. Even with new developments, there is still a need for heavy-duty icebreaking capability, which at present is a critical weakness of U.S. Arctic research capacity. Improvements in power generation for remote sensor arrays, and better broadband communication for transmitting and sharing data, are also important for increasing our ability to conduct research and observations in the Arctic. Improvements in modeling and forecasting will not only provide a clearer window to the future, but will also better guide research needs and help determine optimal placement of field sites. The increasing role of industry in the Arctic creates opportunities for private sector involvement, for example through public-private partnerships.

Growing Human Capacity

Arctic research depends on sufficient human capacity, including scientists trained in the necessary fields who are capable of interdisciplinary collaboration and working across the Arctic. During the International Polar Year, concerted efforts were made to involve young researchers, and those opportunities helped to train the next generation of scientists in Arctic research. Arctic residents can offer a great deal, as well, and the capacity for local involvement in all stages of research can be improved. There are many good examples of such collaborations, but also apparent are indications of "research fatigue" among those who have been the subject of, or otherwise involved in, many studies without seeing a direct return for their efforts. For Arctic residents, a crucial aspect of human capacity is the ability to act on what is learned from research, and to enhance the adaptive capacity of communities and societies as they face rapid and far-reaching changes. Making connections between research activities and real-world challenges requires more effort on all sides.

Investing in Research

The research that gets done is the research that gets funded. Funding mechanisms and program objectives perhaps require re-evaluation to determine whether they are in fact addressing high-priority questions and pressing needs. Society's ability to address emerging research questions in the Arctic is closely tied to the way research funding is organized. Other approaches are used in different countries, and the tradeoffs involved are worth considering to assess whether some of those approaches might be adopted or adapted in the United States. Systems research and synthesis research often require more than individual projects, and thus can be difficult to carry out effectively when proposals are considered individually and projects are conducted independently over short time periods. Funding non-steady state research will be necessary to better understand the dynamics of thresholds, resilience, and transformation in a rapidly changing Arctic. Research ideas from stakeholders often fall outside the priorities identified by the scientific community, and thus may be less likely to receive funding, even if they address key needs. Additionally, long -term observations are often difficult to fund as the value of such records is often not realized until many years later. Mechanisms to coordinate funding from multiple nations are obscure, time-consuming, and fraught with difficulty, leading to reduced international collaboration. The role of the private sector in research is also increasing and could be better integrated with publicly-funded research.

BUILDING KNOWLEDGE AND SOLVING PROBLEMS

Research activities are sometimes separated into categories of “basic” and “applied” science, or “curiosity-driven” and “problem-oriented” research. These categories are not mutually exclusive, but mutually reinforcing. Improving the ways scientific results are used to inform policy and management processes is important. Collaboration is necessary, not just among scientific disciplines or between scientists and those who live in the Arctic, but also with decision-makers, to better understand what they require and how scientific results are factored with other considerations to produce decision outcomes. The United States has demonstrated the will to devote resources to Arctic research. An equal will to apply the results of research is essential, as is a continued commitment to studying what exists, what is emerging, and what awaits us in the Arctic.

1
Introduction

Aurora borealis, base camp, Baffin Island, Arctic Canada. Photo credit: M. Kennedy, Earth Vision Trust

Once ice-bound, difficult to access, and largely ignored by the rest of the world—literally off the map in some projections—the Arctic is now front and center in the midst of many important questions facing the world today. Our daily weather, what we eat, and coastal flooding are all interconnected with the future of the Arctic. Looking within the Arctic, 2012 was an astounding year for Arctic change. The summer sea ice volume smashed previous records, losing approximately 75 percent of its value since 1980 and half of its areal coverage (Jeffries et al., 2013). In 2012 Greenland experienced the largest melt extent of the satellite era (the past 35 years), with melting occurring over 97 percent of the ice sheet's surface, continuing a multidecadal trend of increasing summer melt and mass loss (Tedesco et al., 2013). Receding ice caps in Arctic Canada are now exposing land surfaces that had been continuously ice covered for more than 40,000 years (Miller et al., 2013). Dozens of Alaska villages face pressing threats from riverbank and coastal erosion as waterflow patterns change, sea ice retreats, storms increase, and sea level rises (GAO, 2003). Local and remote effects of Arctic sea ice decline on weather and climate are being explored (Vihma, 2014). All of these pose challenges for human response, from policy to practice. Better understanding can help improve these responses, if science and scientific results are communicated effectively to those in positions to apply them.

The Arctic can be defined in astronomical, cryospheric, biological, cultural, and political ways. None of these definitions are universally suitable. For the purposes of this report, which focuses on emerging research questions in the Arctic, we define the Arctic as the northern region where physical, biological, social, economic, political, and other changes are leading to the emergence of new characteristics, relationships, and systems. Specifically, we focus on the area where change is rapid and far reaching, overturning the status quo.

The changes taking place in the Arctic, from physical, biological, and social shifts driven by worldwide human activity to economic expansion and technological advances, are hallmarks of the Anthropocene epoch (Crutzen and Stoermer, 2000; Revkin, 1992), in which human activity is a dominant force on the global environment. It seems appropriate, therefore, to characterize a report on emerging research questions as a response to the advent of the Anthropocene, whose causes are ultimately largely the same as those driving emerging research needs.

Many of these changes have been expected based on research conducted over the past several decades, including under the Study of Environmental Arctic Change (SEARCH) and during the International Polar Year (IPY) of 2007-2009 (NRC, 2012a). Numerous existing questions remain unanswered, however, and they require continued research support, as the committee heard time and again from the scientific community. In this report, we reiterate some of those most frequently and fervently expressed, but our primary task is to highlight the new questions that have emerged in the wake of recent, and expectation of further, rapid Arctic change, as well as new capabilities to address them.

The Arctic serves as a bellwether for rapid environmental change and its impacts, and has a critical role in the regulation of global climate. The emerging questions presented in this report can teach us about the future Arctic and its role in the global system. Additionally, the way Arctic researchers prepare to address these emerging questions is likely to serve as a model for science globally. Because changes in the Arctic are happening fast and the signal emerges clearly from the noise, in many ways the science of change is currently easier to study in the Arctic than in most places. Arctic science is poised to identify and address emerging questions now, whereas it may be decades before scientists agree on analogous questions for other regions of the world. Arctic research has an opportunity to be the global leader in developing a new science of the dynamics of change. The focus of this report, as outlined in the Statement of Task (Box 1.1), is on these "emerging" research questions. Research questions may be emerging for various reasons. Some of these questions are ones that we are only now able to examine because reduced snow cover and sea ice facilitate access. Others are questions that can only now be addressed because of advances in analytical tools and/or new observing platforms. New technologies and access to new areas allow us to conduct studies that simply were not possible a decade ago. Rapid environmental and social changes pose new research challenges that did not exist in the past. A growing emphasis on interdisciplinary work, sustainability science, and decision support inevitably leads to connections that were not made earlier. New understanding provides insights that lead to questions that could not have arisen before. Other, possibly more important, questions are those that we had not even thought of asking before, and those that only became apparent as a result of ongoing research and rapid change.

We need to think over the long term. We cannot predict with certainty how the Arctic system will evolve during the next 10 to 20 years, but it is urgent that we gain our best estimate of its future state. To even begin to try, we also need to look far beyond the next decade or two, to potential endpoints of the current trajectory of change. The Arctic is currently in a transient state. Climate is changing rapidly, and the Arctic is warming faster than the rest of the planet in all seasons. In response to that warming, the physical and biological components of the Arctic system are continually adjusting. At the same time, the social, political, and economic components of the Arctic system are also changing, in part in response to a changing Arctic environment that is more accessible than at any period in the post-industrialized era, but also in response to related and unrelated geopolitical pressures. As a result, even well-established multidecadal trends may be misleading. Records of past Arctic climates exhibit threshold behavior, with abrupt and profound changes in state that occurred within a decade, and suggest that future abrupt changes are possible in a warming climate regime (Lenton, 2012). Consequently, we need to consider not just the implications of current trends, but also our ability to predict unexpected departures from those trends and their subsequent implcations.

Our task in this report is to assess what we can do now in Arctic research that is new and to identify those questions that we will regret having ignored if we do not invest in answering them soon.

STUDY CONTEXT AND CHARGE TO THE COMMITTEE

This report was prepared by the Committee on Emerging Research Questions in the Arctic, appointed by the National Research Council (NRC) in response to a request from the Arctic Research Commission (USARC), the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Smithsonian Institution to provide guidance on future research questions in the Arctic over the next 10 to 20 years (Box 1.1). The Committee's goal was to provide concise guidance for U.S. Arctic research so that research is targeted on critical scientific and societal questions and conducted as effectively as possible. In doing so, the Committee considered the Interagency Arctic Research Policy Committee (IARPC) to be the main audience for this report. Thus the high level concepts listed in the Table of Contents (particularly in Chapters 3 and 4) are intended to be priorities for IARPC as a whole, with the understanding that individual agencies will prioritize investments in accordance with their specific mission and goals.

STUDY APPROACH AND METHODOLOGY

The Committee on Emerging Research Questions in the Arctic was formed in early 2013 and completed its work over the course of the next 14 months. It held four meetings during which it gathered community input and reviewed relevant literature and other information, including previous reports from numerous regional, national, and international agencies, organizations, and other institutions with active research programs in the Arctic. To inform its analysis, the Committee organized an interdisciplinary workshop to begin identifying emerging research questions and technology and infrastructure needs. The workshop was held in May 2013 in Anchorage, AK and included approximately 50 participants. A second workshop, hosted by the Canadian Polar Commission, was held in September 2013 in Ottawa, ON. Approximately 45 people participated in the Ottawa meeting. The participants of the Anchorage and Ottawa meetings are listed in Appendix B. The Committee gathered additional community input through the use of an online community questionnaire[4] (Appendix C), which received over 300 responses and a series of interviews with 15 Arctic researchers (Appendix B). Starting from the research questions identified in previous reports and by workshop, interview, and questionnaire participants, the Committee used its expert judgment and deliberation to identify important emerging questions.

REPORT ORGANIZATION

Chapter 2 is the *Rationale for Continued Arctic Research*, situating this report's emphasis on emerging research questions in the wider context of Arctic research accomplishments, needs, and support. It is essential to recognize the value of ongoing Arctic research and the priorities identified in many venues, so that this report's emphasis on emerging questions does not overshadow the significance of existing research activities and plans.

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[4] The questionnaire was not intended to be a scientific sampling, nor was any statistical analysis performed.

BOX 1.1
COMMITTEE ON EMERGING RESEARCH QUESTIONS IN THE ARCTIC
STATEMENT OF TASK

This activity is designed to provide guidance on future research questions in the Arctic over the next 10-20 years, identifying the key scientific questions that are emerging in different realms of Arctic science and exploring both disciplinary realms (e.g., marine, terrestrial, atmosphere, cryosphere, and social sciences[a]) and cross cutting realms (e.g., integrated systems science and sustainability science). Based on the emerging research questions, the study will also help identify research infrastructure needs (e.g., observation networks, computing and data management, ship requirements, shore facilities, etc.) and collaboration opportunities. Attention will be given to assessing needs where there may be a mismatch between rates of change and the pace of scientific research. Although it is understood that there is no one answer, the committee is asked to explore how agency decision makers might achieve balance in their research portfolios and associated investments (e.g., what are some of the challenges of trying to do both problem-driven research and curiosity-driven research?). The goal is to guide future directions in U.S. Arctic research so that research is targeted on critical scientific and societal questions and conducted as effectively as possible.

The study committee will:

- Briefly summarize the rationale for continued U.S. research in the Arctic, including how climate change, together with other stressors, stands to affect the region in the coming decades and how changes in the Arctic region will affect other parts of the world.
- Identify, incorporating community input, the key scientific questions that are emerging in different realms of Arctic science, with attention to both disciplinary realms (e.g., marine, terrestrial, atmosphere, cryosphere, and social sciences) and cross cutting realms (e.g., integrated systems science and sustainability science). As possible, discuss or indicate a general sense of priority[b] within the primary areas.
- Identify the types of research infrastructure, data management, technological developments, and logistical support needed to facilitate the research and monitoring efforts that are needed to address the key scientific questions, including discussion of possible approaches to sustain long-term observations in the Arctic.
- Identify needs and opportunities for improved coordination in Arctic research among the different U.S. federal and state agencies and for improved international collaboration in Arctic research.
- Explore how agency decision makers might balance their research programs and associated investments (e.g., balancing work done to respond to urgent global change concerns versus work to advance fundamental knowledge and discovery). In other words, what are some of the challenges of trying to do both problem-driven research and curiosity-driven research?

[a] To provide some boundary on the committee's discussion of emerging research questions, if health is addressed it should be limited to potential health issues related to environmental or climate change.

[b] The concept of priorities varies based on audience. That is, different factors are important to different audiences (importance to Arctic residents, to global population, to the science community attempting to understand the global climate system, or to decision makers working on economic development). In this study, the committee will consider the Interagency Arctic Research Policy Committee (IARPC) to be the primary audience for its report, recognizing that even within IARPC there are differing missions and thus differing needs. The intent is not to provide a literal ranking of research priorities but to provide some scale by which recipients of the report can better judge importance or time-relevance among the identified questions.

In Chapter 3, we present *Emerging Research Questions* in five categories, noting important existing questions, and recognizing the various ways the Arctic and our understanding of the Arctic are changing. The *Evolving Arctic* focuses on the transition to the "new normal" of reduced ice and snow and the cascade of impacts this will have on systems that depend on frozen ground and water. The *Hidden Arctic* explores what could be found as ice barriers diminish—and what could be forever lost amid rapid change. The *Connected Arctic* addresses the fact that changes occurring in the Arctic do not stay in the Arctic, but affect the rest of the northern hemisphere and beyond through rising sea levels, an altered jet stream, changes in the large-scale ocean circulation, invading species of plants and animals, transported chemicals and aerosols, and outside pressures on Arctic residents. Questions of societal changes, conflict and cooperation, and proactive vs. reactive decision making are raised in the *Managed Arctic* section. The *Undetermined Arctic* is concerned with how we can be prepared to detect and respond to the unexpected.

Equally important, Chapter 4 describes *Meeting the Challenges*, addressing what is needed to leverage efficiencies in making Arctic research happen, from collaboration and coordination, to sustained observations, building human and operational capacity, making information actionable as well as accessible, and innovative funding approaches.

The report concludes with Chapter 5, *Building Knowledge and Solving Problems*, which highlights the importance of connecting Arctic research with real-world issues.

2
Rationale for Continued Arctic Research

Supraglacial water channels and small surface ponds on the flanks of Russell glacier, a land terminating glacier on Southwest Greenland   Photo credit: Perry Spector

What happens in the Arctic has far-reaching implications around the world. Loss of snow and ice exacerbates climate change and is the largest contributor to expected global sea level rise over the next century. Ten percent of the world's fish catches come from Arctic and subarctic waters (Lindholt, 2006). The U.S. Geological Survey has estimated that up to 13 percent of the world's estimated remaining oil reserves are in the Arctic (Gautier et al., 2009). The iconic cultures and species of the Arctic capture the imagination of millions of people (ABA, 2013). The geologic history of the Arctic may hold vital clues about volcanic eruptions and their impacts on ocean chemistry and atmospheric aerosols, including the release of large volumes of ash that are thought to have caused mass extinctions in the distant past (Grasby et al., 2011). The physical, biological, and social systems of the Arctic are changing in rapid, complex, and interactive ways, with effects throughout the region and, increasingly, the globe. If we as a global society are to respond effectively to these challenges, understanding the Arctic system has never been more critical and thus Arctic research has never been more important.

The ability to identify and predict the ways in which loss of sea ice affects climate, biology, and society will help us better prepare and adapt, in the Arctic and beyond. Assessing the impacts of industrial activity will help us develop appropriate regulatory strategies that reap economic benefits while minimizing negative consequences, lessons that can be applied far and wide.

18 The Arctic in the Anthropocene: Emerging Research Questions

BOX 2.1
SELECTED RECENT (2013) DEVELOPMENTS IN THE ARCTIC

Winter rain, an unusual event in the high north, drives animal numbers on a Norwegian Arctic island into decline, showing that extreme climate events can affect an entire community of vertebrates (Hansen et al., 2013).

Within the past five years, nine of the 14 villages in Nunavik in northernmost Quebec have had to install cooling systems at community ice hockey arenas to keep the rinks cold during winter (Klein, 2013).

Tracer results from the Greenland Ice Sheet drainage system indicate evolution from a slow process to a fast channelized system over the course of the melt season (Chandler et al., 2013).

Ancient camels may have occupied Arctic forests 3.5 million years ago, a time when the region was densely forested and considerably warmer than today (Rybczynski et al., 2013).

One of the key features of amplified Arctic warming is that winter warming exceeds summer warming by at least a factor of 4, according to model simulations (Bintanja and van der Linden, 2013).

Dynamic bacterial communities associated with snowpacks may be active in supraglacial nitrogen cycling and capable of rapid responses to changes induced by snowmelt (Hell et al., 2013).

An isolated population of Arctic foxes that dines only on marine animals seems to be slowly succumbing to mercury poisoning (Bocharova et al., 2013).

The Arctic Council agreed to expand to include six new countries with permanent observer status in the Arctic Council: China, Japan, South Korea, Singapore, India and Italy (Myers, 2013)

Pliocene polar amplification could be related to the loss of sea ice in the Arctic Ocean, according to model simulations (Ballantyne et al., 2013).

ExxonMobil and Rosneft (a Russian oil company) reached an agreement to create a $450 million Arctic Research Center (OGJ Editors, 2013).

Sediments from Lake El'gygytgyn in northeastern Russia reveal that 3.6 million years ago the Arctic's summers were 8 degrees Celsius warmer than they are today (Brigham-Grette et al., 2013).

Shifts in sea-ice cover could affect oceanic emissions of dimethylsulphide (DMS) — a climate-relevant trace gas generated by ice algae and phytoplankton that acts as a nucleus for cloud droplet formation. Observations and model results suggest that the emission of DMS will increase in the Arctic as the seasonal sea-ice cover recedes. If it escapes to the atmosphere, it could augment cloud formation and cool the Arctic climate (Levasseur, 2013).

A Greenland "Grand Canyon" was discovered. It is 50% longer than Arizona's 277-mile Grand Canyon, but not as deep -- ranging from 650 feet to about 2,600 feet (200 to 800 meters) (Bamber et al., 2013).

Analysis suggests wild food consumption, as practiced in two isolated First Nations communities of northwestern Ontario, can increase blood levels of polyunsaturated fatty acids (PUFAs), which provide a number of important metabolic benefits that could allow the prevention/treatment of type 2 diabetes mellitus, which has risen dramatically in northern communities (Seabert et al., 2013).

The first meeting of the Arctic Circle, a group established to facilitate dialogue and build relationships among businesses and those in the Arctic to address rapid changes in the Arctic, takes place in Iceland.[5]

The genome of a young boy buried at Mal'ta near Lake Baikal in eastern Siberia some 24,000 years ago shows that during the last Ice Age, people from Europe had reached farther east across Eurasia than previously supposed (Wade, 2013).

Crusts deposited on underwater rocks by coralline algae record changes in sea ice over the past 650 years. They show that sea ice decline since 1850 is unprecedented in the record (Halfar et al., 2013).

[5] http://www.nunatsiaqonline.ca/stories/article/65674arctic_circle_conference_attracts_hundreds_to_iceland/

Studying the ways Arctic peoples respond to social and environmental change will help us better understand societal resilience and the conditions that foster it, a pressing challenge everywhere. Understanding how a fast-warming Arctic may contribute to increased extreme weather events will help to evaluate risk outside the Arctic.

These and many other key questions have been identified over the years in various planning documents and other efforts to guide Arctic research. The Committee analyzed many strategic research planning documents produced since the conclusion of the International Polar Year in 2009. These reports included many recommendations for future Arctic research. The sheer number of reports, and the hundreds of participants involved in their preparation, testifies to the strength of community concern and need for deeper knowledge.

In crafting a research strategy for the next 10 to 20 years, it is essential to assess the questions that are emerging in Arctic research, from our increased understanding, from the rapid changes underway, from new opportunities to study areas and phenomena that have remained hidden until now, and from new needs to manage how we respond to the developing Arctic. These questions are addressed in the next chapter. The significance of the emerging questions does not in any way reduce the importance of the existing questions that currently guide Arctic research. On the contrary, the ability to ask emerging questions depends on past results as well as ongoing pursuits to address important issues in Arctic research (e.g., Box 2.1). With this in mind, the identified categories of knowledge underscore both what is important and point toward what is truly emerging, as well as what will be needed to support research in these emerging areas. While previous reports focused on what we know we need to know, this report also considers what we may not yet recognize as unknown.

We know the Arctic system is warming rapidly (Figure 2.1). We also know that sea ice is dramatically thinner and less extensive, and that snow on Arctic land areas is disappearing ever earlier in summer. We know Arctic albedo is decreasing, as it shifts from the high values of ice and snow to the darker grays, greens, browns, blacks and blues of soil, vegetation, and water. We know Arctic communities are feeling the stress of environmental and social change in all facets of their lives. We also know we have not sufficiently sampled much of the Arctic during the long winter darkness. The observed Artic impacts attributed to climate change are summarized in Table 2.1.

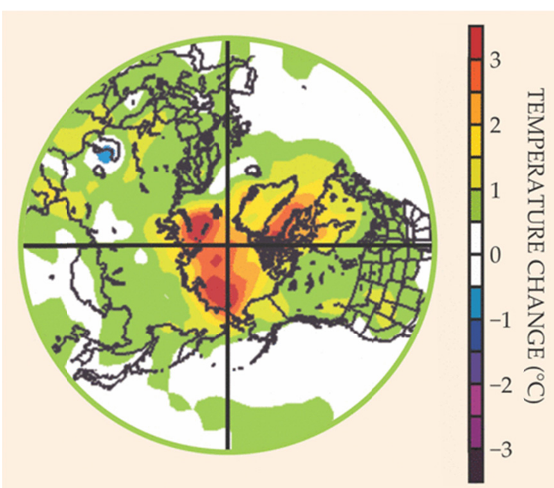

FIGURE 2.1 Annual near-surface air temperature changes north of 30 °N are mapped as the average temperature measured between 2001 and 2012 relative to the average temperature for the 30-year baseline period 1971 to 2000. Arctic temperature increases of 2 to 3 °C, compared with the smaller increases (0.5 to 1 °C) in mid-latitude regions, exemplify Arctic amplification of global climate change. Higher temperatures in all parts of the Arctic indicate a response to global change rather than to natural regional variability. SOURCE: Reproduced with permission from Jeffries et al. (2013). Copyright 2013, American Institute of Physics.

TABLE 2.1 Observed impacts of climate change in the Arctic reported in the literature since the Fourth Assessment Report of the IPCC. SOURCE: adapted from IPCC, 2014, Summary for Policy Makers

Category	Examples
Snow and Ice Rivers and Lakes Floods and Drought	Decreasing sea ice cover in summer (*high confidence*, major contribution from climate change) Reduction in ice volume in glaciers (*high confidence*, major contribution from climate change) Decreasing snow cover extent (*medium confidence*, major contribution from climate change) Widespread permafrost degradation, especially in the southern Arctic (*high confidence*, major contribution from climate change) Increased river discharge for large circumpolar rivers (1997-2007) (*low confidence*, major contribution from climate change) Increased winter minimum river flow (*medium confidence*, major contribution from climate change) Increased lake water temperatures (1985-2009) and prolonged ice-free seasons (*medium confidence*, major contribution from climate change) Disappearance of thermokarst lakes due to permafrost degradation in the low Arctic. New lakes created in areas of formerly frozen peat. (*high confidence*, major contribution from climate change)
Terrestrial Ecosystems	Increased shrub cover in tundra in North America and Eurasia (*high confidence*, major contribution from climate change) Advance of Arctic tree line in latitude and altitude (*medium confidence*, major contribution from climate change) Changed breeding area and population size of subarctic birds, due to snowbed reduction and/or tundra shrub encroachment (*medium confidence*, major contribution from climate change) Loss of snowbed ecosystems and tussock tundra (*high confidence*, major contribution from climate change) Impacts on tundra animals from increased ice layers in snow pack, following rain-on-snow events (*medium confidence*, major contribution from climate change)
Coastal Erosion and Marine Ecosystems	Increased coastal erosion (*medium confidence*, major contribution from climate change) Negative effects on non-migratory species (*high confidence*, major contribution from climate change) Decreased reproductive success in seabirds (*medium confidence*, major contribution from climate change)
Food Production and Livelihoods	Impact on livelihoods of indigenous peoples, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) Increased shipping traffic across the Bering Strait (*medium confidence*, major contribution from climate change)

BOX 2.2
ARCTIC-RELATED FINDINGS IN
CLIMATE CHANGE 2014: IMPACTS, ADAPTATION, AND VULNERABILITY

The physical, biological and socio-economic impacts of climate change in the Arctic have to be seen in the context of often interconnected factors that include not only environmental changes caused by drivers other than climate change but also demography, culture, and economic development.

The rapid rate at which climate is changing in the Polar Regions will impact natural and social systems (*high confidence*) and may exceed the rate at which some of their components can successfully adapt (*low to medium confidence*).

Impacts on the health and well-being of Arctic residents from climate change are significant and projected to increase – especially for many indigenous peoples (*high confidence*) (IPCC, 2014).

These *knowns* are important and establish the foundation for what we do next (Box 2.2). But there are other categories to consider as well, as indicated by the matrix in Table 2.2 that was inspired by R.D. Laing (1970):

If I don't know I don't know
  I think I know
If I don't know I know
  I think I don't know

Most of the reports we examined focus on what *we know we need to know,* following on as the consequences of what we *know*. We know that social and environmental changes are leading to increasing urbanization, but we do not know the consequences of this evolution. Warming promotes northward habitat migration and changing seasonal conditions, leading to new hotspots and dead zones in biological productivity, but we do not know where or when. We know that some of the thresholds we are reaching and crossing have analogs deep in the geological record, such as life in a previously ice-diminished and more acidic Arctic Ocean, and we need to explore those system circumstances and responses. We know that we have not profiled or sampled much of the central Arctic Ocean sediments, and that once we do, there are sure to be surprises in our understanding of geologic evolution.

Things *we think we don't know* are in an important category that is often neglected in scoping out research strategies. This includes things that are known in one community, but largely unknown in others. Traditional knowledge is one example: it has guided the livelihood of indigenous peoples for thousands of years, yet most people who do not live in the Arctic are unaware of its critical observations and known interconnections. Similarly, academic scientific findings, including analyses and interpretations, are often reported in venues and formats that are specific to a discipline, and not accessible or useable by others. Industry research is often proprietary, but could help answer questions if it were widely accessible. Questions posed by stakeholders and decision-makers, as they try to meet the challenges of the changing Arctic, are also important indicators of system responses that are not known by many in the academic Arctic research community.

Things *we don't know we don't know* are things that we cannot foresee at this point in time. They include aspects of the system that we have not yet considered, as well as surprise events after which nothing is the same. An example of this was the dramatic loss of the sea ice cover in the summer of 2007 to 23 percent below the previous record low in 2005 (Stroeve et al., 2008), followed by another dramatic decline five years later in 2012 to 50 percent of the sea ice cover only

30 years before (NSIDC[6]). To prepare for these events, we need to understand the present system, imagine the "what ifs," and be positioned to detect and respond. To understand the system, investments need to be made in fundamental, exploratory, and process research. To be in position to detect these changes and critical circumstances, we need comprehensive, long-term observing capabilities coupled with periodic snapshots of the entire system to establish baselines, as we did during the International Polar Year (2007-2009). And we need to be able to deploy resources quickly once change or an event is detected. This means that both logistics and funding need to be more flexible in terms of timing and also spatial distribution, from local to national and international scales.

The examples in Table 2.1 are illustrative of progress in understanding, issues of current research, informational obstacles that impede progress, and sources of surprises. The table is organized in the following categories: (a) why Arctic research is important (*knowns* are what we have learned), (b) why emerging questions are worth thinking about (*know we need to know* are where the next discoveries lie), (c) why we need continued research support and enhanced collaboration (things we *think we don't know* are holding us back if we continue to ignore them), and (d) why it's essential to be open to new things (*don't know we don't know* are where the surprises will come).

[6] http://nsidc.org/arcticseaicenews/2012/09/arctic-sea-ice-extent-settles-at-record-seasonal-minimum/

TABLE 2.2 Examples from the four categories of knowledge described in the text.

(a) Knowns	(b) Know we Need to Know
• Arctic is warming, more warming is likely • Changes in phase (increased ice loss/increased permafrost thawing) • Albedo reduction, reduced summer sea ice extent and thickness, reduced snow cover • Reduced glacier mass, leading to increased sea level rise and changes in hydrologic cycle • Increased greening • Increased variability and disturbances in Arctic systems • Increased accessibility and activity (e.g., resource exploration, shipping, tourism) • Changes in social, economic, cultural, and political systems • Ocean acidification • Threats to food security • Winter and spring data are lacking	• Identify biodiversity hotspots • Greater understanding of teleconnections • Adaptation and mitigation strategies • Sustainable development and resilience strategies • Seasonality of Arctic systems • Cumulative impacts of environmental and social change • Implications of urbanization • Impact of Arctic change on global climate change • Impact of ice loss and calving from Greenland on rate and magnitude of global sea level rise • Arctic atmospheric connections to mid-latitude weather • Community migration • Rate of change and associated implications • How to re-think Arctic engineering • Landscape evolution • Oceanic restructuring • Changes in marine and terrestrial primary production
(c) Think we Don't Know	**(d) Don't Know we Don't Know**
Knowledge that is known to one group but not others, including: • Traditional knowledge • Industry knowledge • Discipline-specific knowledge • Stakeholder and policy maker information needs • Unpublished or unarchived data	• Unanticipated and/or extreme environmental changes and events Knowledge that will emerge through: • Monitoring and long-term observations • Basic research and process studies • Model-observation intercomparison • Analysis of outliers in paleo data • Systems research and research at system interfaces • Exploratory research • Understanding system thresholds and transitions • Rapid response capability

3
Emerging Questions

Summertime heating at 71 °N on the central Baffin Island plateau in 2009 was sufficient to produce deep convection with accompanying thunder and lightning, events that were nearly unheard of in earlier decades. Photo credit: Gifford Miller

All global climate models forced with increasing greenhouse gases project that the Arctic will continue to warm at a rate greater than the rest of the globe, with concomitant losses in the ice and snow (IPCC, 2013) that form the fabric of the Arctic as we have known it (Figure 3.1). In each of the sections that follow, we identify and discuss in detail *emerging research questions* (those that we are only now able to ask, because they address newly recognized phenomena, use new technology or access, or build on recent results and insights). Research questions emerging from recent change and future projections include understanding the evolving Arctic, exploring what has been hidden due to lack of access or technology, investigating the ways Arctic change will affect the rest of the world, finding ways to manage reactions to change, and being prepared to detect and respond to surprises. Box 3.1 provides an example of these challenges with regard to the coastal zone, where our understanding depends on considering all parts of the system and on working across geographical and disciplinary boundaries.

We also acknowledge the importance of the ongoing research and high-priority questions that others have identified and continue to study, and we list examples of the kinds of *existing questions* that continue to motivate Arctic research. The Committee recognizes that the distinction between existing and emerging questions is somewhat arbitrary and that both sets of questions actually fall on a spectrum of research ideas that blend "existing" and "emerging" to varying degrees. Based on community input and extensive deliberation, the Committee characterized questions as existing or emerging based on the criteria in Box 3.2. The specific emerging research questions presented here are not intended to be comprehensive, but are intended to be representative of emerging topics that deserve attention. Based on community input received through two workshops, a number of interviews, an online questionnaire, and a review of relevant reports, the Committee considered hundreds of potential emerging questions. By their inclusion in this report, the Committee considers the high level topics presented in this chapter (Evolving, Hidden, Connected, Managed, and Undetermined Arctic) to be priorities for IARPC as a whole and leaves individual agencies to prioritize investments in these topics in accordance with their specific mission and goals. The questions in each section are numbered for easier reference and the numbering does not imply priority or relative significance. Prioritization is a collaborative exercise that requires continuing dialog and reassessment, and will best be achieved through an improved interaction between the scientific and policy communities. This is discussed in greater detail at the end of this chapter.

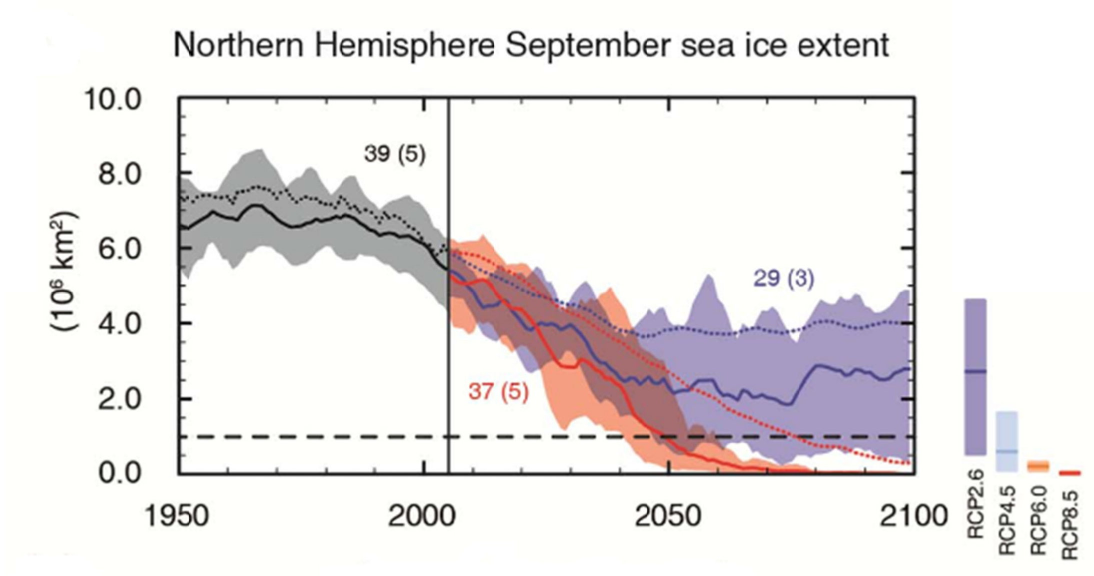

FIGURE 3.1 The Coupled Model Intercomparison Project -5 (CMIP5) produced this multi-model simulated time series from 1950 to 2100 for September sea ice extent in the northern hemisphere. The results are displayed as a 5-year running mean. Time series of projections are indicated by a solid line and a measure of uncertainty is indicated by shading. Projections are shown for two Representative Concentration Pathways. RCP2.6 (blue) and RCP8.5 (red) represent radiative forcing values in 2100 that are 2.6 and 8.5 W/m^2 greater than pre-industrial values, respectively. The solid black line (grey shading indicates the uncertainty) is the modelled historical evolution using reconstructed forcings. The mean and associated uncertainties averaged over 2081 2100 are given for all RCP scenarios as colored vertical bars. The number of CMIP5 models used to calculate the multi-model mean is indicated above and below the curves. The projected mean and uncertainty of the subset of models that most closely reproduce the climatological mean state and 1979 to 2012 trend of the northern hemisphere sea ice is given (number of models noted in brackets). For completeness, the CMIP5 multi-model mean is also indicated by the dotted lines. The black dashed line represents nearly ice-free conditions (i.e., when sea ice extent is less than 10^6 km^2 for at least five consecutive years). SOURCE: IPCC (2013), Figure SPM.7.

BOX 3.1
The Critical Coastal Zone

The coastal zone is a critical region. It lies at the interface where people, land, glaciers, and rivers meet the sea and sea ice. Conditions and relationships there change hourly when there is a storm, seasonally as fast ice grows and melts, and over years as coastlines are eroded. It is where populations have congregated for thousands of years and, therefore, where people face both their greatest threats and opportunities in the Anthropocene. Coastal zone issues cut across the emerging research questions in this Chapter: the Evolving, Hidden, Connected, Managed, and Undetermined Arctic.

In the coastal zone, the terrestrial transitions to the marine. Logistical requirements and agency responsibilities shift in this region and therefore, to some degree, scientific communities shift as well. Less than 10 percent of Alaska has contemporary shoreline data. In addition, shoreline conditions are not uniform, varying from mudflats, to sandy ice-cored cliffs, to river deltas, to tidewater glaciers. Sometimes the coast is highly populated, often it is not. This, coupled with the lack of research infrastructure along much of the Arctic coast, means that the coastal zone has not received as much attention as needed to understand its changing role. Coastal river output, for example, profoundly affects shelf stratification and circulation processes as well as discharging important dissolved and suspended materials to the ocean. Arctic rivers have a unique annual cycle in which a substantial fraction of their annual discharge, along with the largest fluxes of freshwater, suspended sediment, nutrients, dissolved and particulate organic carbon, and trace metals, occurs during a brief spring freshet (Alkire and Trefry, 2006; Rember and Trefry, 2004; Syvitski, 2002). These discharges and fluxes impact landfast ice and coastal dynamics as well as bacterial and algal production and carbon cycling. Potential consequences of climate change on this interface are poorly understood. Most general circulation models do not resolve the scales of the landfast ice zone or the coastal currents and so may fail to correctly "process" the terrestrial discharge. The evolution of estuarine shelves in response to alterations in the terrestrial hydrologic cycle is also uncertain, as is the role of changing terrestrial carbon in Arctic estuarine food webs (Dunton et al., 2006) and the impact of inputs of nutrients and organic carbon on the productivity of coastal systems, including coastal lagoons. Similarly, the tidewater glacier ice/ocean/sea ice/sea floor interface has long been known to be critical in determining glacier stability, but warming oceans and diminishing sea ice affect contributions to sea level rise.

While concerns about sea level rise and coastal erosion have been growing in recent decades, response to further changes cannot be delayed. This is true not only for Alaskan villages, but also for coastal communities in Florida and other low-lying regions that face similar threats. One of the most pressing questions of the Anthropocene is how to set priorities for relocations or infrastructure that may be needed, and how to pay for them (Huntington et al., 2012). What are the strategies in determining when to implement coastal protection zones or to abandon near shore areas to erosion and sea level rise? This is a discussion that society needs to face at the scale of communities, states, and nations. It will require a suite of foundational observations, models, and research, including social, cultural, and economic analyses to make such decisions.

FIGURE Coast Guard Base in Kodiak, Alaska. SOURCE: U.S. Coast Guard.

BOX 3.2
CRITERIA FOR IDENTIFYING EXISTING
AND EMERGING RESEARCH QUESTIONS

Existing Questions are those that have been the subject of ongoing research but remain unanswered or for other reasons deserve continued attention.

Emerging Questions are those that we are only now able to ask because they (1) address newly recognized phenomena, (2) build on recent results and insights, or (3) can be addressed using newly available technology or access.

EVOLVING ARCTIC

Emerging questions:

E1. Will Arctic Communities have Greater or Lesser Influence on Their Futures?

E2. Will the land be wetter or drier and what are the associated implications for surface water, energy balances, and ecosystems?

E3. How much of the variability of the Arctic system is linked to ocean circulation?

E4. What are the impacts of extreme events in the new ice-reduced system?

E5. How will primary productivity change with decreasing sea ice and snow cover?

E6. How will species distributions and associated ecosystem structure change with the evolving cryosphere?

In this section, we focus on the effects of Arctic change on the Arctic system itself. Already it is evolving at an unprecedented rate, and this is widely seen as just the precursor to what is in store (ACIA, 2005; AMAP, 2012). The most prominent physical change seen thus far is the evolution of the cryosphere, with cascading effects on the biological, chemical, and physical systems of the ocean, land, and atmosphere (Hinzman et al., 2013; Jeffries et al., 2013). These changes will cause large-scale disruption of current systems and infrastructure, offer new challenges and opportunities, and entail potential catastrophes (NRC, 2013).

At the same time, social, cultural, political, and economic changes have been rapid and widespread throughout the Arctic, manifesting themselves in various ways in different regions and at different times (e.g., AHDR, 2004). Cash economies have merged with or overtaken traditional modes of production and distribution. There has been a shift away from colonial relations and indigenous rights have been recognized in land claims settlements and the creation of new political arrangements such as Nunavut in Canada and Self-Rule Government in Greenland. Languages are being lost while other traditional practices are strengthened by new programs and institutions based in the Arctic. These and related topics are addressed in emerging questions in this section as well as in Connected Arctic and Managed Arctic.

The rate at which change is occurring may be more important than its magnitude, as both natural and social systems try to match their rate of adaptation to the rate of change. Extreme events and non-linearities, as well as abrupt or unanticipated changes, will challenge both natural and human systems. Many of these changes are immediately obvious, on time scales of days or weeks; however, the longer-term (years to decades) evolution of the system in response to these changes remains unknown. Also, although in many cases the direction of change is known, the critical

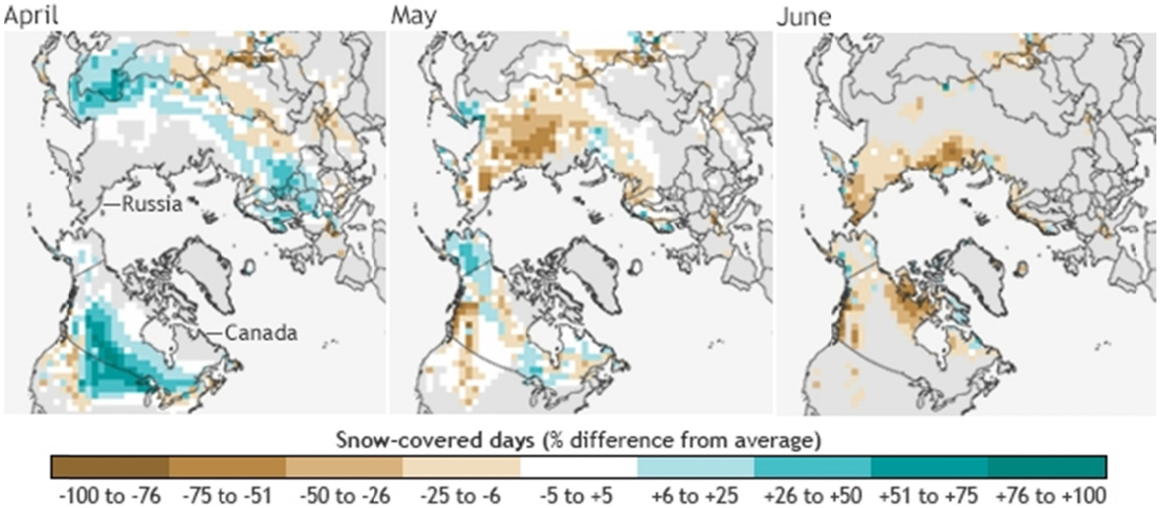

FIGURE 3.2 For up to nine months of the year, snow covers the Arctic land surface. Unlike sea ice and glaciers, most terrestrial snow cover is seasonal, melting and disappearing completely each spring and summer. The timing of this melt, which is influenced largely by surface temperatures, affects the length of the growing season, the timing and dynamics of spring river runoff, permafrost thawing, and wildlife populations. According to the 2013 Arctic Report Card, reductions in Arctic spring snow cover have "direct effects on the global climate system" because snow-free land absorbs much more sunlight. SOURCE: NOAA.

unknown is the rate of change. Due to both the rate of ongoing change and the profound impact of those changes on all facets of the Arctic system and its connections to other global processes, it is likely that the Arctic region will present some of the greatest challenges to our societies.

The Arctic cryosphere, or "frozen Arctic", is composed of permanent and seasonal sea ice, ice sheets, glaciers, lake and river ice, snow, and permafrost (Overpeck et al., 2005). During the last decade, changes in extent, thickness, and seasonal timing in all of these components have been observed, with the most prominent being the decline in summer sea ice extent in 2012 to a record low of 3.4 million square kilometers (NSIDC[7]), dramatic decreases in sea ice age, thickness, and volume (Perovich et al., 2013), and increasing trends of snow-free periods (~11 days/decade in spring and ~2 days/decade in autumn) at higher latitudes in North America (Derksen and Brown, 2012). In most regions, permafrost temperatures have increased over the past 30 years, and a general increase in active layer thickness has been observed as well, although there are large regional variations (IPCC, 2013). The rapid loss of permanent Arctic ice and the changing extent and timing of seasonal ice and snow cover (Figure 3.2) have important ramifications for multiple components of the Arctic system (Overpeck et al., 2005).

Focusing within the Arctic, the most visible manifestations of the future implications of the evolving Arctic are those connected with human activity. Already, ship traffic in the Arctic is increasing with expanded access due to decreased summer sea ice, and with concomitant greater risks of environmental disaster and threats to human safety (Arctic Council, 2009). Over 400 ships engaged in commerce, tourism, and research transited through Bering Strait in 2012, a dramatic increase from the just over 200 in 2008 (USCG, 2013). Passages, particularly of cruise ships and small personal vessels, through the still mostly icebound Northwest Passage are becoming commonplace, and the Northern Sea Route is now transited almost routinely by commercial vessels.[8] Interests in oil and gas reserves have boomed, accompanied by prospects of financial gain—including local and non-local employment. This development is accompanied by the risks of

[7] http://nsidc.org/arcticseaicenews/2012/09/arctic-sea-ice-extent-settles-at-record-seasonal-minimum/
[8] http://www.nytimes.com/2013/09/15/world/europe/russia-preparing-patrols-of-arctic-shipping-lanes.html

coastal and terrestrial environmental disturbance and stresses on local communities such as housing in villages (e.g., Lloyds, 2012). Permafrost degradation represents another potential impact on local communities and infrastructure. Increasing permafrost temperatures and active layer depth can have serious and costly effects on roads, buildings, and industrial facilities. Permafrost temperatures are projected to increase and this may lead to additional engineering challenges to infrastructure (ACIA, 2005).

With decreased sea ice have come more threats from weather, manifest as more frequent and more intense storms that threaten the now exposed Arctic coast and the human infrastructure on those coasts (Forbes, 2011). In the terrestrial environment, changes in the timing and extent of snow cover have wide-ranging ecological effects on soil, plant, and animal communities, as well as impacts on lakes, rivers, and wetlands, and on social and economic infrastructure. Snow also acts as an insulator for Arctic soils, and future increases in snow depth (predicted for the high Arctic during autumn and winter) may result in higher winter soil temperatures, increased biogeochemical processing of organic materials, and increased respiration (Vincent et al., 2011). The timing of snow is also critical as earlier winter snow can have an insulating effect, while late spring snow can have a cooling effect (Zhang, 2005). Ecosystems of the northern latitudes are most vulnerable to a changing climate because low temperatures and limited sunlight restrict species diversity, levels of primary productivity, and decomposition rates, and they also affect water and energy exchange processes.

The freshwater cycle plays a central role to every physical and biological process in the Arctic, so we cannot overstate its importance. The Arctic freshwater system is an inherent component of the global hydrological cycle, and as such plays an essential role in linking Arctic climate dynamics with the global system. The Polar Regions actually have a net negative annual average radiation balance, that is, more heat is emitted to space as long wave radiation than is absorbed from solar radiation. The total Earth energy balance must of course equal zero, so that energy deficit is made up by heat transported from lower latitudes, through hydrologic processes of moisture advection (latent heat) and dry static energy (sensible heat plus geopotential energy). In recent decades, several of the processes associated with the hydrologic cycle appear to have intensified (Rawlins et al., 2010; White et al., 2007). A major research question has been the cause of the significant increase in discharge of Eurasian rivers in the last century (Peterson et al., 2002), which now appears to be associated with significant increases in atmospheric moisture transport (Zhang et al., 2013b). Other important teleconnections have recently been identified but characterization of mechanisms remains elusive (Overland, 2014; Tang et al., 2013).

Regionality is as important as seasonality for understanding the evolving Arctic. System-level response will depend on where you are within the Arctic. Basins will respond differently from shelves, and inflow shelves driven by Atlantic and Pacific inflows (like the Barents and Chukchi) will respond differently from interior shelves strongly influenced by river discharge (such as the Siberian Sea). Examining regional differences in the responses of the physical, biological, and social systems of the Arctic will be an important component of addressing the emerging questions presented in this section.

Looking to the future, understanding the evolving Arctic poses multiple research questions and directions. Some of the most compelling questions center on the impacts of diminished ice and snow on the terrestrial and marine systems. A number of questions, such as the impacts of ocean acidification and of the loss of sea ice as a substrate for marine organisms, while extremely important and requiring continued research and funding support, are now so well recognized by both the science community and the general public that they are no longer “emerging” and therefore existing questions such as these will not be detailed here.

Examples of existing questions:

- What will be the climatic, ecological, and societal impacts of sea ice loss?
- How will changing seasonality in sea ice and snow cover affect trophic interactions?
- How is the Arctic/Northern Hemisphere hydrologic cycle changing, and how will those changes affect such processes as vegetation change, sea ice formation, sea water stratification, cloud properties, the surface energy balance, and potentially the Atlantic Meridional Overturning Circulation?
- What are the consequences of changing vegetation patterns and resulting responses by wildlife to ecosystem evolution in the tundra and boreal regions of the circumpolar north?
- How do Arctic clouds, aerosols, radiation and boundary layer processes drive change in the Arctic climate system?
- What will be the impacts of ocean acidification on marine species and ecosystems?
- How will climate-induced natural changes and associated human activities (e.g., shipping, interest in resource development) affect marine mammal populations?
- What are the short- and long-term implications of social, cultural, and economic change among Arctic peoples?
- How will the ecosystem and built infrastructure respond to widespread degradation of permafrost?
- How will rapid Arctic change affect the interactions between scientific discovery and policy making?

Will Arctic Communities have Greater or Lesser Influence on Their Futures?

As summer sea-ice cover decreases and a seasonally nearly ice-free Arctic appears increasingly likely within a few decades, interest in new trade routes and petroleum deposits continue the post-Cold War transformation of the Arctic from a military and hunter-gatherer region to one that embraces a wide range of social and economic aspirations (Åtland, 2009). Such a transformation will expose social-ecological systems to both negative impacts and positive opportunities.

While national and regional governments remain powerful agents of policy making, global markets, intergovernmental forums, and nongovernmental organizations play an increasing role in determining the attractiveness and viability of economic development in the Arctic. Perhaps more important, though, is the evolving role of Arctic communities and institutions. In particular, the role of indigenous and other local communities, in an era where knowledge networks and consultative processes can play a prominent role in policy formation, is plausibly much greater than ever before.

New and emerging research priorities need to focus on the ways that contemporary Arctic communities navigate and shape their evolving circumstances,[9] drawing on a tradition of flexibility, resilience, and adaptive capacity in an environment of high natural variability. The cascading effects of rapid change will stress these traditions in new ways (Hovelsrud et al., 2011; see Box 3.3). The assertion of indigenous rights and the capacity to exercise those rights are increasing in much of the Arctic. Research to date has identified the major institutional and environmental influences on Arctic communities, such as the role of government and the availability of fish and wildlife (AHDR, 2004). More work is needed to understand how these influences function, separately and together,

[9] http://www.nytimes.com/2012/09/19/science/earth/arctic-resources-exposed-by-warming-set-off-competition.html

BOX 3.3
ADAPTATION CHALLENGES IN COASTAL FISHERIES

Projected impacts of ocean warming in the North Atlantic include shifts in the spawning and feeding grounds of several economically significant fish populations, including Arctic cod, herring, and capelin (Loeng and Drinkwater, 2007). West and Hovelsrud (2008) note that these changes will have ramifications across a range of scales, from local communities to regional labor markets to national and international regulatory regimes. Existing successful adaptation strategies, involving flexibility in fishing location, timing, and species (Jentoft, 1998), are increasingly limited by environmental, economic, and management constraints and a progressively more globalized market. West and Hovelsrud (2010) employed a range of methods to address the impacts of, and cross-scale interactions inherent to, these adaptation challenges in the small Norwegian fishing town of Lebesby. They used climatic information from the Arctic Climate Impact Assessment (ACIA, 2005), statistics from national sources such as the Norwegian Directorate of Fisheries, ethnographic approaches (interviews, meetings, and participant observation), and published assessments of marine ecosystem dynamics to assess the adaptive capacity. Based on this comprehensive approach, West and Hovelsrud (2010) found that critical elements limiting the resilience of this community to change were (1) the mismatch between global market prices and local fish supply, and (2) problematic demographic shifts, including outmigration and an aging fisher population.

how these relationships are likely to change over time at local, regional, and global scales, and how Arctic communities can best exercise their adaptive capacity (the ability of a system to prepare for stresses and changes so that responses can be developed and implemented to minimize negative impacts in a timely manner). Lessons learned from Arctic communities will also be valuable for other indigenous and remote cultures facing similar stresses due to climate and other changes. At stake is the ability of Arctic communities to determine their own futures, to balance cultural, environmental, and economic needs as they, and not others, see fit. The alternative is that national and global forces dominate, leaving increasingly less room for Arctic communities to shape their own affairs. Reality is likely to include elements of both outcomes.

Will the Land be Wetter or Drier and what are the Associated Implications for Surface Water, Energy Balances, and Ecosystems?

Our ability to predict Arctic watershed and ecosystem evolution remains tenuous at best yet is critical to understanding the Arctic's evolving role in the carbon and hydrologic cycles, climate, and energy exchange processes. Most global climate models (GCMs) predict increases in both summer and winter precipitation in high northern latitudes (IPCC, 2013; Knutti and Sedlacek, 2013) although the magnitude and the rates of change remain uncertain. Most of the uncertainty is due to the ambiguity associated with selection of the correct emission scenario. In Arctic soils, ice-rich permafrost prevents infiltration of rainfall and snow meltwater, often maintaining a surface moist-to-saturated active layer, and can block the lateral movement of groundwater. But, as permafrost degrades, changes in interactions between surface and groundwater occur that affect the surface energy balance and essential ecosystem processes. As permafrost disappears, it will be replaced with seasonally frozen ground, bringing additional scientific and engineering challenges.

Significant changes have already taken place over the past 50 years in response to a warming climate (Lantuit et al., 2012; Soja et al., 2007) including thawing permafrost (IPCC, 2013 and references therein; Romanovsky et al., 2010; Figure 3.3), expanding shrub growth in the Arctic tundra (Sturm et al., 2001), drying of lakes (Carroll et al., 2011), and expanding growing seasons and increasing plant productivity (Walker et al., 2012).

FIGURE 3.3 Stable, cold permafrost (left) is often characterized by low-centered polygons, which form over centuries as massive ice wedges develop, creating the polygonal edges. As climate warms, the permafrost thaws and the massive ice wedges melt, causing subsidence of the surface and enhanced surface drainage networks (right). These disturbed sites are becoming more common and will continue to increase with continued warming and increases in wildfire or other such disturbance. Changes in surface condition affect ecosystems, trace gas fluxes, surface energy and water budgets, and runoff stream chemistry. SOURCE: Larry Hinzman.

Permafrost soils store almost as much organic carbon (approximately 1,670 Petagrams (Pg); Tarnocai et al., 2009) as is found in the rest of the world's soils combined. Tarnocai et al. (2009) have estimated that the soil carbon stocks in the Arctic may account for greater than 25 percent of global soil carbon stocks in the top meter and perhaps a third of the carbon stocks in the top three meters. Tremendous carbon stocks exist below three meters in deep ice-rich deposits of Eurasia and North America (Schirrmeister et al., 2011). Changing active layer and permafrost conditions and increased erosion would promote carbon loss from these huge stores. The short and long-term impacts to terrestrial and marine ecosystems are unknown. The potential carbon loss to the atmosphere is also largely unknown and of concern.

If warming continues as projected, large-scale changes in surface hydrology are expected as permafrost degrades (Hinzman et al., 2013). Where groundwater gradients are downward (i.e., surface water will infiltrate subsurface groundwater), as in most cases, we may expect improved drainage and drier soils, which would result in reduced evaporation and transpiration (ET). In some special cases, where the groundwater gradient is upward (as in many wetlands or springs), surface soils may become wetter or inundated as permafrost degrades.

Serreze et al. (2002) demonstrated that ~80 percent of high-latitude summer precipitation results from recycled evaporation. A decrease in evapotranspiration (ET) fluxes would therefore lead to a decrease in precipitation, all else being equal. Because GCMs do not currently include realistic treatment of permafrost impacts on surface hydrology, simulations of 21st century high-latitude climate change are more uncertain, and at this point it is not even possible to quantify these errors. Further, because soil moisture is a primary factor controlling ecosystem processes, interactions between ecosystems, and GHG emissions, the model predictions of such processes are also considered highly uncertain. These interdependent processes will exert primary controls on several important feedback processes, and they vary across space and time in some as yet unknown way. Important climate feedback processes associated with degrading permafrost include changes in latent, sensible, and radiative heat fluxes as the soils become drier or wetter, as vegetation changes, and as carbon emissions evolve.

Marked changes in surface structure and land-surface evolution are anticipated with continued warming in the Arctic. Numerous surficial landslides have been reported with increased summer thawing (Figure 3.4). Thermokarsts are examples of severe surface subsidence associated

FIGURE 3.4 Permafrost slump at Yukon River Bridge, adjacent to the Dalton Highway and Trans-Alaska Pipeline System. These slumps have become more common as permafrost thaws and the surface gives way in a landslide. SOURCE: Erik Bachmann, Alaska State Division of Geological and Geophysical Surveys.

with thawing of massive ground ice. They are usually enhanced by fluvial erosion and continued thermal degradation. Such landscape processes are altering drainage networks, usually increasing the density of drainage channels, but also increasing the sediment load and altering stream water chemistry, with consequent effects to aquatic and marine ecosystems, as well as human infrastructure and activities.

How much of the Variability of the Arctic System is linked to Ocean Circulation?

Recently, the National Academy of Sciences addressed the improvements needed in observations and models of both the sea ice and the atmosphere in order to enhance sea ice predictions (NRC, 2012b). A complementary issue is that the ocean also plays a critical role in the Arctic system but it is unclear how the present state of the Arctic and its future evolution are linked to the advection and mixing of oceanic heat and freshwater. In this regard, fundamental questions emerge pertaining to the Arctic Ocean's circulation, including the mechanisms, rates, and variability of its transport pathways, vertical and horizontal mixing processes, and the fate and dispersal of the waters flowing across its surrounding shelves. These processes span a broad spectrum of time (Schlosser et al., 1995; Bönisch and Schlosser, 1995) and space scales and are intimately linked to one another (Spall, 2013) and to the North Atlantic and North Pacific oceans. Alone and in aggregate these processes profoundly affect the Arctic's ice, atmosphere, and marine ecosystems.

There is a negative feedback between vertical mixing of heat and melting ice; an increase in heat flux enhances ice melt but increases vertical stratification, which then suppresses the heat flux shown by Martinson et al. (2001) in a model for the Weddell Sea in the Antarctic. It is not apparent how this feedback will be modified as ice thickness diminishes and, in the extreme, in a seasonally ice-free Arctic Ocean. For example, Pinkel (2005) has suggested that with a reduced ice cover, mixing by internal wave energy might increase greatly. On the other hand even small but sustained changes in the vertical mixing of heat may pre-condition the ice cover to more rapid melting (Polyakov et al., 2010). Oceanic heat and salt fluxes can occur through a variety of horizontal and vertical mixing processes, each of which varies in time and space (on both the basin and shelves) in response to changes in the Arctic's ice cover, stratification, boundary currents, and atmospheric forcing (Guthrie et al., 2013). The stratification of the Arctic Ocean also affects the cycling of nutrients and thus exerts important controls on primary production. An increase in stratification will inhibit the mixing of nutrients into the surface layer of the ocean and tend to suppress production. Understanding the factors that affect these turbulent fluxes in the Arctic Ocean is essential for understanding how the Arctic Ocean will evolve.

Over the last two decades, the Arctic has witnessed dramatic and rapid changes in the inflow of Atlantic Water (Polyakov et al., 2012; Schauer et al., 2008) that has resulted in warming in both the Eurasian (Morison et al., 1998; Polyakov et al., 2011; Quadfasel et al., 1991; Steele and Boyd, 1998) and Canada basins (Carmack et al., 1995; McLaughlin et al., 2009; Shimada et al., 2004). There have also been substantial changes in the oceanic accumulation of freshwater and the pathways by which freshwater (Morison et al., 2012; Proshutinsky, 2010) is transported through the Arctic Ocean. These changes are intimately linked to the wind, which forces ocean currents and/or causes changes in the thickness of the upper ocean layer (Yang, 2006). Moreover, the structure of the boundary currents varies in time and location due to local and remote winds and buoyancy forcing (Pickart et al., 2011). There have also been significant changes in the seasonal phasing and volume of river discharge into the Arctic (Shiklomanov and Lammers, 2011) and the fluxes of heat and freshwater through the Bering Strait (Woodgate et al., 2012).

Arctic climate models exhibit substantial differences among themselves and with observations in their ocean temperature and salinity distributions and circulation (Holloway et al., 2007; Holloway et al., 2011). While essential ocean physics may be missing from many models, explicitly capturing the structure of boundary currents, eddy formation and decay, and mixing represent substantial hurdles for the present generation of Arctic atmosphere-ice-ocean models (Newton et al., 2008). Currently we possess only a rudimentary understanding of the time-varying nature of these processes and then at only a few locations and for limited time periods. It also appears that a major driver of the cyclonic circulation of the Atlantic Water is the salinity contrast between the high salinity Atlantic Water flowing in the boundary currents and the low-salinity shelf water entering the basin (Spall, 2013). This implies that the response of the Arctic Ocean depends critically on several issues; 1) processes in the North Atlantic Ocean that establish the thermohaline properties and mass transport of the Atlantic Water entering the Arctic Ocean, 2) the fluxes through the Bering Strait (which depend upon North Pacific Ocean processes), and 3) mixing and dispersal of the riverine discharges rimming the basin. The latter two contributions are subsequently modified upon crossing the continental shelves surrounding the basin.

Arctic continental shelves are enormous, occupying 35 percent of the Arctic Ocean area. They support important cultural and subsistence resources for local residents and are the most likely marine region where substantial increases in human industrial activities will occur in the near future. The shelves also serve as the Arctic Ocean's estuaries in regulating the fate and dispersal of both the Arctic's river discharges (of which many are large and flow year-round) and their dissolved and suspended burdens. They are the site of the largest changes in sea ice extent and seasonality in the Arctic Ocean, but the extent to which changes in winds, air-sea heat fluxes, and shelf currents affect the shelf sea ice environment has hardly been addressed. An unresolved issue is how the estuarine role of shelves will evolve in response to alterations in the terrestrial hydrologic cycle and a changing landfast ice regime.

What are the Impacts of Extreme Events in the New Ice-Reduced System?

The evolving Arctic increases the potential for unpredictable and extreme events such as storms, wildfires, and anomalous precipitation. Increased storminess and cyclone activity, particularly in the Western Arctic, has been documented (McCabe et al., 2001), as have the relationships between Arctic sea ice transport and cyclones (Maslanik et al., 2007). More recent changes in Arctic climate, combined with record reductions in minimum sea ice extent, suggest a qualitative shift in the Arctic atmospheric circulation (Overland et al., 2012).

The complex interplay between Arctic storminess, sea ice cover, and upper-ocean structure is an active and intriguing question. Increased storminess may contribute to the degradation and reduction in summer sea-ice extent, as demonstrated with a modeling study for the summer of 2012 when a massive cyclone (Figure 3.5) transited the western Arctic (Zhang et al., 2014). Furthermore, the reduction in summer sea ice and the increasing frequency and severity of storms has direct impacts such as elevated sea state and the accompanying increased flooding, erosion, and incidence of *ivu* (ice pile-up on shore), with attendant threats to human infrastructure and well-being (Lynch et al., 2008). Severe storms may also have significant impacts on the marine ecosystem. Effects range from loss of sea-ice substrate through mechanical disruption to increased primary production in response to increased nutrient availability through vertical mixing, to increased upwelling of high pCO_2 waters into shallower depths (e.g., Mathis et al., 2012; Zhang et al., 2013a). For coastal ecosystems, storm surges of seawater into lakes promote replacement of endemic taxa with brackish water species (e.g., Thienpont et al., 2012).

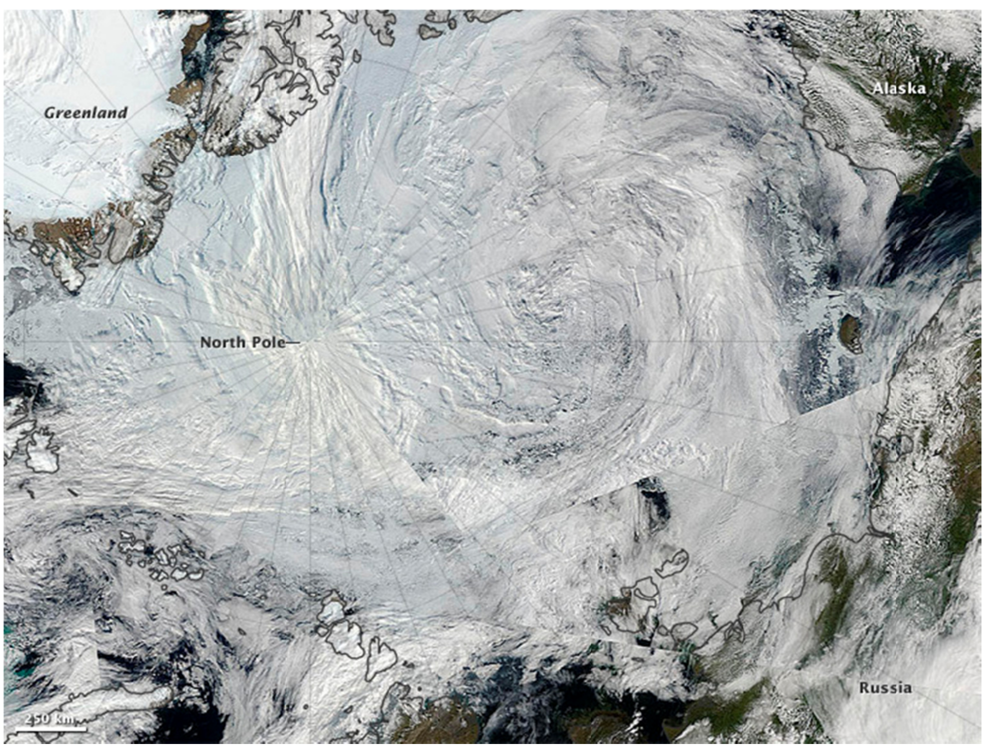

FIGURE 3.5 The great Arctic cyclone of 2012. This image from August 6, 2012 shows the cyclone centered in the middle of the Arctic Ocean. SOURCE: NASA Earth Observatory.

Greater frequency and severity of storms increases the threat of wildfire ignited by lightning strikes. The potential for wildfire is also associated with soil moisture conditions and the availability of fuel. Warmer and drier climate change scenarios project greater wildfire frequency, extent, and severity in the high northern latitudes (Balshi et al., 2009; Flannigan et al., 2005). Wildfire was identified as a major emerging issue by the North Slope Science Initiative (NSSI). Recent observations of the wildfire patterns in boreal regions have revealed increasing trends in size and frequency, attributed to a warming climate (Kasischke and Hoy, 2012; Kasischke and Turetsky, 2006). Tundra fires have been historically rare events on Alaska's North Slope (Barney and Comiskey, 1973) with a total of 122 wildfires since the Alaska record began in 1950. An unprecedented wildfire in terms of size, severity, and duration occurred on Alaska's North Slope in 2007 (Anaktuvik fire, 103,600 ha) and burned from July to September in tundra (Jandt et al., 2012). Wildfire in tundra and taiga transition zones has not been thoroughly mapped or recorded. Observations of storms, lightning strikes, fire frequency, extent and severity are needed in the tundra to determine whether the fire regime is changing.

On land, heavy rain-on-snow is expected to become increasingly frequent in the Arctic, with potentially large consequences resulting from changes in snowpack properties and ground-icing. Winter rainfall and thaw-refreeze events can form an impenetrable ice layer within the snowpack that restricts grazers' access to forage plants, however effects on both plants and animals associated with winter thaw-refreeze events remain unclear (Rennert et al., 2009). There is some evidence that extreme rain-on-snow events can lead to widespread mortality or range displacement of reindeer, caribou, and muskoxen (Stien et al., 2010). However, observations of the frequency, timing, extent, and size of thaw-refreeze events, at relevant scales, remain limited.

Even in the absence of winter rain, extreme winter warming events that subsequently expose plants to cold winter air may lead to the loss of overwintering flower buds that will not produce flowers the following summer (Semenchuk et al., 2013). While many species are resistant to exposure, exposing flower buds to cold winter air can lead to large population and community changes. There is also evidence of disruption of fish habitat following winter breakup of river ice. The potential for future warming to increase the frequency, extent, and severity of winter rain events, with potentially widespread consequences for plants and animals that depend on access to sheltered subnivean (occurring under the snow) space will require collaboration across several disciplines and enhanced meteorological monitoring systems at scales appropriate to detect these changes.

Additional potential extreme events include an unprecedented meltback of summer sea ice and a terrestrial or marine anthropogenic environmental disaster such as an oil spill (e.g., the *Deepwater Horizon* explosion and oil spill in the Gulf of Mexico). There is a need for development of models and other decision-support tools, policies, and strategies for hazard mitigation, including assessing community and ecosystem risks and preparing response strategies.

How will Primary Productivity Change with Decreasing Sea Ice and Snow Cover?

The concept that increased availability of sunlight to primary producers, either through reduction in sea ice and snow cover in the ocean or through reduction in snow cover on land, will lead to increased primary production seems intuitive. However, primary production is also dependent on the availability of nutrients and, in terrestrial systems, on soil moisture and temperature.

Surprisingly high levels of marine primary production and chlorophyll standing stock have been observed recently at some locations. For example, Arrigo et al. (2012) reported a massive under-ice phytoplankton bloom of unprecedented magnitude and far (100 km) from the ice edge that appears to have been promoted by light penetration through melt ponds in the overlying sea ice. There is increasing awareness of the importance of melt ponds and that melt ponds may become more numerous and ubiquitous given the thinner seasonal sea ice (Frey et al., 2011). These melt ponds may promote greater primary production by ice algae, potentially at the expense of water-column phytoplankton blooms because of competition for nutrients between the two types of primary producers. The ubiquitous presence of ice-edge blooms is now also recognized, with new analyses of satellite data (Perrette et al., 2011). Whether these increased productivities are new, in response to the changing environment, or are newly recognized due to increased capability or opportunity for study, is at present unknown.

Each summer, the euphotic zone (upper layer that supports photosynthetic activity) of the ocean is depleted of nutrients well before winter sea ice has formed and the Arctic has entered the sunlight-devoid polar night. This would suggest that unless nutrients are replenished in the euphotic zone from regeneration, vertical mixing, or external inputs, then marine primary production will not increase substantially with increased availability of light. Over much of the Arctic, vertical mixing of nutrients is unlikely given the strength of the pycnocline unless that feature is eroded by warming of the deeper Atlantic Water below or by mixing (e.g., Rainville and Woodgate, 2009). However, the reduced sea ice extent and greater area of open water may promote increased inputs of nutrients to the euphotic zone through physical processes such as shelf-break upwelling (e.g., Pickart et al., 2013). Increased riverine input of nutrients, a consequence of permafrost thawing and release of nutrients, as well as increased advective input of nutrient-rich water from outside the Arctic may increase ocean euphotic zone primary production (e.g., ACIA, 2005; Holmes et al., 2013). By contrast, increased freshwater in the Beaufort Gyre resulting from increased ice melt has deepened the pycnocline and nutricline there to below the bottom of the euphotic zone (McLaughlin and Carmack, 2010). Ultimately, whether marine primary production increases in the future will depend on a complex balance of physical factors that are evolving in response to the changing cryosphere.

In the Arctic terrestrial environment, earlier snowmelt and longer growing seasons lead to increased vegetation productivity, often referred to as "greening" (Bhatt et al., 2010; Walker et al., 2012; Figure 3.6). Warming soils and deepening active layers provide a more tolerant environment for a greater diversity of plant species and increased productivity, and thus there has been a rapid expansion of woody shrubs into tundra (Myers-Smith and Hik, 2013). This greening of the Arctic is visible from space, and although warming and greening is documented in North America, some areas in northern Russia and along the Bering Sea coast of Alaska are cooling and vegetation productivity is declining (Post et al., 2013), perhaps a consequence of changes in atmospheric circulation patterns over the Eurasian continent in summer (Tang et al., 2013). Gamon et al. (2013) observed that productivity in Alaska was associated primarily with varying precipitation and soil moisture, and only secondarily with growing degree days, which can lead to reduced primary productivity in years with earlier snowmelt.

Recent observations, however, call into question the assumption that earlier Arctic growing seasons will lead to greater vegetation productivity, indicating that better calibrated observations will be necessary to adequately forecast future changes in Arctic terrestrial productivity. In situ monitoring of actual vegetation responses using field optical sampling is needed to obtain detailed information on surface conditions that cannot be extracted from satellite observations alone (Gamon et al., 2013).

How will Species Distributions and Associated Ecosystem Structure Change with the Evolving Cryosphere?

Arctic ecosystems and the biodiversity they support are under increasing pressure from environmental and societal changes occurring at multiple spatial, temporal, and organizational scales. Species-poor Arctic ecosystems tend to lack functional redundancy and so are potentially vulnerable to cascading effects from the loss of a single species. As the Arctic evolves,

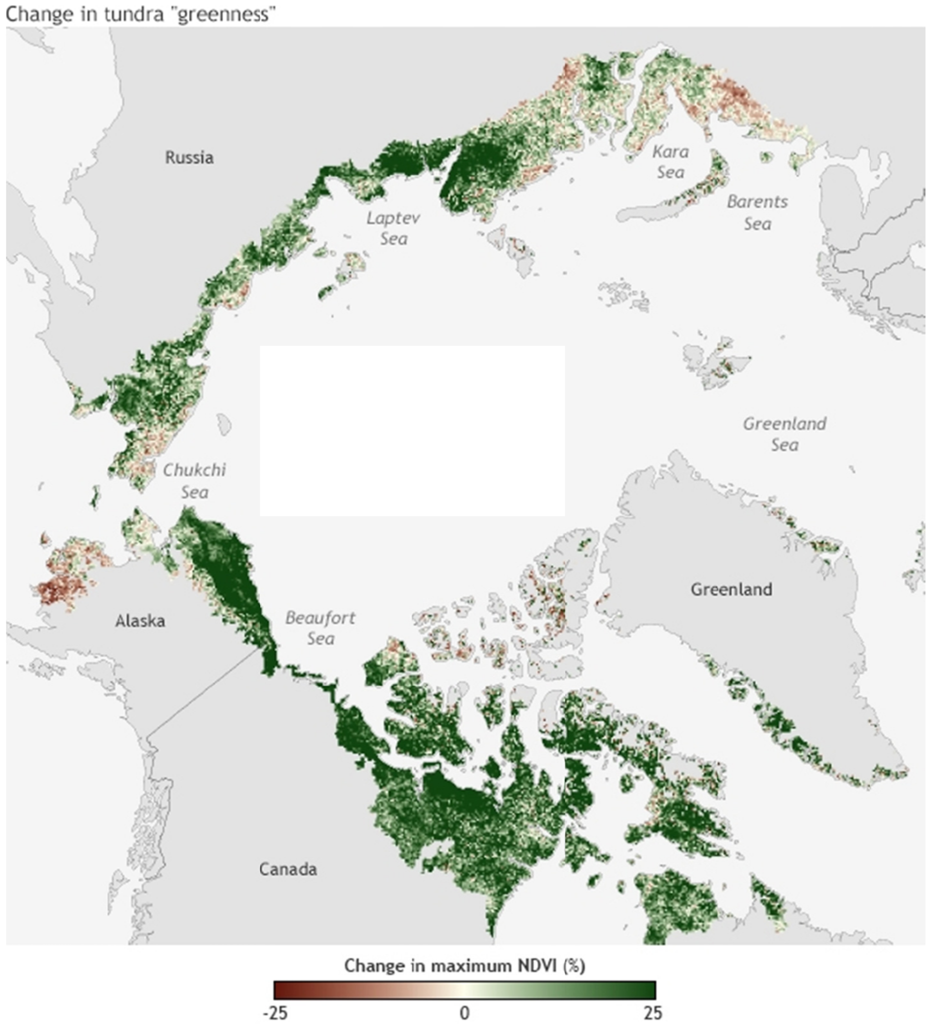

FIGURE 3.6 Land areas adjacent to newly opened water in the Arctic are becoming "greener." Since observations began in 1982, Arctic-wide tundra vegetation productivity has increased. In the North American Arctic, the rate of greening has accelerated since 2005. SOURCE: NOAA.

some organisms will succeed and some will fail. There will likely be poleward shifts in major marine and terrestrial biomes, with the Arctic Ocean geographically limiting the shifts of terrestrial species. The species that succeed will be those that can successfully adapt to and exploit the changing environment by expanding their geographic range and prominence (abundance, dominance) in the ecosystem through more successful recruitment, survival, and competition. The species that fail will be those that cannot successfully adapt because of ecological factors including physiological intolerance, phenological mismatch with the environment, and inability to compete. These species will decrease in importance in the ecosystem and may become locally or regionally extinct.

Species changes will have significant impacts on food web structures and may result in drastically modified ecosystem function. A shift in the phytoplankton community of the Canada Basin from larger to smaller species (Li et al., 2009) has already resulted from freshening caused by sea ice melting and increased river discharge. The northern Bering and Chukchi Seas are at present benthically-dominated, with much of the ice algal and phytoplankton primary production being used by a rich benthic community (e.g., Campbell et al., 2009; Grebmeier, 2012). With decreased seasonal sea ice, one scenario is that these ecosystems could transition to a pelagically-dominated structure, with greater biomass retained in the water column (including the emergence of abundant pelagic fish).

Changes in permafrost are likely to have a large impact on terrestrial ecosystems, particularly forests. The softer soil that results from permafrost thaw interferes with tree root systems, creating "drunken forests" (e.g., Figure 3.7). White spruce in Alaska's tundra have been growing faster in warmer temperatures (Andreu-Hayles et al., 2011) and further research is needed to understand whether this result will be seen in other forest types or whether trees will instead be stressed by warmer temperatures (Figure 3.8). Warming will likely result in a poleward migration of the northern treeline as well as shrubs invading the tundra. The cascading ecological impacts (e.g., on bears, caribou, small mammals, and insects) and potential geographic limitations on shifts in boreal forest cover are unknown. In the tundra, shrubs are replacing lichens and other tundra vegetation (USGCRP, 2009). Recent evidence indicates that coastal permafrost thaw and associated sedimentation has facilitated a shift in Black Brant goose (*Branta bernicla nigricans*) population distribution from inland lakes to coastal areas (Tape et al., 2013).

Species with value to small local communities may become more available, as already seen with the increased catches of salmon in the northern Chukchi Sea (Carothers et al., 2013). Increasing abundances of commercially important pelagic fish, or benthic invertebrates, could result in the development of new Arctic fisheries, once sufficient understanding of the ecosystem is available to sustainably regulate that activity. However, new Arctic fisheries may have different social and economic impacts on different communities and groups, as some may have declining opportunities while the opportunities of others improve. Locally important terrestrial species may

FIGURE 3.7 Trees in this Alaska forest tilt because the ground beneath them, which used to be permanently frozen, has thawed. SOURCE: NOAA.

FIGURE 3.8 Researchers sample a dead spruce at treeline in northeastern Alaska. SOURCE: Susy Ellison.

decline. For example, caribou are an important food source for some indigenous communities, and they in turn rely on the lichen that is being replaced by shrubs in some parts of the tundra (USGCRP, 2009). Changing ranges of species and populations of species also affect genetic diversity and increases the potential for hybridization between congeneric species, such as between the *Calanus glacialis* and *C. finmarchicus* in the eastern Arctic (Parent et al., 2012) and between grizzly (*Ursus arctos horriblis*) and polar bears (*Ursus maritimus*; Kelly et al., 2010).

Trophic interactions modulate ecosystem responses to climate change in the Arctic (Post et al., 2009). For example, herbivory (e.g., grazing by reindeer and muskoxen) shapes plant productivity and community responses to warming, which may, in turn, be mediated by changes in predator or decomposer communities. These interactions are fundamental in shaping complex feedback processes between consumers and resources. These processes are not easily captured by studies of dynamics at single trophic levels and more detailed studies are required to determine the role of climate warming in trophic dynamics (e.g., Roslin et al., 2013), especially in aquatic systems, soils, and sediments.

Warming changes the ecology of infectious agents and influences the emergence of disease in humans, domestic animals, plants, and wildlife. For example, warming in the Arctic has altered the transmission, development rates, and distribution of an important parasitic nematode of muskoxen in the Canadian Arctic (Kutz et al., 2005). The potential for new and expanded parasite and disease pressures for wildlife will have ramifications for northern communities, and the subsistence harvest of species that sustains many of these populations. Changing distributions of disease-bearing insects such as ticks (Lyme disease), parasites, or pathogens (e.g., the skin disease affecting seals and walrus observed in the Chukchi and Beaufort Seas) could have both direct and indirect negative impacts on humans. However, there is only a very basic foundation for understanding responses to climate change of other host–parasite systems in the Arctic (Kutz et al., 2005).

Looking ahead, when summer sea ice is gone, and light limitations are lessened in spring through summer and autumn, what will be the next rate-limiting factor that will determine the ecology? Perhaps iron? How will the northernmost land fauna adapt to a warming climate, when they are unable to migrate farther north? As the Arctic readjusts to new conditions, what potential trophic flips are in store?

HIDDEN ARCTIC

Emerging questions:

H1. What surprises are hidden within and beneath the ice?

H2. What is being irretrievably lost as the Arctic changes?

H3. Why does winter matter?

H4. What can "break or brake" glaciers and ice sheets?

H5. How unusual is the current Arctic warmth?

H6. What is the role of the Arctic in abrupt change?

H7. What has been the Cenozoic evolution of the Arctic Ocean basin?

The Arctic has long been hidden from most of Earth's inhabitants. Physical access to key archives has been limited by sea ice cover, terrestrial ice cover, lack of research icebreakers, lack of terrestrial infrastructure, limited access, and the sporadic nature of international research campaigns. Much of what was previously concealed by logistical challenges is becoming increasingly accessible, aided by reduced sea ice, greatly improved remote sensing, and advances in instrumentation, analytical tools, and observational platforms. This means we can now discover what has long been unseeable.

However, significant logistical, political, and financial challenges remain to fully capitalize on these new opportunities. Much of our current research is centered around hypothesis testing, through proposals designed with convincing evidence of feasibility. The rapid changes that are anticipated in the coming decades include the likely threshold behavior and challenges to resilience that are less well understood than steady state processes (see Investing in Research section in Chapter 4).

As both sea ice and glacier ice retreat, what surprises will be revealed that had been hidden from view? How will land ice retreat? How will accelerated melting and glacier dynamics affect ice loss, and therefore rates of sea level rise? Now that we will be able to access the Arctic basin more easily, what will we learn about the geologic evolution of sea ice loss?

What will the future Arctic look like? Archives in the sediments beneath the sea and lakes, along with records from within and beneath glacier ice can tell us a great deal about how the Arctic responded during warm periods in the geologic past. Similarly, both sediment and ice archives help in understanding the Arctic's role in abrupt change.

Examples of existing questions:

- What will we learn about the Arctic's past from sedimentary archives accessed through lake and ocean drilling and proxies contained in ice cores?
- How is the large-scale opening of the Arctic shelves changing interactions among ice, ocean, atmosphere, ecology, and society?
- What surprises will be revealed as we map the Arctic?
- What new perspectives will be revealed through genomic and microbial analyses?

What Surprises are Hidden Within and Beneath the Ice?

Within the Permafrost

Permafrost holds vast stores of carbon, including gas hydrates (sometimes called methane clathrates). What are the consequences of releasing subsea gas hydrates or terrestrial methane and CO_2 held in permafrost? The potential for rapid release of methane, as may already be occurring from permafrost areas on the shelf of the East Siberian Sea, is a possibility but poorly understood (IPCC, 2007). About 10,400 gigatonnes of methane are currently stored in hydrate deposits, more than 13 times the amount of carbon in the atmosphere (Dickens, 2003; Kennett et al., 2008). The potential for exploitation of gas hydrates is also of great interest in many areas, including the Arctic, but with uncertain prospects for commercial application. Tremendous stores of carbon (over 1.7 gigatonnes) are also trapped in terrestrial permafrost, almost twice the amount of carbon present in the atmosphere (Schuur et al., 2009). The potential consequences of carbon release from these reservoirs remain poorly understood.

The frozen, dark, oxygen-deprived environment beneath ice sheets where there is no basal flow, beneath permanent snowbanks, and within permafrost is ideal for the preservation of organic remains and biomolecules (e.g., DNA) that otherwise have poor preservation potential if subaerially exposed. Unexpected finds of organic human artifacts as snowbanks have melted back in Alaska have offered new revelations about the early human enterprise (Dixon et al., 2007), ancient mammal DNA in bones recovered from permafrost allow reconstruction of population density changes through time (Shapiro et al., 2004), rooted tundra plants entombed for millennia but now exposed by receding ice caps allow insights into past summer temperatures (Miller et al., 2013) and ancient DNA preserved in newly exposed soils may allow greater fidelity in the reconstruction of ancient environments.

Within the ice

Various physical and chemical proxies preserved in ice cores, particularly from Greenland and Antarctica, have provided some of the most compelling evidence for abrupt climate shifts in the past and for changes in atmospheric composition and circulation on timescales of decades to millennia. It is reasonable to presume that there remain unrealized proxies preserved within the ice that future research may uncover. The unparalleled resolution and age control that make ice cores optimal archives of the past warrant continued searches for new environmental proxies in ice.

Beneath the Ice

In many settings thin ice caps on low-relief terrain act as preservation agents, rather than erosive agents, preserving intact even the most delicate features of the pre-glacial landscape, including rooted tundra plants and the soils in which they lived, that are now being revealed as ice caps recede under unusually warm summers. Rooted tundra plants that have been entombed for millennia allow insights into past summer temperatures (Miller et al., 2013) and ancient DNA preserved in sub-ice soils allows greater fidelity in the reconstruction of ancient environments (Willerslev et al., 2007). Within one to three years of subaerial exposure, these important widespread climate and environmental archives are lost forever, emphasizing the emerging need for comprehensive sampling as ice caps rapidly recede.

For up to nine months landfast sea ice mantles the shallow shelves fringing the Arctic coasts of North America and Eurasia that receive the bulk of the river runoff to the Arctic Ocean. The landfast ice zone also encompasses areas of shallow sub-sea permafrost so thermodynamic perturbations to this zone may have consequences on methane release from the seabed. Much of our understanding of wind- and buoyancy-forced shelf circulation derives from mid-latitude studies, but we cannot readily transfer these lessons to the Arctic when landfast ice shields the underlying shelf waters from the direct influence of the wind. The landfast ice zone dynamically partitions the shelf into two regions, one where winds and drifting ice govern the circulation and one where shorefast ice controls the inner shelf flow. River outflows form shallow, buoyant currents that are typically restricted to within 20 km of the coast (Chant, 2011) so that their natural trapping scale is within the width of landfast ice zones. Models suggest sluggish along shore, under-ice flows, ice-edge jets, and complicated secondary cross-shelf circulation cells that inhibit mass and material exchanges with the outer shelf (Kasper and Weingartner, 2012). These dynamical differences have implications for the transport of contaminants introduced into shelf waters and they suggest that biogeochemical processes might evolve quite differently between the two portions of the shelf. Understanding these issues has implications for the formation of dense shelf waters in winter, the seasonal evolution of shelf stratification, and the fate of materials borne by the plume. It also has implications pertaining to the biological "connectivity" of adjacent shelves, since buoyancy-forced coastal currents are potentially capable of flowing along vast shore distances.

What is Being Irretrievably Lost as the Arctic Changes?

The loss of snow and ice is uncovering parts of the Arctic, but at the same time much is being lost. Coastal and riverbank erosion threatens villages and archeological sites (Brunner and Lynch, 2010; GAO, 2003; Lochner, 2012; Figure 3.9). Nearly all coastal sites are being impacted by erosion due to changing sea levels and stronger storms that are destroying archeological sites that have never been documented because of the vast extent of the coastline. Archeological sites are also at risk from a rising water table due to sea level rise (e.g., Coffrey and Beavers, 2013). Well-preserved organic artifacts previously protected within the cryosphere are being exposed by retreating ice (e.g., Andrews and MacKay, 2012). The least understood and documented loss is that of riparian sites due to ice jam floods and riverbank erosion (e.g., Ott et al., 2001). This loss of information affects future excavations and our understanding of how people adapted and lived in the past. This record is now recognized to have major value to bioscience (aDNA, stable isotopes, etc.), paleoclimatology, and culture, and has huge potential for expanded joint investigation. Iceland and Greenland, for example, offer the rare combination of archeological sites and contemporaneous written records, but many are threatened by thawing and decomposition. This threat is urgent and widespread. There is a great need for coordinated logistics, combined international resource application, and well-designed response strategies that will combine mitigation with a coherent interdisciplinary science program.

Ecological communities, too, are at risk. Unique freshwater ecosystems on the ice shelves of Ward Hunt and Ellesmere Islands in the Canadian Arctic have been lost as the ice shelves disintegrate (Mueller et al., 2003) and freshwater drains to the ocean or mixes with seawater in the absence of ice barriers. The loss of Arctic features and phenomena that are poorly understood or even unknown is a major challenge, especially if they are in remote areas where access is difficult, reducing the chances of discovery and hindering any research efforts even if discoveries are made.

Climate and environmental change is not the only cause of loss in the Arctic. Arctic languages are also being lost rapidly (Barry et al., 2013) due to social and other changes. A wealth of cultural practice and traditional knowledge is lost as languages diminish and disappear. While not a new trend, language loss may be increasing in the face of modern media and telecommunications. At the same time, however, information technology and education reforms have provided new ways to support and perpetuate the use of languages spoken by relatively few people, providing hope for a change in the overall trend.

Difficult decisions may be necessary concerning what can be saved and what cannot. The capability for rapid response in cases of imminent disappearance requires funding, logistics,

FIGURE 3.9 A nearly century-old whaling boat in July 2007 along the Beaufort Sea coast near Lonely, Alaska. The boat washed away to sea just a few months later due to erosion. SOURCE: Benjamin Jones, USGS.

cooperation, and other planning (see Chapter 4). Awareness of what is being lost is only a first step, but a critical one.

Why Does Winter Matter?

Winter occupies the bulk of the Arctic year. Winter conditions and processes, including ice formation and snow build up, determine the timing and patterns of snow and ice melt in spring, thus affecting physical and biological environments as well as climate feedbacks. With the observed changes in seasonality, it is increasingly important to understand what happens in the winter, and how winter processes affect conditions for the rest of the year.

Only a few studies to date have focused on this period of the annual cycle, especially in the biological sciences, in part because of a misplaced perception that the systems are essentially dormant during winter and in part because of difficulty in accessing those ecosystems due to the harsh winter conditions and the barrier of sea ice or of deep snow. This relative lack of knowledge has compromised our ability to understand the winter ecology of many organisms and to model these systems over the full annual cycle, ultimately limiting our ability to predict the ecosystems response to ongoing climate change.

Hidden beneath sea ice and snow, the ecology of the winter biota of the Arctic marine and terrestrial systems remains elusive. We now understand that rather than being dormant or dead during winter, the biota of the marine and terrestrial ecosystems retain some activity during the cold, dark winter months (e.g., Darnis et al., 2012; Sturm et al., 2005). We also now have the technology to better study aspects of these systems during this forbidding period of the year. The reduction of thick, multiyear ice over a significant portion of the Arctic Ocean also may permit greater access by research vessels during winter.

In the ocean, winter conditions are critical to the present-day density stratification that defines much of Arctic oceanography, and changing stratification is key to heat storage and energy release. Process studies are needed to understand how future winters may differ from today. If summer is ice free and the halocline breaks down through strong wind mixing and other processes, what will be the impact on winter ice formation in the central Arctic Ocean (see Evolving Arctic question 3)? Wind mixing is usually only significant down to 10 m, thus it is not likely that wind alone will destroy stratification. But with changing conditions in the shelf seas, stratification may be weakened enough to allow large polynyas to develop where deep convection could occur within the Arctic Ocean. An Antarctic analog for this is the Weddell Sea (Gordon et al., 2007). How could such a change impact local changes in marine ecosystems as well as global redistribution of heat through the Atlantic Meridional Overturning Circulation (AMOC; see Connected Arctic question 3)?

What Can "Break or Brake" Glaciers and Ice Sheets?

Over the last decade, Arctic ice masses, in particular the Greenland Ice Sheet (GrIS), have continued to offer new surprises. Supraglacial lake water has been shown to hydrofracture through more than a kilometer of ice to reach the bed, causing localized acceleration of ice flow (Das et al., 2008; Joughin et al., 2013; Zwally et al., 2002), with local effects propagating inland through stress coupling (Price et al., 2008). Meltwater and subglacial hydrology has been shown to be an important, yet poorly understood, control on sliding dynamics (Shepherd et al., 2009; Schoof, 2010). Water produced from surface melting may refreeze at depth resulting in englacial (within the glacier) warming from latent heat release (Phillips et al., 2013) and/or it may persist in storage, both englacially and subglacially (Rennermalm et al., 2012) as well as in saturated zones of glacial firn (ice that is in the intermediate stage between snow and glacial ice; Forster et al., 2013; Humphrey et al., 2012). Outlet glaciers from the GrIS have undergone rapid fluctuations in flow speed and calving rate (Howat et al., 2005; Howat et al., 2007; Joughin et al., 2004; Joughin et al., 2008). Increases in flow velocity have propagated to the north (Khan et al., 2014; Rignot and Kanagaratnam, 2006). Large "Antarctic scale" calving events have begun in North Greenland outlet glaciers (Falkner et al., 2011; Figure 3.10). Beneath the ice, new subglacial topography mapping has revealed extensive, never before seen subglacial canyons comparable in scale to the Grand Canyon (Bamber et al., 2013). On the surface, a confluence of factors combined in the summer of 2012 to produce surface melting on 97 percent of the GrIS, the scale of which, while not unprecedented in the climate history reconstructed from ice cores, has not been observed since systematic satellite observations began in the 1970s (Nghiem et al., 2012). Although they are not large reservoirs of stored fresh water, smaller glaciers and ice caps are losing mass at a much greater rate than the GrIS, and as such are currently the dominant cryospheric contributor to sea level rise (IPCC, 2013; Meier et al., 2007).

These new observations and discoveries highlight the need for persistent and pervasive observation and process studies on land ice in the cryosphere, both small glaciers and the GrIS. Many of the findings cited above were made possible through remote-sensing campaigns, both satellite and airborne. In particular, the intensive Operation IceBridge air campaigns have enabled change detection in particularly fast-changing regions. Field instrumentation campaigns have also been critical in developing these observations and findings, underscoring the need for continued field research. Finally, model-based process studies of ice sheet behavior in a warming climate have helped shed light on the causes of positive and negative feedbacks, and need to be continued and strengthened.

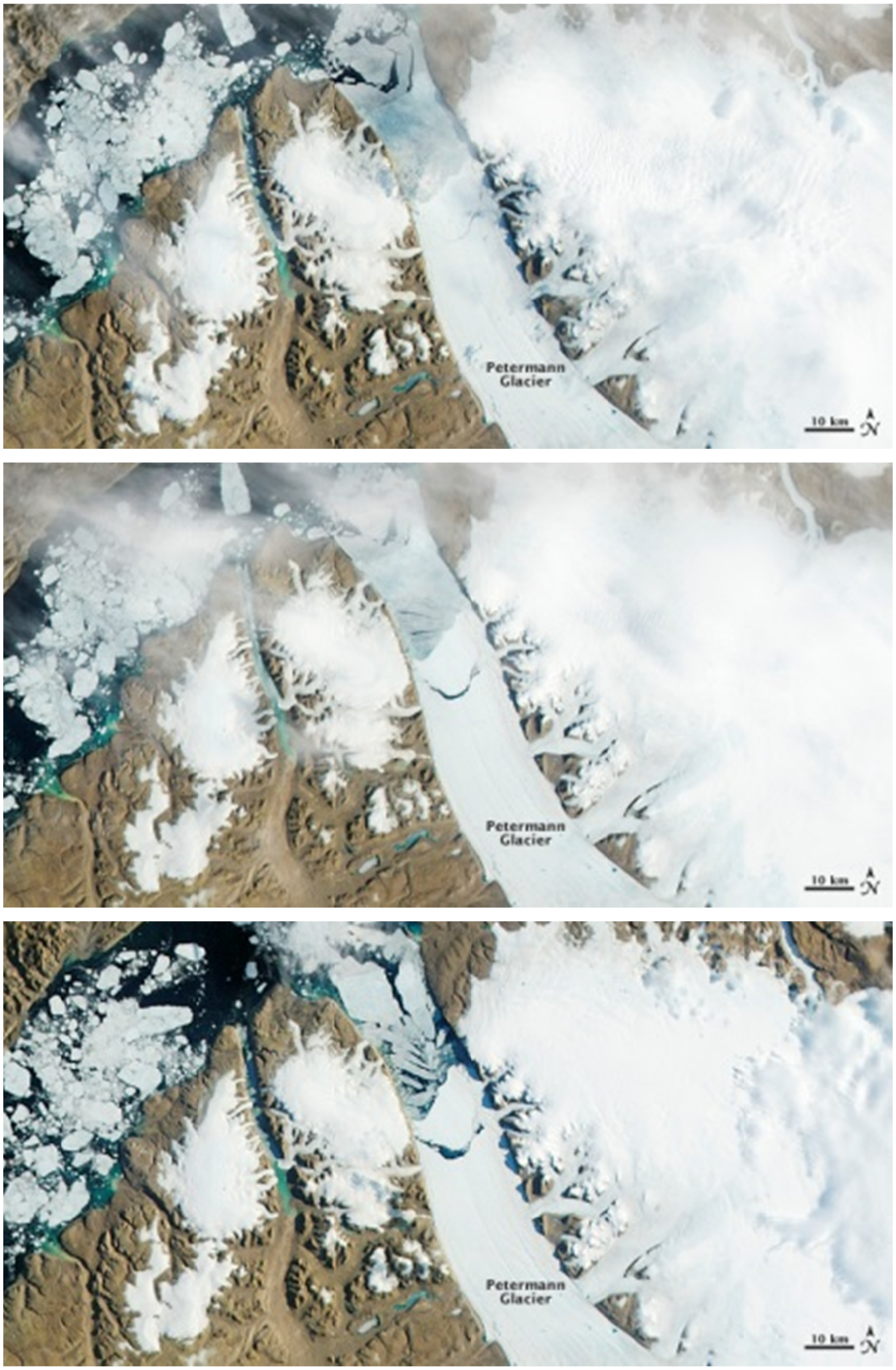

FIGURE 3.10 The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite observed Petermann Glacier and an iceberg calving and drifting downstream July 16–17, 2012. At 1025 UTC on July 16 (top image), the iceberg was still close to the glacier. At 1200 UTC that same day (middle), the berg had started moving northward down the fjord. Thin clouds partially obscure the downstream view. One day later, at 09:30 UTC on July 17 (bottom), a larger opening between the glacier and the iceberg, as well as some breakup of the thinner, downstream ice, was clearly visible. SOURCE: NASA Earth Observatory.

"Breaking" Glaciers and Ice Sheets

Are there positive feedback mechanisms hidden at the ice-bed interface that we have yet to appreciate and understand? Is there a threshold at which the coupling between ice and bed will become weaker? How is inland ice deformed internally by warming through latent heat transported by percolating meltwater from events such as the widespread surface melt of Greenland in summer 2012? What effect will warming ocean water have on sea-terminating outlet glaciers and ice shelves? What is the interplay among surface melt, basal hydrology, and enhanced ice motion? These are currently among the most pressing questions in glaciology because of the strong influence Greenland could have on the rate of future sea level rise.

"Braking" the Current Decline of Land-Ice Cover

Is there any potential negative-feedback mechanism that would slow the rates of sliding and internal deformation that carry ice to low-elevation ablation areas (areas where loss of snow and ice occurs)? For example, the thinning of the GrIS results in a lower basal shear stress—is there a threshold where the coupling between ice and bed will become stronger, resisting further change? Will evolving subglacial hydrological systems in a warming climate reduce the accelerating effect of meltwater at the bed?

The search for new, unanticipated feedback mechanisms requires innovative measures: new process-based modeling studies, in particular of the ice/bed interface in the presence of liquid water, new technologies to determine the location and characterization of liquid water at the ice/bed interface, and new means for making observations at the difficult-to-access calving fronts of fjord-terminating glaciers. Ongoing observations of ice topography and flow rates would help assess the evolution of negative feedback mechanisms, as indicated by changes in flow rates and driving stresses. Finally, new remote-sensing platforms on multiple scales (e.g., unmanned aerial vehicles [UAVs], aircraft, spacecraft) will enable a sharper focus on "current events" in glacier and ice sheet motion, allowing us to identify these new feedbacks as and when they begin to take effect.

How Unusual is the Current Arctic Warmth?

Arctic Ocean sea-ice loss during recent decades has exceeded most model projections, leading to an emerging recognition that sea ice may be more sensitive to climate forcing than previously anticipated. In this context, understanding the paleo-record of both sea ice appearance and loss has emerging significance, facilitated by increasing accessibility of archives and new geochemical and paleoenvironmental tools to track the evolution of sea ice from sedimentary archives. Focused research into quantifying the dimensions and distribution of sea ice and on the status of land ice during known past warm times in Earth's history, when continental configurations were similar to present, will inform our understanding of the sensitivity of Arctic ice to changing radiative forcing and ocean circulation patterns (Polyakov et al., 2010), and thereby improve our projections of the future Arctic.

Key warm periods in the past, when Arctic summer temperatures were higher than the 20th Century average, are given in Table 3.1.

Analyses of previous warm periods in the geological record indicate that there have been several extended time periods when sea ice was absent, only present in winter, or with less extensive summer ice than the 20th century average in the Arctic Ocean (e.g., Backman and Moran, 2009; Ballantyne et al., 2013; Brigham-Grette et al., 2013; St John, 2008), and when the GrIS was much reduced. In the early Cenozoic, the pole-equator temperature difference was much less than it currently is, and mean annual temperatures were at least 20 °C warmer than present at 71 °N (Markwick, 1998; Tarduno et al., 1998; Vandermark et al., 2007). Arctic Ocean surface waters reached ~20 °C during the warm Paleocene - Eocene Thermal Maximum, ~55 Ma ago (Sluijs

TABLE 3.1 Past warm periods

Time Interval	Carbon Dioxide Concentration	Arctic Temperature with respect to 20th century average	Environmental Conditions
Early Holocene thermal maximum (10 to 5 ka)	260 ppmv	Summers 2 to 3 °C warmer	Reduced sea and land ice, possibly seasonally ice-free Arctic Ocean; Greenland Ice Sheet smaller
Marine Isotope Stage (MIS) 5e; (130 to 120 ka)	~310 ppmv	Summers 2 to 8 °C warmer	Sea level 5 m higher than present; high seasonality; greatly reduced summer sea ice; intensified flux of Atlantic Water into the Arctic ocean. Ice-free Arctic lands, except for Greenland, which was reduced by 2 to 4 m sea-level equivalent, and some mountains higher than 5 km
Marine Isotope Stage (MIS)-11 (424 to 374 ka)	~285 ppmv but 30 ka duration	Summers warmer than during MIS 5e	Longer (~30 ka) warm interval; sea level 9 3 m higher.
MIS-31 (~1.1 Ma)	~325 ppmv	Summers similar to MIS 11	Greenland ice sheet smaller
Mid-Pliocene (3.5 Ma)	~400 ppm	Summers 10 to 20 °C warmer; winter temperature anomalies larger than summer anomalies	Warm temperature anomalies in both seasons persisted for several hundred thousand years, longer than orbital tilt/precession cycles; sea level 20 to 40 m higher than present; ice-free Arctic Ocean in summer, possibly year round. No Greenland Ice Sheet; glaciers in North America limited to rare, cirque and valley glaciers.
Early Cenozoic (70 to 50 Ma)	~2000 to ~500 ppmv	Even greater temperature and sea level departures than in the mid-Pliocene	Occurred before the Antarctic Ice Sheet was established. This era may provide evidence of oceanic circulation regimes that expand the range of plausible future ocean circulation patterns, even though continental configurations differed substantially from present

et al., 2006), precluding permanent sea ice (Moran et al., 2006). Grains sand-sized and coarser found in marine sediment far from land (ice-rafted debris [IRD]) likely requires ice-transport, either by calving glaciers or sea ice, although floating trees and other debris may also contribute to the delivery of coarse material far from shore. Rare IRD and sea-ice diatoms first appear in Arctic Ocean sediment ~47 Ma (St John, 2008; Stickley et al., 2009), and suggest seasonal sea ice may have been

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initiated then, although the conditions necessary to sustain persistent ice in the Arctic Ocean remain poorly understood.

A continuous high-resolution lacustrine record, supported by fragmentary paleontological data suggest that during the mid-Pliocene (~3.5 Ma) summer temperatures were ~8 C warmer than today, when the partial pressure of CO_2 was ~400 ppmv (Brigham-Grette et al., 2013). Alley et al. (2010) summarize the Cenozoic history of the GrIS; based on IRD distributions, calving glaciers may have been present on Greenland as early as 16 Ma (Moran et al., 2006), but establishment of a GrIS probably occurred after the mid Pliocene, when large increases in IRD flux occurred throughout the northern North Atlantic. However, warm intervals, including one or more intervals of re-forested Greenland, occurred after initial formation of a GrIS (Funder et al., 2001; Willerslev et al., 2007). Particularly warm intervals of the mid- to late-Quaternary are Marine Isotope Stage (MIS) 31 (~1.1 Ma), when summers were up to 4 to 5 °C higher than the Holocene (Melles et al., 2012), MIS 11c (~0.4 Ma), when summers were also 4 to 5 °C higher than the Holocene (Melles et al., 2012), CO_2 was ~285 ppmv, less than in MIS 5e, but of much longer duration (30 ka; Siegenthaler et al., 2005), the GrIS was much smaller than present (Willerslev et al., 2007), and sea level was 6 to 13 m higher than today (Raymo and Mitrovica, 2012). During the last Interglaciation, MIS 5e (~125 ka), summers were similarly warm (Miller et al., 2010 and references therein), the GrIS about a third smaller than present and sea level was +5 m (Overpeck et al., 2006). MIS 5e and 31 also had strong insolation forcing, with coincidence of high obliquity, eccentricity, and precession resulting in perihelion coinciding with boreal summer. During the Holocene, the present interglaciation (the past 12 ka), the Arctic was warmest between 9 and 6 ka, with summers 1.7 0.8 °C above the 20th Century average (Kaufman et al., 2004; Miller et al., 2010 and references therein). As Greenland currently has been steadily losing mass in recent years (Svendsen et al., 2013), an emerging realization is that more complete Arctic-wide environmental reconstructions for intervals when the GrIS was substantially smaller than present may provide important constraints on the future state of the Arctic.

Understanding the local and global conditions associated with these times will help us to better anticipate future changes. How sensitive is sea ice to warming? How might biota respond? How much of the GrIS could be lost and at what rate? How might precipitation, freshwater discharge, and ocean circulation patterns shift? Is the mid-Pliocene a realistic analog for a future Earth equilibrated with current greenhouse gas concentrations and other forcings?

Increased access to the central Arctic Ocean offers opportunities to extract marine sediment cores that are expected to provide a more complete history of Arctic Ocean circulation and surface conditions through the late Cenozoic. A substantial challenge is the development of improved proxies that are directly linked to specific concentrations of sea ice. Emerging tools in organic geochemistry are the arena where new sea-ice proxies are most likely to be discovered.

What is the Role of the Arctic in Abrupt Change?

From a human perspective (as well as much of the rest of the biosphere), the rate of change is more important than the magnitude of change, and both extreme events and non-linearities (abrupt change) are likely to be our greatest future challenges.

Abrupt change refers to changes in the physical climate system and abrupt impacts in physical, biological, or social systems triggered by a gradually changing climate over a timescale of years to decades. Rapid change is more problematic for societal adaptation than regular, gradual change because it is unpredicted and unexpected, and hence, unprepared for, forcing reactive, rather than proactive behavior. These changes may propagate systemically, rapidly affecting multiple interconnected areas within and beyond the Arctic (NRC, 2013).

Because of strong positive feedbacks and teleconnections to the global system, the Arctic may be the region most likely to face these challenges, and these may in turn result in abrupt change in distant regions. A recent NRC report, *Abrupt Impacts of Climate Change: Anticipating*

Surprises, identified the disappearance of late-summer Arctic sea ice as an abrupt climate change that is already happening, and the potential climate surprises that could occur as a result of methane release from permafrost and methane hydrates (NRC, 2013). As access to key climate archives increases, we will gain a greater understanding of how abrupt changes have occurred in the past, in turn shedding light on how they may happen in the future.

Naturally forced abrupt climate change in the Holocene

The increasing distance of Earth from the Sun during northern hemisphere summer since ~11 ka, caused by Earth's orbital irregularities, led to a decay of northern hemisphere incoming solar radiation in the summer, especially across the Arctic. Earth is currently close to its northern hemisphere summer insolation minimum, after which summer insolation will begin to slowly increase again. An emerging realization is that as northern hemisphere summer insolation decayed, the high latitudes cooled irregularly (Wanner et al., 2011), with local to regional evidence for abrupt, step-wise, environmental change (Geirsdottir et al., 2013). Evidence of, and an explanation for, abrupt shifts under uniform, hemispherically symmetric insolation forcing are emerging research questions.

Volcanism

Sulfur-rich explosive volcanism can inject SO_2 into the stratosphere, where it rapidly converts to sulfuric acid aerosols that cool Earth's surface but warms the stratosphere for one to three years (Robock, 2004). A series of decadally-spaced eruptions may have a more sustained climate impact (Schneider et al., 2009). What remains hidden is whether explosive volcanism served as a trigger for abrupt climate change during the Holocene that persisted for decades to centuries, and whether the sensitivity of the Arctic system to explosive volcanism is dependent on the background state (Zanchettin et al., 2013).

Solar Irradiance

There is an extensive literature evaluating the role of solar irradiance variability on the climate evolution of the past millennium (e.g., Mann et al., 2009), although the likely range of solar irradiance variability on centennial timescales has been reduced in recent years (Schmidt et al., 2011). The largest remaining uncertainty is likely whether changes in the UV spectral strength of solar radiation impact stratospheric circulation through ozone formation in such a way that it strongly impacts the Arctic system.

What has been the Cenozoic Evolution of the Arctic Ocean Basin?

Our understanding of the geologic history of the Arctic Ocean has been inhibited by our inability to recover key sedimentary archives and underlying crustal rocks from the central Arctic Ocean. Instead, the history of the region has been derived from extrapolation of geophysical data and incomplete industry well data and land-based outcrops. With the exception of a single long record from the Lomonsov Ridge that extends back to the Paleocene-Eocene Thermal Maximum (PETM; ~56 Ma) with several hiatuses, there is a serious lack of direct evidence to reconstruct the evolution of the Arctic Ocean basin and its climate history. Understanding the tectonic evolution of the Arctic Basin can in turn inform our understanding of ocean circulation and biogeography, topics that were discussed in greater detail in the previous section on the Evolving Arctic. As it becomes possible to drill into the Arctic Basin seafloor, it becomes practical for the first time to study these important research topics.

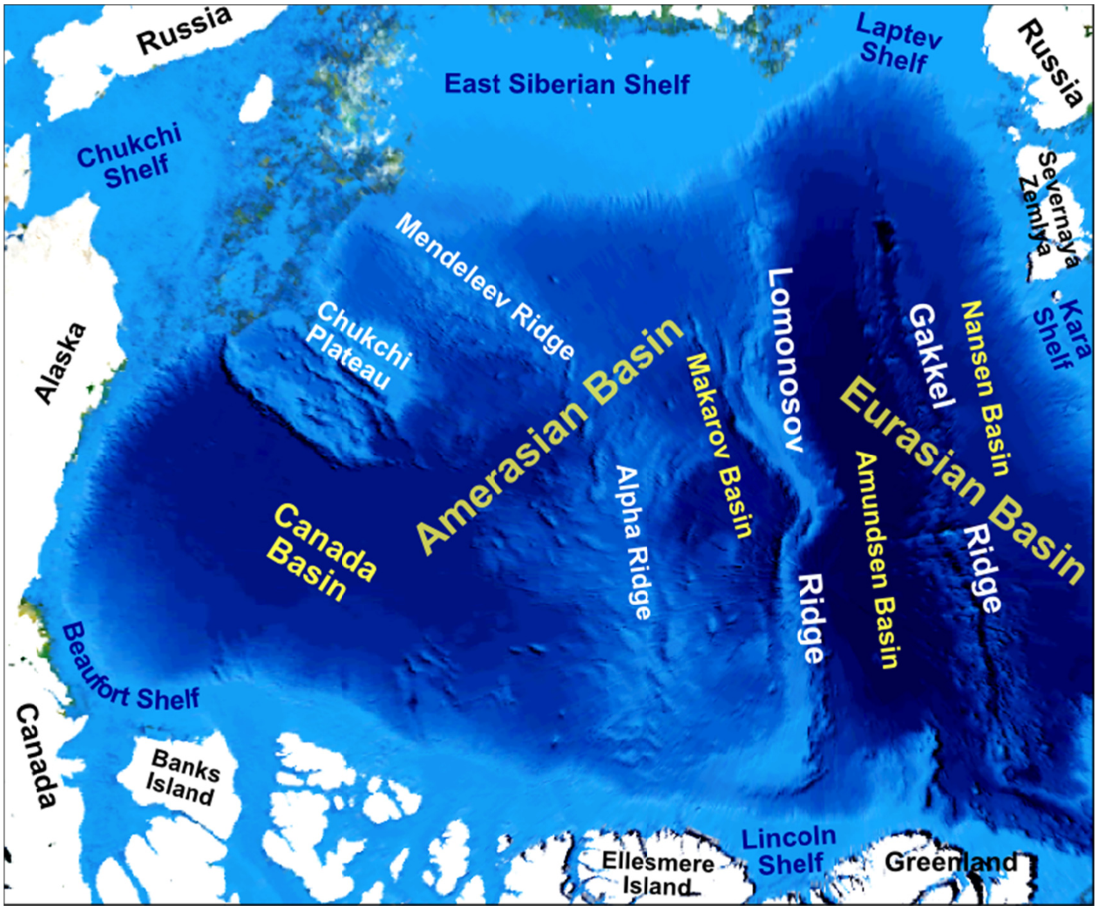

FIGURE 3.11 Bathymetric features of the Arctic Ocean basin. SOURCE: Wikipedia

Ridges, sediment-filled basins, stranded extended crustal blocks, and seamounts of unknown origins, dominate the complex bathymetry of the Arctic Ocean Basin (Figure 3.11). These features, which are still not well studied, record the tectonic and magmatic evolution of this ocean basin. The Lomonosov Ridge is thought to be an extended crustal block that rifted off the Kara Shelf in northern Russia. The Lomonosov Ridge divides the Arctic Ocean into two basins—an eastern part referred to as the Eurasian Basin and a western part known as the Amerasian Basin. The Gakkel Ridge in the middle of the Eurasian Basin is the northernmost extension of the Mid-Atlantic Ridge, and has the characteristics of a typical mid-ocean ridge. The Gakkel Ridge divides the Eurasian Basin into two smaller basins—Nansen and Amundsen. The Alpha Ridge and Mendeleev Ridge divide the Amerasian Basin into the Makarov Basin and Canada Basin. The Alpha and Mendeleev Ridges may represent, at least in part, hotspot volcanic tracks, although data remain rather scarce for a definitive assessment.

Development of the Amerasian Basin

As year-round sea ice continues to retreat in the Arctic Ocean, large areas of the Amerasian Basin are made accessible to a variety of studies, including the ocean floor for its bathymetric features, geological structures, volcanic eruption history and sedimentation. The geological development and evolution of the this basin remains poorly understood because until only recently many important submarine structures, such as faults, ridges, and volcanic lineaments have been inaccessible because of sea ice and therefore have remained unmapped. The Canada Basin is bordered by North America on the southeast and the Chuckchi Plateau—a block of extended continental crust—on the northwest. Based on limited data, it has been proposed that the Canada Basin opened by counter-clockwise rotation of this crustal block and its collision with the Siberian margin. This is known as the "windshield wiper" model for basin opening, and its verification hinges on whether future studies definitively identify magnetic anomalies in the central Canada Basin.

High Arctic Large Igneous Province

Large igneous provinces (LIPs) that erupted in both marine and terrestrial environments throughout Earth's history are thought to cause environmental devastation, and perhaps even mass extinctions, because of the massive volumes of material erupted onto Earth's surface in what is presumed to be a short amount of time (~ 1 million years). This hypothesis notwithstanding, there has never been satisfactory demonstration that indeed LIPs are emplaced in only ~ 1 million years. This is because they are too thick (up to 35 km) to drill through to obtain samples for dating of the entire volcanic sequence. The High Arctic Large Igneous Province (HALIP) centered on the Alpha and Mendeleev Ridges of the western Arctic Ocean offers a unique opportunity to test the model about its emplacement inasmuch as its eruptive history is recorded in the sedimentary record of Canada Basin. Drilling through a few kilometers of sediments is a much easier proposition than drilling through tens of kilometers of volcanic material in relatively deep water.

CONNECTED ARCTIC

Emerging questions:

E1. How will rapid Arctic warming change the jet stream and affect weather patterns in lower latitudes?

E2. What is the potential for a trajectory of irreversible loss of Arctic land ice and how will its impact vary regionally?

E3. How will climate change affect exchanges between the Arctic Ocean and sub-polar basins?

E4. How will Arctic change affect the long-range transport and persistence of biota?

E5. How will changing societal connections between the Arctic and the rest of the world affect Arctic communities?

The Arctic is connected with the global system through a variety of mechanisms, both direct and indirect (Figure 3.12). These linkages span physical, biological, social, and economic realms. Thus as the Arctic undergoes a profound physical transformation to what has been described as a "new normal" of the Anthropocene and residents begin to experience the effects of globalization profound changes in the entire global system are expected.

The Arctic is warming at least twice as fast as the rest of the Northern Hemisphere, resulting in the loss of approximately 75 percent of the volume of summer sea ice in only three decades, greatly increased surface melting on Greenland, unprecedented thinning and retreat of glaciers, thawing of permafrost, and marked warming of the Arctic Ocean surface (Blunden and Arndt, 2013). Because of the Arctic's essential role in Earth's heat engine that drives global-scale air currents, it is unlikely that changes of this magnitude would not have an impact on the large-scale atmospheric circulation. Those responses may become more widespread as greenhouse gases

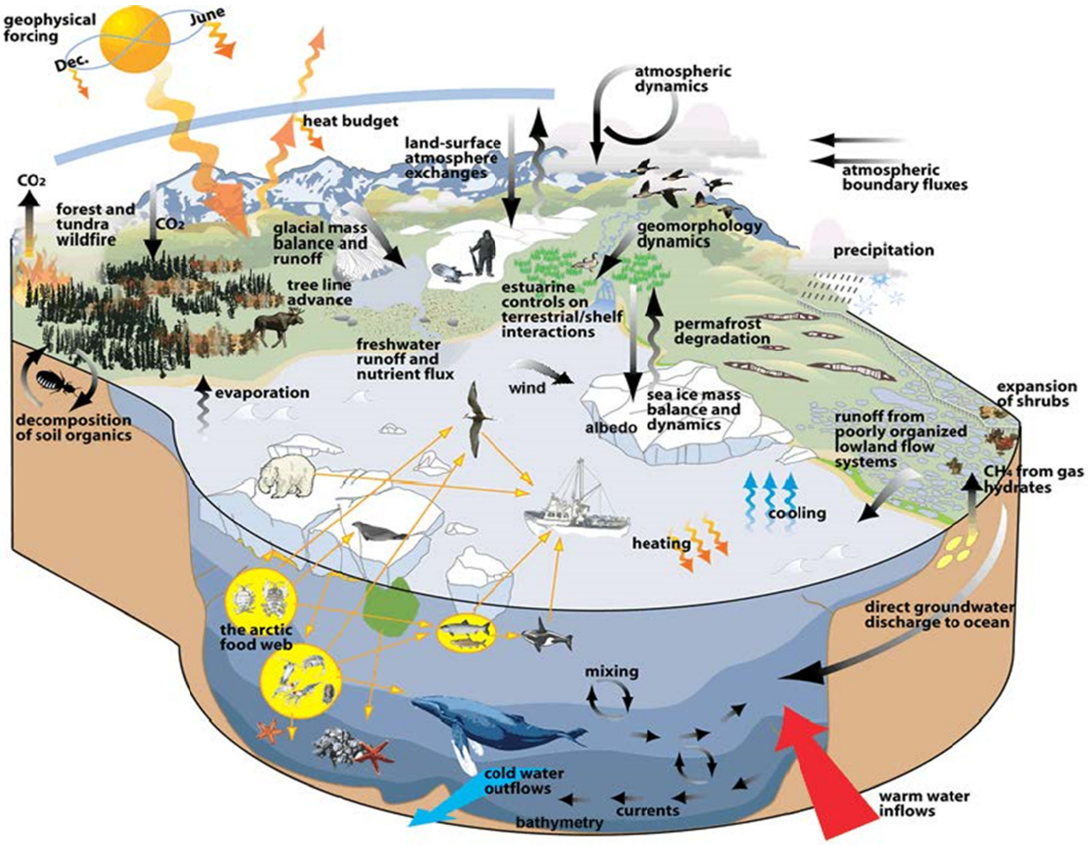

FIGURE 3.12 The Arctic system is made up of various components including a complex network of process interactions, interdependent feedbacks, thresholds, and linkages with lower latitudes (e.g., warm water inflows/cold water outflows). There are many interconnections among system components, and important changes in one component may influence numerous other parts of both the Arctic and global systems. SOURCE: Adapted from the Study of Environmental Arctic Change.

continue to accumulate. Conversely, changes in tropical and mid-latitude temperature patterns will also affect wind patterns, which, in turn, will influence Arctic change. A variety of positive feedbacks amplify these effects. Great uncertainty revolves around the linkages among changes in the Arctic freshwater system (e.g., increased precipitation and river runoff, decreased sea ice, earlier snow melt in spring) and potential impacts on physical and biological systems within and beyond the Arctic (Francis et al., 2009). Understanding the details of these interactions is in its infancy, but its importance is difficult to overstate.

People living in temperate latitudes are beginning to care about the impact of Arctic changes on their way of life. According to a recent polling study by Hamilton and Lemcke-Stampone (2013), the public generally accepts that the widely publicized disintegrating sea ice in the Arctic is affecting mid-latitude weather patterns. Further, an individual's responses to poll questions are tempered by the weather conditions prevailing just prior to being interviewed, among other factors (Figure 3.13). The potential for a causal linkage between Arctic amplification (enhanced warming in the Arctic compared to the rest of the northern hemisphere; e.g., Pistone et al., 2014) and mid-latitude-weather resonates with the public in terms of recognizing the immediacy of climate change.

Connections are also apparent in how the Arctic will respond to climate change, including mitigation and learning from others' experiences. Anthropogenic carbon emissions are

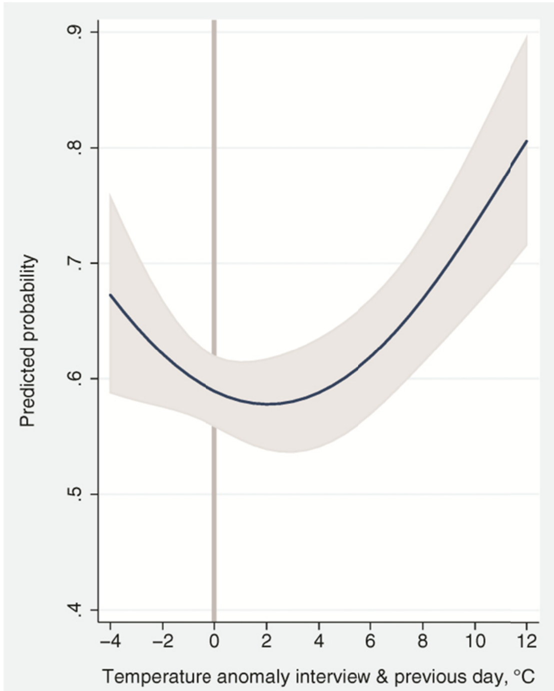

FIGURE 3.13 Predicted probability of "major effects" response as a function of a 2-day temperature anomaly.
SOURCE: Hamilton and Lemcke-Stampone (2013).

predominantly from mid-latitudes, and thus addressing the major driver of Arctic climate change will require action outside the Arctic. The cost of adaptation measures in the Arctic, such as erosion control, is likely to be much higher than Arctic residents or societies can afford, and therefore will require funding from sources largely outside the Arctic (e.g., Huntington et al., 2012). As the impacts of climate change are felt throughout the world, successful responses can be shared with other societies and regions, and collective actions can be considered. Many ongoing research efforts are focused on these changes (see existing questions below). This section highlights emerging questions related to interactions between the rapidly warming and thawing cryosphere and the physical, biological, and social systems south of Arctic boundaries.

Examples of existing questions:

- Which factors are most important in driving seasonal variability of sea ice, ice sheets, snow cover, and the active layer over permafrost?
- Why do global climate models underestimate the loss of Arctic ice?
- How can we quantify the role of climate feedbacks, their variability in space and time, and their impact on both climatic and environmental variables?
- How will changes in atmospheric circulation affect pollutant sources, pathways, and processes in Arctic ecosystems and communities?
- How will northern communities be affected by externally- as well as internally-forced societal and environmental change?

How will rapid Arctic warming change the jet stream and affect weather patterns in lower latitudes?]

Several studies based on theory, observations, and models have explored various mechanisms that may link Arctic amplification with changes in the large-scale atmospheric circulation of the northern hemisphere. Some of these proposed mechanisms include slowing the mid-latitude upper-level westerlies and increasing the amplitude of planetary waves, with enhanced potential for blocking and more persistent and/or extreme weather events (e.g., Francis and Vavrus, 2012; Petoukhov et al., 2013; Tang et al., 2013). Some of these studies provide robust evidence for linkages and some do not (e.g., Barnes, 2013; Screen and Simmonds, 2013; Screen et al., 2013). This is a rapidly evolving avenue of research (Palmer, 2013; Vihma, 2014).

The depletion of the Arctic cryosphere (sea ice, glaciers, snow, and permafrost), combined with new studies implicating Arctic amplification as a driver of more frequent extreme weather, has reignited discussions of weather as a manifestation of climate change (Jeffries et al., 2013; Lynch et al., 2008). Climate model projections of future Arctic amplification vary widely (Holland and Bitz, 2003), leading to uncertainty in the response of large-scale circulation as well as weather patterns. The capability of models to simulate extreme weather events related to the changing jet stream is also in question. A better understanding of the details of the response will enable decision-makers to prepare for changes ahead. However, predicting these extremes in the short term with numerical weather prediction models and projecting their variability in the long term with GCMs present a substantial challenge. Recent studies suggest the changing character of the jet stream includes an increase in blocking patterns and highly amplified flows, which requires realistic simulations of non-linear dynamics at mesoscales that at present appear to stymie the relatively coarse dynamical models used for global weather forecasting and climate projection (Masato et al., 2013). High-resolution models are generally more successful in simulating these mechanisms.

Climate models vary in their simulations of past and future Arctic amplification, leading to uncertainty in the projections of dry static energy transport (Hwang et al., 2011). Meanwhile, as global temperatures increase, so does the maximum physical limit of water vapor concentration in the atmosphere. The dependence of water vapor concentration on temperature is not linear, as one degree of warming at high temperatures results in a larger increase in water vapor than at low temperatures. This delicate interplay adds complexity to projections of changing poleward moisture transport, as a more rapidly warming Arctic partially offsets the non-linearity in the temperature/water vapor dependence. The importance of knowing future changes in moisture cannot be overstated, as it affects the amount of latent heat energy that fuels storms, the magnitude of its greenhouse effect, and moisture availability for cloud formation (which affects the surface radiation budget) and precipitation intensity.

The thermal responses to increasing greenhouse gases in the troposphere and stratosphere differ. As vertical atmospheric stratification changes, the exchange of wave energy between the troposphere and stratosphere is modified (e.g., Cohen et al., 2007). The impacts of these changes on the large-scale circulation are poorly understood, but are likely to affect weather patterns around the northern hemisphere.

Modes of natural variability within the coupled ocean-atmosphere system have been identified and studied (El Niño-Southern Oscillation, Pacific Decadal Oscillation, Northern Annular Mode, Quasi-biennial oscillation, etc.), each with their distinctive influence on the large-scale circulation. Dramatic reduction of sea ice and early-summer snow on high-latitude land areas, along with increasing atmospheric water vapor, have led to an emergence of the signal of Arctic amplification from the noise of natural variability only within the past decade or two, and most strongly in the autumn and winter. As a new driver in the system, little is known about how natural oscillations and large-scale patterns will interact with the thermodynamic and dynamic effects of a rapidly warming Arctic.

Arctic vegetation change, too, can contribute to hemispheric weather patterns. Models suggest that the greening of the tundra has led to greater predominance of high-pressure systems during the Arctic summer (Jeong et al., 2012). Greener tundra has a lower albedo than snow covered tundra, resulting in more absorption of solar radiation. The resulting warming of Eurasia may affect the strength of the Indian summer monsoon, although current understanding of the combined effects of tundra greening and snow cover changes is incomplete and warrants further investigation.

What is the Potential for a Trajectory of Irreversible Loss of Arctic Land Ice and how will its Impact Vary Regionally?

A direct and crucial linkage between the Arctic and global physical systems is the loss of land-based ice to the ocean and the effect on global sea levels, which will affect billions of people living in coastal cities around the world. The IPCC AR5 (2013) reports that the rate of sea level rise has accelerated over the 20th century to an average of ~3.2 mm per year from 1993 to 2010. Assessments of contributions from various sources have become more accurate, but large uncertainties remain, especially with regard to future projections. Sea level rise from 1993 to 2010 was caused by thermal expansion of the ocean (~39 percent), glacial changes (~27 percent); land water storage (~13 percent); Greenland (~12 percent); and Antarctica (~9 percent) (IPCC, 2013). Sea level rise (SLR) projections for the 21st century vary widely (0.26 to 0.82 m; IPCC, 2013). Land-based ice in the northern hemisphere (e.g., glaciers, ice caps, and the GrIS) will contribute to future SLR. Of greatest concern is future loss from the GrIS due to its large ice volume, its potential for a sustained long-term impact on SLR, and uncertainty regarding the sensitivity of the mechanisms that maintain its stability.

The greatest uncertainty in making reliable predictions comes from the inability to project future ice sheet responses to warmer air and ocean temperatures, the possibility of outlet glacier destabilization, and even the unlikely but possible rapid collapse of marine-based sectors of Antarctica (e.g., Pine Island Embayment).

It is now recognized that ocean heat plays an important role in forcing increased ice discharge via processes such as circulation of the water near the ice, rapid melting of floating glacier tongues, calving at the glacier terminus, and the glacier's response (changing terminus position, elevation, and velocity field). Assessing the magnitude and sensitivity of these various controls (including outlet glacier discharge) on GrIS stability is essential and requires comprehensive in situ and remotely sensed observations coupled with advanced modeling studies. Without observational and modeling improvements it will be impossible to assess the likelihood and characteristics of a trajectory (how much and how fast) for irreversible GrIS melt.

Sea level rise will not be spatially uniform due to three factors: land subsidence, differential ocean warming that changes the distribution of water across the planet, and the huge mass of frozen water on Antarctica and Greenland that exerts a gravitational pull on the surrounding liquid water. As ice sheets lose mass, regions in close proximity to the major ice sheets will experience lower rates of sea level rise, while regions farther afield, particularly the tropical Pacific Ocean, will experience higher rates of sea level rise (Spada et al., 2013). Other factors affecting regional rates of SLR include varying thermal expansion and changes in ocean circulation. Much uncertainty surrounds the relative roles of these various factors affecting local rates of SLR, including shifting ocean currents in response to changes in wind patterns and ocean density profiles, the thinning rate of the GrIS, and differential rates of land subsidence, to name just a few.

How will Climate Change Affect Exchanges between the Arctic Ocean and Sub-polar Basins?

The Arctic Ocean, like the Arctic atmosphere, is connected to its lower latitude complement (Carmack et al., 2010), although the oceanic connections or pathways are more physically constrained. The Arctic Ocean affects deep water convection through control on the volume and pathways by which freshwater is exported into the North Atlantic Ocean through the Canadian Arctic Archipelago and through Fram Strait (Dickson et al., 2002; Serreze et al., 2006). The North Atlantic Ocean is the formation site for deep water that feeds the meridional overturning circulation. At present the North Atlantic's deep water formation sites are delicately structured in their ability to sustain deep convection (Aagaard and Carmack, 1989; Schlosser et al., 1991). The reviews of Alley (2007) and Srokosz et al. (2012) underscore the numerous paleoclimatic and modeling studies indicating that variations in the strength of the AMOC have far-reaching effects on global winds, temperatures, and precipitation patterns. These studies also show that changes in the strength of the AMOC occurred on decadal (abrupt) or centennial to millennial (slow) time scales in the past. Rates may change in a warmer world.

Better understanding is needed of the constraints on Arctic freshwater production and its influence on the AMOC. River runoff feeds a large amount of freshwater into the Arctic Ocean surface, most of which is exported southward by sea ice and upper-ocean flux. Increasingly, freshwater discharged from the retreat of the GrIS will play a role. Understanding the controls on the outflow of freshwater, and hence improving its predictability, is essential because of its influence on the stratification of the water column in the Greenland, Icelandic, Norwegian, and Labrador seas, which are important regions of deep water formation (Aagaard and Carmack, 1989; Jahn et al., 2010). Massive increases in freshwater export from ice sheet meltwater in the Arctic, such as occurred during the Younger-Dryas event ~12,000 years ago, are believed to have caused a shutdown of the AMOC and a major re-organization of Earth's climate (Broecker et al., 1989). The current generation of IPCC models predicts a slowing, but not abrupt shutdown, of the AMOC through the 21st century in response to GHG warming (IPCC, 2007). Nevertheless, these forecasts remain uncertain given the large scatter among models in the predicted strength of the AMOC, particularly in their dispersal of liquid freshwater export in narrow boundary currents. There are large differences among models in their ability to capture interannual variability in the liquid freshwater export.

The low salinity upper ocean waters exported from the Arctic Ocean may have important effects on the carbon cycle and ocean acidification processes in the North Atlantic by changes in stratification, chemical buffering capacity, and the biological uptake of CO_2. For example, an increase in haline stratification, associated with enhanced freshwater export, will inhibit deep convection and consequently reduce the efficacy by which atmospheric CO_2 is sequestered in the deep ocean. In addition, the total alkalinity of the freshwater export (either in ice or liquid form) is low and therefore exerts a diluting effect on carbonate mineral saturation states at the surface.

At present the Arctic Ocean is a sink for anthropogenic CO_2 (Anderson et al., 1998) and accounts for 5 to 14 percent of the global balance of CO_2 sources and sinks (Bates and Mathis, 2009). A continued reduction in sea ice cover and a concomitant enhancement in phytoplankton production (assuming no nutrient limitation) is expected to further increase CO_2 uptake in Arctic surface waters (Bates, 2006; Fransson et al., 2001). However, the increased production will also enhance organic matter remineralization in subsurface waters that will exacerbate ocean acidification. Indeed this appears to be occurring at present insofar as acidification rates in the Arctic Ocean are substantially greater than elsewhere in the global ocean (IGBP, 2013). These subsurface waters, having a low pH, high dissolved inorganic carbon, and low total alkalinity, are eventually exported into the North Atlantic (Shadwick et al., 2009; Shadwick et al., 2013) potentially expanding ocean acidification effects there as well.

Outflows from the Arctic Ocean may impact North Atlantic marine communities and biological production. For example, the freshening associated with the Great Salinity Anomaly (Dickson et al., 1988) appears to have contributed to a reorganization of the plankton and fish communities of the North Sea (Edwards et al., 2002). Greene and Pershing (2007) show that an increase in low-salinity, Arctic-derived shelf waters into the Gulf of Maine and Georges Bank in the mid-1990s led to a major decadal-scale shift in zooplankton communities that, together with the vulnerability of the already overfished stocks, subsequently altered the commercially important cod and haddock fisheries.

How will Arctic Change Affect the Long-Range Transport and Persistence of Biota?

Marine and terrestrial biota in the Arctic are affected by changes in, and transport from, lower latitudes, and changes in the Arctic may influence areas beyond the Arctic. Transport of expatriate organisms into the Arctic, for example, has long been recognized,[10] by natural processes and by human activity (invasive species; Lassuy and Lewis, 2013). In the western Arctic Ocean, copepod species (Figure 3.14) characteristic of the northern Pacific/Bering Sea have been observed in low but detectable numbers throughout the Chukchi Sea and extending into the Arctic Basin, associated with water types of Pacific Ocean origin (e.g., Ashjian et al., 2003; Hopcroft et al., 2010; Matsuno et al., 2011). During the last decade, transport of a number of additional species spanning the benthic and pelagic environments and across multiple trophic levels (e.g., phytoplankton to seabirds) has been recognized (e.g., Hollowed et al., 2013; Post et al., 2013; Wassmann et al., 2011). For example, Alaskan salmon are now much more common, and increasingly utilized as subsistence food, along the Alaskan north coast in Barrow and Nuiqsut (Carothers et al., 2013). Atlantic cod are abundant around Svalbard, displacing the endemic polar cod (AWI, 2013; Renaud et al., 2012).

Transport into a region by itself does not predict that a species can become established in that region and persist, potentially permanently displacing endemic species. The expatriate species may be able to survive in the short term but, because their life histories and physiology are not adapted to the environmental conditions (e.g., temperature, phenology of production, light cycles), they may not reproduce. For example, it has been hypothesized that Alaskan salmon cannot reproduce along the north coast of Alaska (Carothers et al., 2013) and that Bering Sea pollock will not experience a northward shift in distribution because of persistence of very cold water (<0 °C) at depth in the northern Bering Sea (the “cold pool”) and further north (Sigler et al., 2010).

If, on the other hand, subarctic species can adapt to and successfully reproduce in Arctic conditions, then their biogeographic ranges can expand. In the future, with warmer temperatures and earlier and potentially higher primary production with a longer productive season, temperate organisms transported into the Arctic may be able to persist—that is, to reproduce and maintain populations in the Arctic. It also has been suggested that temperate species may have better resistance to ocean acidification (AWI, 2013). Changes in persistence of expatriate species can result in changes in community composition, displacement of endemic Arctic species, changes in pelagic-benthic coupling, changes in the size composition of planktonic and benthic organisms, and thus the availability of prey for forage fish and seabirds and, ultimately, marine mammals.

Recognizing colonization by expatriate marine species is difficult because few long-term records exist (Wassmann et al., 2011). The situation is better for terrestrial ecosystems where there are some long term records (e.g., Jeffries et al., 2012; Post et al., 2013). Lack of understanding of physiological tolerances, temperature-dependent rate processes, and species phenologies also hampers our ability to predict northward expansion of marine and terrestrial organisms. Studies focusing on the potential for expatriate species to survive and persist, including modeling,

[10] http://www.sciencedaily.com/releases/2013/11/131104112713.htm

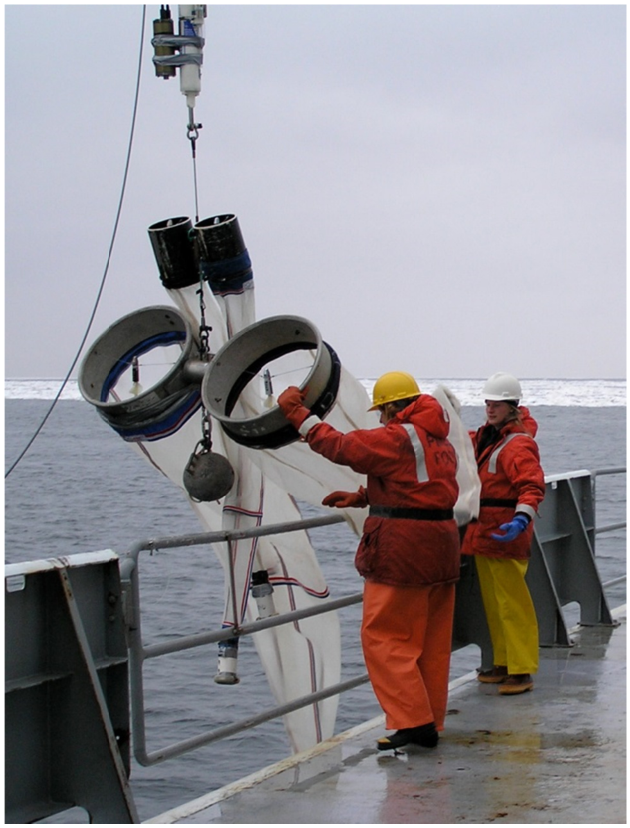

FIGURE 3.14 Researchers deploy a bongo net to sample zooplankton at the ice edge in the Bering Sea aboard the Research Vessel Thomas G. Thompson. SOURCE: NOAA.

observations, and experimentation to determine species specific responses and vital rates under varying environmental conditions, are necessary to gain this predictive capability.

A byproduct of many types of phytoplankton is dimethyl sulfide (DMS), which serves as effective condensation nuclei for the formation of clouds. As the Arctic Ocean transitions to a seasonally ice-free state, the resulting shifts in distributions and abundance of phytoplankton are likely to influence DMS production. Large uncertainty surrounds the magnitude of this change on cloud production within and beyond the Arctic.

How will Changing Societal Connections Between the Arctic and the Rest of the World Affect Arctic Communities?

In social and political terms, the Arctic functions less as a circumpolar unit and more as a series of northward extensions of individual countries and regions. It is difficult, for example, to travel from Arctic Canada to Alaska or Greenland without first going south. Similarly, trade and supply routes typically run north-south rather than east-west (Box 3.4). Organizations such as the Inuit Circumpolar Council, the Northern Forum, and the University of the Arctic work against this pattern, making connections within the Arctic based on common language and interests. For the most part, Arctic regions have been the beneficiaries of government spending and subsidies. Fisheries and, more recently, petroleum and mineral exploration have helped change that pattern of dependence to some extent, and interests in development are increasing. Thus, some parts of the

BOX 3.4
BERING STRAIT SHIPPING

Commercial shipping through the Bering Strait both promises economic gains and threatens cultural and environmental disturbance (Arctic Council, 2009). The governance of shipping is a matter of policy and regulation, but scientific findings can contribute to decision-making processes in several ways.

As a business matter, shipping to and through the Arctic will depend on global markets for the commodities being transported and the viability of Arctic routes as shipping lanes. Understanding Arctic economic activity in a global context can help assess the likely trajectories of development, including shipping. The loss of summer sea ice is the key factor in opening the Arctic to commercial vessels. Predicting sea ice distribution in the short term can help companies determine when a given shipping season is likely to begin and end. Long-term predictions can help evaluate the need for ice-capable ships to extend the season or allow ships to traverse lingering ice.

Long-term observations of the physical, biological, and social environment are essential for identifying impacts from shipping, both from normal operations and from accidents such as fuel spills. In a time of rapid environmental and social change, disentangling the effects of shipping from other changes will require developing a detailed understanding of the workings of the social-ecological system in the Bering Strait region, as well as the connections of this system to the larger Arctic and global systems.

Shipping also brings the potential for technological innovation. Automated information system (AIS) units can be deployed on small hunting vessels, to alert large ships to the presence of local hunters. Ships traveling in Arctic waters are also a platform of opportunity for collecting observational data from regions that typically have limited or expensive scientific access.

Developing appropriate rules and recommendations for ships through the Bering Strait depends on taking all of these factors into account, balancing economic opportunity, maritime safety, and environmental and cultural protection. It will also require national actions by the United States and Russia, bilateral collaboration, and likely action through the International Maritime Organization (IMO), responsible for shipping regulation outside national waters worldwide (e.g., Robards, 2013). Whether attempts to establish appropriate regulatory measures lead to conflict or cooperation remains to be seen.

Arctic may reach economic self-sufficiency, at least to some degree. The appeal of Arctic resources, however, will also attract many more people, greater outside influence, and the attention of more countries (e.g., the application of several countries for observer status at the Arctic Council[11]).

A seasonally ice-free Arctic Ocean will open new trade routes and facilitate access to untapped oil and natural gas reserves (Gautier et al., 2009), repositioning the Arctic from a post-Cold War periphery to a region central to national and international economic interests (Åtland, 2009). While Arctic states and Arctic residents anticipate financial benefits from increased development of fossil fuels and minerals, shipping routes, tourism opportunities, and fisheries, the region is also exposed to the ongoing environmental and infrastructural risks associated with global climate and environmental change, potential oil spills, and other hazards. Economic development can bolster local adaptive capacity to climate change and climate mitigation policies by encouraging local investments, while at the same time encouraging stronger links to the global society, along with an enhanced appreciation by outsiders of their unique surroundings and relationships with nature. That said, many developments also contribute to local vulnerability by contributing to global climatic changes.

Arctic communities are attempting to ensure their participation in policy processes such as the Arctic Council (Sejersen, 2004). Arctic indigenous communities, many of whom have corporate

[11] http://www.economist.com/news/international/21578040-arctic-council-admits-its-first-permanent-asian-observers-warmer-welcome

and constitutional rights, are part of consultative processes that can delay proposed developments that threaten traditional land and resource use, or can shift the way benefits from economic development are distributed (see also Evolving Arctic Emerging Question 1). Different groups are not always cohesive and do not necessarily share the same views, and hence anticipating how consultative processes will shape decision-making is never straightforward. At the same time, they have their own perspectives on security and risk that often run counter to state-centric definitions. While states may emphasize the significance of energy security, for example, indigenous communities may place more significance on food security (Hansen et al., 2013).

The increase in resource exploration has also led to greater interest from, and presence of, non-Arctic countries. China is working with Iceland and Greenland to help develop minerals. Korea and Singapore are developing Arctic shipping capability with an eye to the Northern Sea Route. These activities will influence international relations in the Arctic Council and beyond (see Managed Arctic Emerging Question 2). They will also affect Arctic communities, through the influx of new people, new cultures, new ideas, and new problems as well as new opportunities. Modern telecommunications and transport have also spurred the development of connections between Arctic peoples and indigenous peoples elsewhere in the world, as they discover common experiences of colonization and common challenges of maintaining cultures in the face of social and environmental change. In short, even as east-west interactions remain challenging in some ways, north-south connections to and from the Arctic are growing stronger and more influential in both directions.

MANAGED ARCTIC

Emerging questions:

M1. How will decreasing populations in rural villages and increasing urbanization affect Arctic peoples and societies?

M2. Will local, regional, and international relations in the Arctic move toward cooperation or conflict?

M3. How can twenty-first century development in the Arctic occur without compromising the environment or indigenous cultures while still benefitting global and Arctic inhabitants?

M4. How can we prepare forecasts and scenarios to meet emerging management needs?

M5. What benefits and risks are presented by geoengineering and other large-scale technological interventions to prevent or reduce climate change and associated impacts in the Arctic?

The Arctic has been managed, to one degree or another, intentionally or otherwise, since the first humans arrived in the region tens of thousands of years ago (e.g., Fitzhugh et al., 1988; Pavlov et al., 2001). Early hunters affected animal populations, altered vegetation in and around their camps and settlements, and used the resources they found to support themselves and to trade with their neighbors (e.g., Krupnik, 1993). Over time, humans spread throughout most of the Arctic (e.g., McGhee, 2007), excepting only a few remote island groups. And they spread again, as new technologies supplanted old, as one group supplanted or blended with another, as people found new ways to use resources and new resources to use.

The beginnings of the modern era followed the same pattern, with whalers and seal hunters voyaging north (e.g., Bockstoce, 1986), with explorers seeking new lands and new trading routes (e.g., Berton, 2000), and with inevitable clashes and blendings of cultures and people (e.g., Slezkine, 1994). In the 19th and 20th centuries, the idea that the Arctic has intrinsic value started to develop, leading in time to the recognition of indigenous rights (e.g., Hensley, 2010) and a need to conserve Arctic places and species (e.g., Nash, 2001). Nations claimed sovereignty over the lands of the Arctic, and then over increasing areas of the sea and now out to the extended continental shelves. The commerce and colonization of the emerging Anthropocene brought further technological advances and cultural change, as well as the introduction of disease and other detriments to health and well-being (Bockstoce, 1986). These patterns continue today, as globalization reaches remote communities, as national and international policies affect traditional practices, and as interest in resource development increases (e.g., GAO, 2003). Material well-being has advanced substantially throughout the Arctic, life expectancy has increased, and much is now possible that never was before.

At the same time, the impacts of climate and environmental change pose new challenges (e.g., ACIA, 2005; Box 3.5). Permafrost degradation and coastal erosion threaten the structures and viability of many communities (GAO, 2003). Changing weather and ice conditions increase the hazards faced by those traveling on land and sea (e.g., Pearce et al., 2011). Changes in vegetation and wildlife bring new opportunities (e.g., Noongwook et al., 2007) but also undermine established patterns of hunting, fishing, and gathering (e.g., Gearheard et al., 2006). These changes occur within a wider context of continuing economic, cultural, and political change. Many reindeer herders and small-scale fishermen find their livelihoods less and less able to support them (e.g., Helander and Mustonen, 2004). Many indigenous languages are endangered and some have disappeared (Barry et al., 2013). New modes of governance, through the settlement of land claims or the evolution of political relationships with nation-states, allow greater self-determination (AHDR, 2004), while the Arctic Council provides a new way for nations to cooperate with each other and with indigenous peoples (Axworthy et al., 2012).

All of these topics have been, and continue to be, studied in depth and in many places, deepening our understanding of the ways people affect the Arctic environment and the Arctic environment affects people, there and throughout the world. Indigenous peoples are taking an ever-greater role in designing and carrying out research in their areas. As noted in Chapter 2, this research has never been more important, as countries and companies look north, and as Arctic communities do more and more to shape their own futures. Identifying ways to achieve sustainability for communities and for economic development activities, finding successful adaptations to a changing environment and the underpinnings of preparedness and resilience, and enhancing food security and well-being are among the areas vital to the future of the Arctic, areas where research can offer a great deal.

Examples of existing questions:

- What are the impacts of climate and environmental change on Arctic communities and how can communities adapt effectively?
- How can Arctic indigenous languages be sustained?
- How can food security be improved in the Arctic?
- How can the well-being of Arctic peoples be improved, for example to reduce suicide rates?
- How do the distinctive features of Arctic climate change (long time horizon, uncertainty, variable spatial scale, complexity of natural systems, interdependence of actors) shape human perception and response?
- How will changing government policies, with regard to economic support and resource use, affect the sustainability of Arctic communities?

BOX 3.5
A BALANCE OF SUPPLY AND TRANSPORT CONTROLS THE FLUX OF SEDIMENT THROUGH RIVERS AND STREAMS

Sediment supply is controlled by both the delivery of material to channels from the surrounding landscape and the rate of sediment exchange between the river and floodplains and islands bordering the channel. The ability of rivers to transport delivered sediment depends on the rate, timing, and magnitude of water carried by the channel. The river channel patterns and mobility may dynamically adjust to changes in both sediment supply and river discharge. Observed and predicted changes across Arctic watersheds will likely impact rivers and streams at all levels. Changes in precipitation magnitudes and timing will alter river hydrographs, which will in turn change the rate and timing of sediment transport. Increased erosion from hillslopes and upland regions will increase the flux of sediment to river channels. If the increased flux of sediment exceeds the channel current transport capacity then the channel form may respond. Common responses include shallowing and/or widening until the river slope increases sufficiently to increase sediment transport to meet the new supply rates. Channel widening, in response to increased sediment supply or to increases in bank erosion rates will also cause flow to spread out and the channel to become shallower. Bank erosion rates may be affected by watershed scale changes in discharge and sediment supply and by local changes in channel flow patterns and bank strength related to permafrost and/or vegetation.

Changes in channel form and mobility have the potential to significantly impact both stream habitats and human infrastructure and transportation. Sedimentation and changes in channel form can alter spawning habitats, water quality, and in stream water temperatures. Widening and shallowing of rivers can negatively affect river navigation making channels impassable or shifting flow away from long established villages (see Figure). In other settings, changes in the pattern and/or rate of bank and bed erosion may damage human infrastructure including villages, bridges, and pipeline crossings. The last barge to navigate the river to Noatak was in 1985. It became stuck in the shallow river and remained trapped all summer. Since then, all their supplies, including fuel and building materials, must be delivered by air freight.

FIGURE These images, taken on September 26, 2013 (top) and September 28, 2013 (bottom) show that the Noatak River has become so filled in with sediments in the last few years that it is no longer possible to get a barge into that river. This has significant ramifications for the village. SOURCE: Sarah Betcher.

In addition to these established research areas, several themes are emerging as the Arctic and its societies change, as the impacts of climate change grow greater, and as those with stakes in the Arctic become more numerous and widespread. We highlight five such emerging areas of research, not as an exhaustive list of what can and should be done, but as examples of the ways in which research can and should adapt in recognition of new trends and patterns in the way the Arctic is managed, locally, regionally, and globally.

How will Decreasing Populations in Rural Villages and Increasing Urbanization Affect Arctic Peoples and Societies?

A growing shift in Arctic populations is that indigenous people are moving into urban settings (AHDR, 2004). Whether because their home communities are disappearing or for economic reasons, those making such moves are facing major life decisions that will affect generations to come. The people will have to adapt their ways of life, and at the same time they will bring their values and culture with them into a new environment. Based on the 2010 U.S. Census, Alaska Natives compose 14.8 percent of Alaska's population, and over half of Alaska Natives live in Anchorage.[12] Many questions remain about how indigenous peoples are adapting to the urban setting (Voorhees, 2010). Will they sustain their cultural traditions, lose them in the urban melting pot, or create new ways of living and being?

Such decisions will affect not just their social and economic well-being as indigenous peoples but their culture, place, and the larger society of which they are part. Indigenous people such as the Yupik, Iñupiat, and Inuit are synonymous with the Arctic, yet major portions of their populations have already moved out of rural settings and often out of the Arctic entirely. These moves bring a gamut of social and cultural challenges and issues, including many negative ones that attract the majority of attention. Success stories, however, seem to happen with far less fanfare. How have these individuals made the transition, and what have they kept with them in the way of language, food, stories, dances, and other cultural practices? One obstacle is that discussions of being indigenous in an urban setting appear to be taboo in many circles, with the implication that one is less "indigenous" for living in a city.

The flip side of urbanization is the loss of small communities in the Arctic, from outmigration or from loss of the physical site of the community. For centuries indigenous peoples living in the Arctic adapted readily to an ever changing environment (Krupnik, 1993). They built sod homes near resources, and if things changed they were able to move easily, without regulations or restrictions. Today is a different story. The homes, water and sewer, power grids, schools, runways, and roads of modern Arctic communities have grown through time, and now impede the ability to respond to a changing landscape. When indigenous people in Alaska move to larger cities, they may give up their hunting rights, such as with the Migratory Bird Treaty Act. It may be legally difficult for people living in urban areas to return to their home village to hunt migratory birds. Similarly, if someone moved to Fairbanks, he or she probably would not be called a "coastal native" and thus probably could not hunt marine mammals. Coastal communities threatened by erosion face difficult decisions regarding relocation. What happens when a community is no longer physically viable or is too expensive to maintain (e.g., Huntington et al., 2012)?

The lack of opportunities, resources, and services in small communities, especially for those who have left to pursue higher education or training, leads to outmigration, the second major challenge for remote communities. Often, young women leave and do not return, creating a gender imbalance (e.g., Hamilton, 2010). Today, many young men are also leaving, resulting in a dearth of young people in most rural communities. While many move back as they grow older, many remain in cities. How will outmigration affect rural communities not just in terms of raw numbers but also the loss of those with valuable skills and aspirations? What rights, to subsistence and to governance,

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[12] http://quickfacts.census.gov/qfd/states/02000.html

do those who have left retain in their home communities, and how will these be recognized and allocated?

A great deal of research effort has been focused on various aspects of these questions, but rarely with a complete look at the various factors in migration, urbanization, and sustainability of individuals, communities, and cultures. Yet these trends will help define the indigenous experience through the 21st century, and thus deserve careful study and open discussion that can help indigenous peoples chart their own futures in a rapidly changing social and natural world.

Will Local, Regional, and International Relations in the Arctic Move Toward Cooperation or Conflict?

During the Cold War, the Iron Curtain extended through the middle of the Bering Strait and also along the Norwegian-Soviet border, separating nations and also indigenous peoples from their relatives and areas of travel and use. The demise of the Soviet Union and the creation of the Arctic Council have helped promote communication and cooperation, and Norway and Russia recently resolved a disputed maritime boundary in the Barents Sea. But claims to extended continental shelves, access through the Northern Sea Route and the Northwest Passage, and divergent policies for wildlife management or resource development offer many sources of potential conflict. Growing interest in the Arctic by non-Arctic countries raises the stakes higher with greater uncertainty (e.g., Wall, 2013). Locally and regionally, similar divergent paths can be seen, for example between local governments and large corporations as to the conditions under which industrial activity will take place. A recent election in Greenland hinged on the way the Self-Rule Government should approach mining and oil development.

> Throughout human history, mankind has raced to discover the next frontier. And time after time, discovery was swiftly followed by conflict. We cannot erase this history. But we can assure that history does not repeat itself in the Arctic.
>
> — Chuck Hagel, U.S. Secretary of Defense, November 2013, regarding his department's newly released *Arctic Strategy.*

This question of cooperation or conflict leads to additional lines of inquiry, about the role of indigenous peoples within nations and internationally, for example through the Arctic Council and the United Nations, about the respective ambitions and policies of Arctic and non-Arctic countries, about the distribution of risks and rewards from resource development, and more. The aspirations of Arctic peoples to achieve greater self-determination are particularly noteworthy (see Evolving Arctic question on this topic), with different approaches taken in various regions, and work towards a common voice through organizations such as the Inuit Circumpolar Council and the Saami Council.

As exploration, economic development, and political assertion increase, the potential for conflicting pathways increases, but so do many incentives for cooperation. Rules for Arctic shipping are under discussion as the International Maritime Organization (IMO) develops its Polar Code, and regional arrangements are also under development. Various scenarios for the future of international relations in the Arctic have been proposed, but these remain speculation at present (e.g., Arctic Council, 2009). Local patterns may differ from national ones, as for example the United States and Russia cooperate on marine safety and related issues in the Bering Strait area even as Washington and Moscow spar over larger geopolitical differences. Canada and Russia are pursuing extended continental shelf claims in the Arctic Ocean.

Non-Arctic countries take a greater interest in Arctic affairs, raising concerns over their level of influence. For example, China is pursuing development opportunities in Greenland and Iceland, and South Korea is building ice-capable ships. They seek engagement in the Arctic Council and other forums for joining forces with Arctic countries. The Arctic Council, in turn, has shown greater willingness to extend observer status to non-Arctic countries, although so far not to the European Union as its own entity.

The newly formed Arctic Circle, a group established to facilitate dialogue between businesses and Arctic governments and organizations, is attempting to establish itself as a business-friendly alternative to the Arctic Council. Many corporations are producing or exploring for natural resources such as oil, gas, lead, zinc, gold, and diamonds, providing employment opportunities and tax revenues as well as potential impacts on the environment and local communities.

Indigenous communities collaborate with one another to a greater degree than ever before, including working beyond the Arctic directly and through international working groups and forums for indigenous rights, though there are often differences between and within communities over whether and how resource development should take place.

Research has been done in all these areas, enhancing our understanding of the relationships among the various entities as well as the factors that influence those relationships. It is important that such research continue, from simply tracking the activities of the Arctic Council, to documenting the ways that indigenous communities interact with and learn from another; from evaluating the effectiveness of community consultations by industry or governments, to exploring the potential role of indigenous communities in exploration and development activities.

Little is known, however, about the trajectories of these forms of interaction and how cooperation or conflict in one region or sector will affect cooperation or conflict elsewhere. These trajectories and their interactions will determine the overall course of human relations in the Arctic in the decades to come, and a better understanding of their direction may allow intervention to reduce conflict or better planning for infrastructure, policies, governance, and other human arrangements that are likely to operate for decades, well into an uncertain future.

How can Twenty-first Century Development in the Arctic Occur without Compromising the Environment or Indigenous Cultures while still Benefitting Global and Arctic Inhabitants?

Whether spurred by new opportunities for access, by global economic factors (such as energy supply and cost), or by the aspirations of local populations, the Arctic is on the brink of a period of exploration and development that will bring both opportunity and risk (e.g., Gautier et al., 2009; see Box 3.6). In recent remarks to the inaugural Arctic Circle forum, Scott Minerd, Global Chief Investment Officer, Guggenheim Partners, likened the physical and economic opening of the Arctic to the "discovery" of the Americas. He highlighted the potential for economic benefits as well as the potential for environmental degradation and for detrimental impacts on indigenous people. In the United States for example, the Outer Continental Shelf Lands Act specifically mandates expeditious and orderly development, subject to environmental safeguards. Billions of barrels of oil are expected to be found (e.g., Gautier et al., 2009), but operating in remote regions is hazardous. Under the Law of the Sea Treaty, Arctic nations have the potential to extend territorial claims (Exclusive Economic Zones; Figure 3.15) to the seabed of extended continental shelves, which has fostered a rapid exploration of the geology of the continental-basin margin, a clear indication of interest in capitalizing on resource development opportunities in these areas.

The effort to bring about sustainable exploration and development will require an enhanced understanding of Arctic physical, ecological, social, political, and economic systems. The management of these Arctic systems will be accomplished through a matrix of local and national regulatory frameworks, international agreements and standards, and private sector technical

BOX 3.6
UNDERSTANDING ADAPTIVE CAPACITY IN TUKTOYUKTUK, CANADA

> Our traditional activities are not as common as they used to be, and what our grandparents used to do on a regular basis each year has died. A lot of us don't even know half the stuff they used to do to survive.— Tina Steen, Tuktoyaktuk resident (quoted in Andrachuk and Smit, 2012)

Tuktoyaktuk (*Tuktuyaaqtuuq*) is a community of almost 1,000 people located on the shore of the Beaufort Sea in the Northwest Territories, Canada, part of the Inuvialuit Settlement Region (Figure 5.1). The area has experienced 2 to 3 ºC of warming over the last 50 years (Furgal and Prowse, 2008), along with more frequent and intense storms, permafrost degradation, and sea ice retreat (Small et al., 2011). A major discovery of shale oil was made in the Northwest Territories in 2013, with implications for expansion of the deep water port in Tuktoyaktuk. Other new developments include construction of a highway to the town, and emergence of plans for new Beaufort Sea oil drilling platforms.

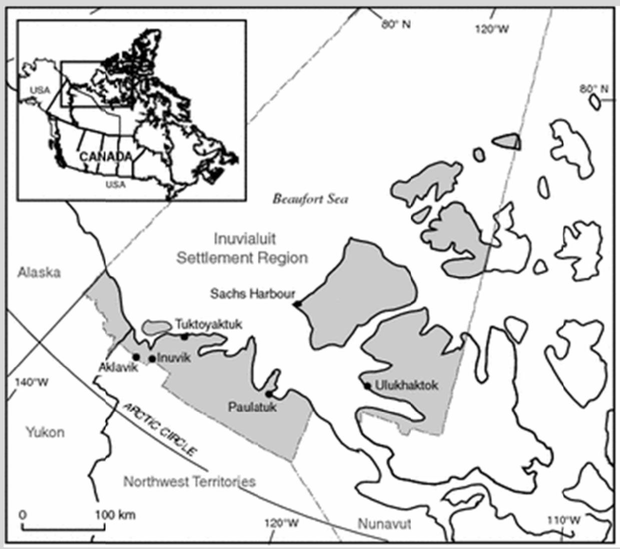


FIGURE The Inuvialuit Settlement Region and Tuktoyaktuk. SOURCE: Pearce at al. (2011)

As a result of these environmental, social, and economic transformations, the community is experiencing a confluence of impacts ranging from accelerating coastal erosion (Galley et al., 2012) to cultural sustainability issues (Pokiak, 2012). Understanding the challenges presented by this evolving context requires a diversity of methods across the natural and social sciences (Cohen, 1997). For example, the harvesting of geese is more than a subsistence activity for the people of Tuktoyaktuk, it is an essential part of the process of renewal in the spring, embodying the spiritual connection between people and land. To that end, reaching an understanding of wildlife management implications of the rapid changes affecting the community is a research activity that requires collaboration between ecologists and climate scientists, regional government representatives, and the community-based Inuvialuit Game Council and local hunters and trappers committee (Bromley, 1996; Hines and Brook, 2008).

Authors such as Brunner and Lynch (2010) and Andrachuk and Smit (2012) elaborate on the range of collaborative efforts that will support more robust responses to complex and rapid changes in the Arctic system. Depending on the geographic and social context, studies range from knowledge-based approaches that engage with traditional epistemologies; to institutional approaches to understand how actors mobilize to further social, economic, or political agendas; to approaches that seek to build local capacity in explicit ways (Fischer, 2003). The most effective approaches, however, share a foundation in rigorous basic natural and social sciences.

operating standards that either currently exist, or are to be developed (e.g., Holland-Bartels and Pierce, 2011). A common theme of these management structures is that successful implementation is contingent upon the strength of the science upon which decisions and requirements are based.

Basing policies and practices on science then raises a debate as to the adequacy of information available to support certain development decisions. Conversely, it also raises a debate as to the adequacy and capability of policy frameworks to respond to the available information to support development decisions. A great deal has been done to obtain scientific knowledge about the various components of the Arctic system. As the utilization of the Arctic by indigenous peoples has formed a strong base of traditional knowledge, repeated waves of Arctic development, including commercial whaling in the 1800s, militarization in the mid to late 1900s, and oil and gas exploration of the late 1900s to early 2000s, have each driven associated expansion of research and knowledge of the Arctic (e.g., Table 4.1). This research has helped industry to design operations for safety and environmental protection, government agencies to develop appropriate regulations to meet national expectations for careful practices, and Arctic communities to enhance self-determination and to determine how to harness economic development for lasting benefit.

At the same time, there is much yet to be learned about the Arctic in relation to economic development. It is assumed that resource development in the Arctic will increase, but economic forecasting will be critical in determining whether this is the case. The functioning of Arctic ecosystem and social-ecological systems lags behind our understanding of the components of those systems (Holland-Bartels and Pierce, 2011), limiting our ability to project how further changes will affect people and the environment. Resource development in the Arctic is occurring in a context of rapid and large-scale environmental (ABA, 2013; ACIA, 2005) and social change (AHDR, 2004), and assessing the extent, rate, and trajectories of such changes is essential to being able to evaluate how locally driven changes interact with globally driven ones. Increasing understanding of the cumulative impacts from resource development, including subtle impacts and those that increase over time, needs to be matched by a better understanding of the options for avoiding or mitigating those impacts. Finally, the use of scientific knowledge to achieve effective governance needs to be examined, to determine how science can best support sound decisions in recognition both of what we know and of what we do not know.

There are a number of key issues that may be related to development of the Arctic that deserve specific mention. Whether it is related to increased shipping, increased size and development of communities, or oil and gas development, the potential for oil and other hazardous material spills is increasing in the Arctic. Oil spill related research ranges from the technical engineering side of increasing prevention and intervention and the design of effective recovery technologies to understanding the potential interplay between oil and Arctic biological resources and ecosystems and potential mitigation and restoration measures. A carefully developed suite of research initiatives is needed to address each of these oil spill related topics from prevention to restoration. The NRC *Committee on Responding to Oil Spills in Arctic Marine Environments* recently covered this topic in much greater detail (NRC, 2014b).

The introduction of increased vessel traffic and industrial activities has the potential to produce sound related impacts in an area that has heretofore been largely isolated from the general increase of sound in the world's oceans. The relative increase of sound levels above baseline and the implications to marine species and the use of these resources by subsistence communities is a key question of concern.

How can We Prepare Forecasts and Scenarios to Meet Emerging Management Needs?

The Arctic environment—including its weather, snow conditions, and ice conditions—is changing rapidly. In addition, the scope and scale of human activity in the region are increasing.

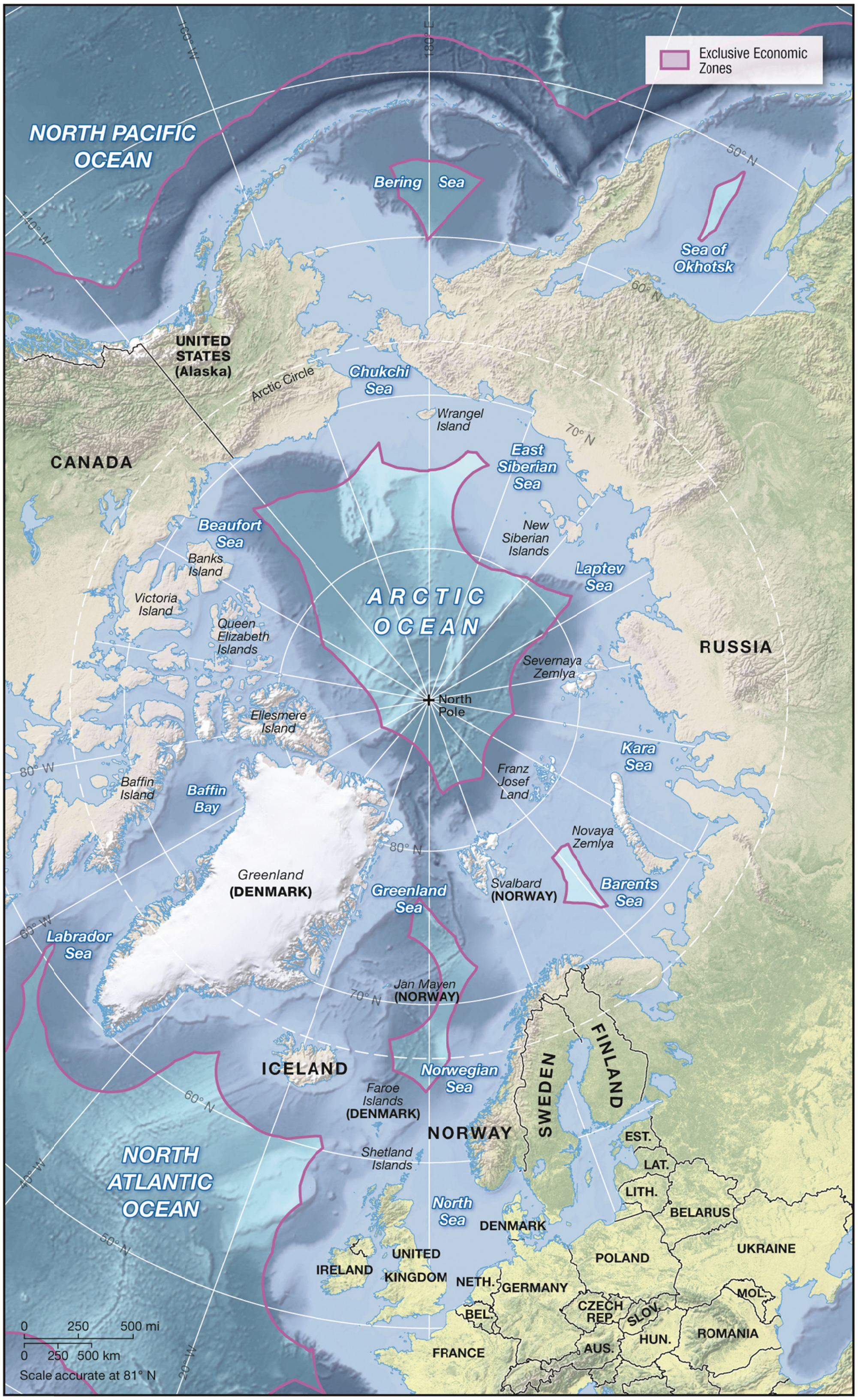


FIGURE 3.15 Exclusive Economic Zones (EEZs) in the Arctic Ocean.

TABLE 4.1 Historical timeline depicting the evolution of U.S. Arctic research programs (Westlien, 2010).

1893	Arctic Drift Stations
1947	Arctic Research Laboratory
1959	Project Chariot Environmental Studies
1970	Western Beaufort Sea Ecological Cruises
1971	Arctic Ice Dynamics Joint Experiment
1975	Outer Continental Shelf Environmental Assessment Program
1979	Marine Mammal Monitoring
1980	Oil Industry Science
1997	Surface Heat Budget of the Arctic
1998	Shelf Basin Interactions Project
2004	Russian–American Long-Term Census of the Arctic
2005	Government and Industry Science

The result is that past experiences are not as reliable in predicting the future as they once were, at a time with an ever greater need for forecasts and scenarios from daily to decadal time frames. Development of both physical and economic forecasts and scenarios in collaboration with those who will use them can help meet the needs of those living and working in the Arctic. For example, improved forecasting capabilities can help save lives in rural communities. Many coastal communities in Alaska are dealing with changing weather patterns, and this has already impacted their ability to harvest traditional foods for themselves. Communities and their members have to take more risks in trying to provide food[13] due to unpredictable weather, abnormal sea ice conditions, and animals shifting migration routes. Knowing the weather patterns is critical in this case for a community's survival.

Specific forecast and scenario needs, including time frame and region, will vary by user. For example, hunters and fishers may want reliable daily to 3-day wind and visibility forecasts, whereas vessel captains or offshore oil rig managers may need ocean, weather, and ice forecasting over a 3 to 10 day time frame so that they can reroute a vessel or shut down an oil rig and evacuate the crew. Seasonal to annual forecasts are increasingly important for longer-term planning of logistics and personnel, and particularly important for staging of wildfire crews and supplies. As operations push into the shoulder seasons, forecasts are especially critical because the phase change from liquid to solid, and vice versa, impacts the viability of tundra travel and oil exploration, ice roads, ice platforms, shipping lanes, and more. In addition to projections of the natural Arctic system, longer term community planning requires decadal projections and scenarios of key social indicators. Because of the implications for sea level rise and teleconnections to Northern Hemisphere weather, Arctic scenarios spanning 20, 50, and 100 years are of global interest to a wide range of users.

As the Arctic transitions toward less snow and ice, conditions are becoming more variable and harder to predict (Krupnik and Jolly, 2002). The improvement of operational weather forecasting will rely on an enhancement of the automated weather observation network, addition of Doppler radar (NEXRAD) stations, and improvements in forecast models. Training for weather forecasters needs to include Arctic phenomena. Open pack ice moves more quickly than

[13] http://aksik.org/village/savoonga

consolidated sea ice, and there are shifts in the direction of ice movement as well (Pfirman et al., 2010b; Pfirman et al., 2010a). Increased calving of marine glaciers produces increased iceberg hazards: 22 percent of the GrIS drains through marine-terminating glaciers (Nick et al., 2009). More traffic, and traffic in new regions, places more people and infrastructure at risk.

Better observations and models are also important to improve predictability for specific locations for explicit forecast lead times and seasons. Location-specific forecasts of sea ice distribution, thickness, and/or age are essential. Improving forecast skill will require a coordinated network of upper air, land, and ocean surface measurements, and model inter-comparison and sensitivity studies. Beyond the atmosphere and ice, forecasts for the ocean, permafrost, hydrology, and ecosystems, as well as warnings for storm surges and other hazards and extreme events (see Evolving Arctic question 4) are essential. Also needed are integrated ensemble forecast systems designed specifically for application to the Arctic, with high resolution products that can be used for risk management and other decision-making.

Turning to longer time frames, consideration of scenarios for the next 20, 50, and 100 years allows exploration of causes and effects. The IPCC (2013) and AMSA (Arctic Council, 2009) assessments have shown the value of scenario development in assessing tradeoffs between proactive vs. reactive choices and responses. Scenarios for the next 20 years may focus on potential resource development, and conflict/cooperation issues (see Managed Arctic question 3). Industries and land/resource management agencies that need a 50 to 100 year planning horizon would need to address a new Arctic normal of changed plant and animal species, a mostly open Arctic Ocean, and changed Northern Hemisphere circulation patterns. Additionally, scenario analyses will permit consideration that the global community may act to address the causes of the current warming and recovery/restoration may be an emerging issue (see Managed Arctic question 2). Just as with the shorter term forecasts, different stakeholders with diverse perspectives will have a range of needs over the next century, and new unknowns will emerge from this analysis.

Forecasting and scenario development present opportunities for exploring public-private partnerships and for international cooperation. Currently, Arctic forecasting is occurring largely within the United States, Canada, Russia, and the European Union, with many inconsistencies in data sharing protocols, data and forecast formatting, and forecast and warning language. Collaboration could provide mutual benefits to advance the field in general, while providing more valuable products to users throughout the world. Key research topics in this area include probing the limits of forecasting ability and connecting user needs with specific forecast products.

What Benefits and Risks are Presented by Geoengineering and Other Large-scale Technological Interventions to Prevent or Reduce Climate Change and Associated Impacts in the Arctic?

With the Arctic headed for long-term declines in glacier and sea ice, some have proposed turning toward geoengineering activities that would reduce ice loss, or potentially even allow ice to be restored (MacCracken et al., 2013). Indeed, the Arctic may even be the impetus that sparks a global discussion of geoengineering. An emerging aspect of geoengineering is whether there are any strategies that could be applied to just the Arctic. Further research would help us understand the implications of geoengineering in the Arctic.

Historically, two categories of activities have been discussed as geoengineering approaches (Figure 3.16): (1) carbon dioxide removal (CDR) techniques that aim to enhance the escape of long wave (thermal infrared) radiation and (2) albedo modification (commonly referred to in the literature as solar radiation management [SRM]) that seeks to counter indirectly the heating effects of anthropogenic climate change by deflecting short wave (solar) radiation from entering the Earth system (Boucher and Randall, 2013; NRC, 2010). This second category is considered indirect because it does not seek to address the primary cause of anthropogenic climate change—increasing concentrations of carbon dioxide in the atmosphere—and thus does not address the biogeochemical effects of that carbon dioxide, such as ocean acidification.

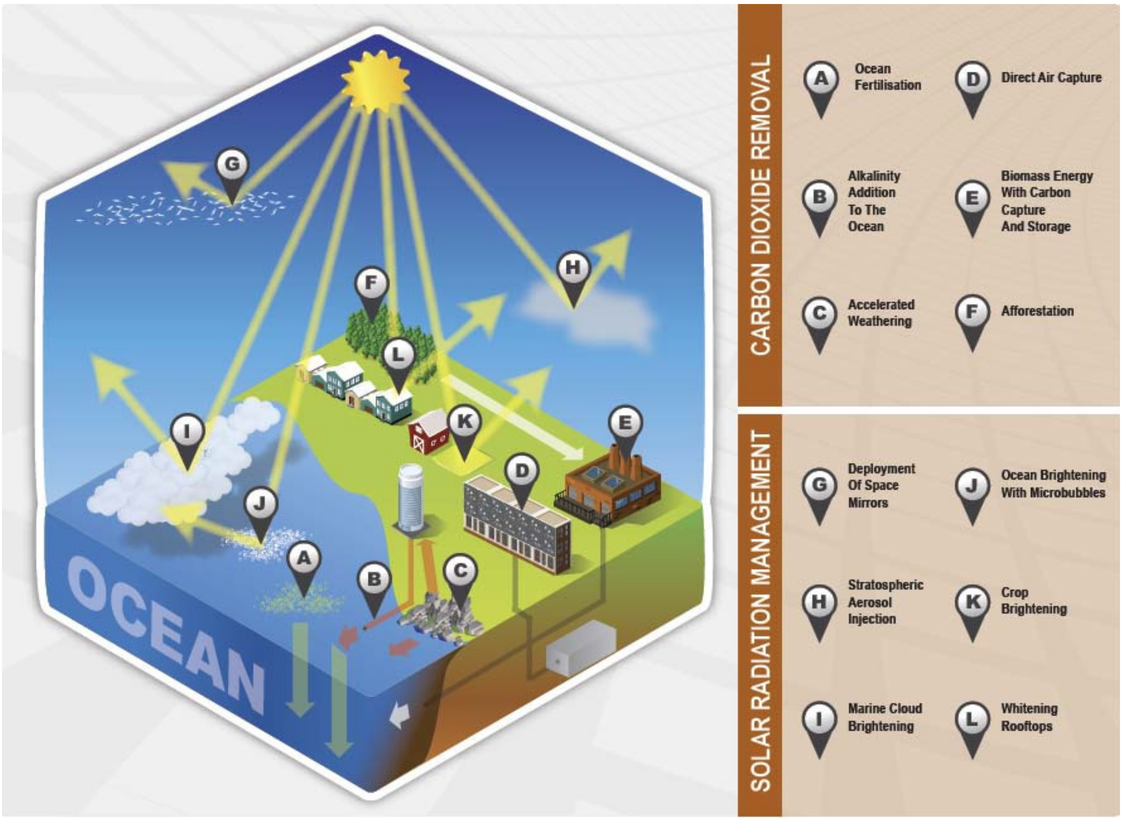


FIGURE 3.16 Summary of various carbon dioxide removal and solar radiation management geoengineering approaches. SOURCE: IPCC (2013), FAQ 7.3, Figure 1.

Geoengineering has the potential for delivering both large societal benefits and significant natural and societal risks. Some CDR methods are well established and have been commercialized on a small scale, such as afforestation and biofuel approaches. However, only limited research has been conducted to assess the technical feasibility and ecological impacts of many of the potential approaches in either category, particularly those that act on shorter time scales or larger spatial scales. Further, approaches that address regional problems, such as seeding clouds with sea salt to increase their brightness over Arctic ice (e.g., Caldeira and Wood, 2008; Wood and Ackerman, 2013), face limitations in our ability to understand and model key phenomena (Fyfe et al., 2013). Also, Tilmes et al. (2014) conclude that regional dimming has challenges in preserving sea ice under global warming, because the impact is largely counteracted by increasing northward heat transport as well as changes in Arctic clouds. Research that improves our understanding of the phenomena and interactions in this complex system, in the context of natural variability and a variety of forcings, is a critical component of our ability to address key gaps in our understanding of the benefits and risks of geoengineering approaches.

A landmark study by the Royal Society of the United Kingdom made the recommendation to develop a code of practice for geoengineering research (Gardiner, 2011; Royal Society, 2009). A key contribution to the governance of research (including field testing), development, and any eventual deployment of geoengineering technologies was the “Oxford Principles” (Rayner et al., 2013). These principles state, in short, that geoengineering is a public good, which implies that public participation, open publication, and independent assessment are key elements of appropriate governance.

The NRC *Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts* is currently conducting a technical evaluation of selected geoengineering techniques. The Committee will examine feasibility and potential environmental, economic, and national security impacts, as well as identifying future research needs. The Committee will briefly explore societal and ethical considerations related to geoengineering. In this context, Arctic research would be useful in three areas of knowledge gaps in geoengineering approaches: (1) Arctic climate systems understanding, particularly in the areas of cloud-radiation interactions, biogeochemistry, and Arctic teleconnections; (2) Arctic social, environmental, and economic research that addresses technological effectiveness in the context of both actual and perceived risks to Arctic natural systems and peoples; and (3) research into the pragmatic implementation of ethics and governance principles under which research is conducted.

UNDETERMINED ARCTIC

Other important elements of the Arctic system remain hidden, not because they are physically inaccessible, but because of our incomplete understanding of the system. These are the intriguing things we *don't know we don't know*.

Providing openings for "to be determined" questions is often implied in strategic assessments, acknowledging our inability to predict the future. Given the rapid pace of change in the Arctic, and the surprises encountered thus far, it is appropriate in this report to treat this category explicitly. As noted in Chapter 2, the only ways to prepare for what we do not know are to understand the system as best as possible, and to be positioned to detect and prepare to respond to changes and events.

This requires at the same time that (1) we invest in the most fundamental and basic research, including exploration as well as hypothesis driven research, comparison of models with observations, cross-scale experiments, research at the interfaces of disciplines, understanding feedbacks and nonlinearities, investigation of outliers and extremes in the paleoclimate record, and creative, non-traditional approaches, (2) we invest in comprehensive monitoring systems, and (3) international funding, logistics, and governance frameworks are flexible enough to deploy resources on rapid time scales and appropriate locations. A research question in and of itself is how governments will structure their responses to the abrupt transitions, changes, and surprises that are sure to come in the future. These three elements also questions related to the things *we know we know* and the things *we know we don't know*.

The Committee was tasked with exploring "how agency decision makers might balance their research programs and associated investments (e.g., balancing work done to respond to urgent global change concerns versus work to advance fundamental knowledge and discovery). In other words, what are some of the challenges of trying to do both problem-driven research and curiosity-driven research?" We do not see fundamental knowledge and discovery as a trade-off versus urgent global change research, but rather as an investment in better preparing us for what the next urgent issue might be.

Similarly, while many view monitoring and long-term observations as a technical issue or something that can be cobbled together, the committee sees it as worth high profile and comprehensive investment: monitoring and long-term observations are at the frontline of detecting the next big thing (Figure 3.17). As one example, the satellite record has been essential to the Arctic community because it provides a circumpolar perspective and a clear record of change, even over the short duration of the satellite era. Without investment in satellites, their sensors, and the technical and scientific capacity to make use of the resulting data, our understanding of the Arctic would be far poorer. The Committee's Statement of Task requested that attention "will be given to assessing needs where there may be a mismatch between rates of change and the pace of scientific research." It is only by maintaining long-term observations that we have an ongoing way of being

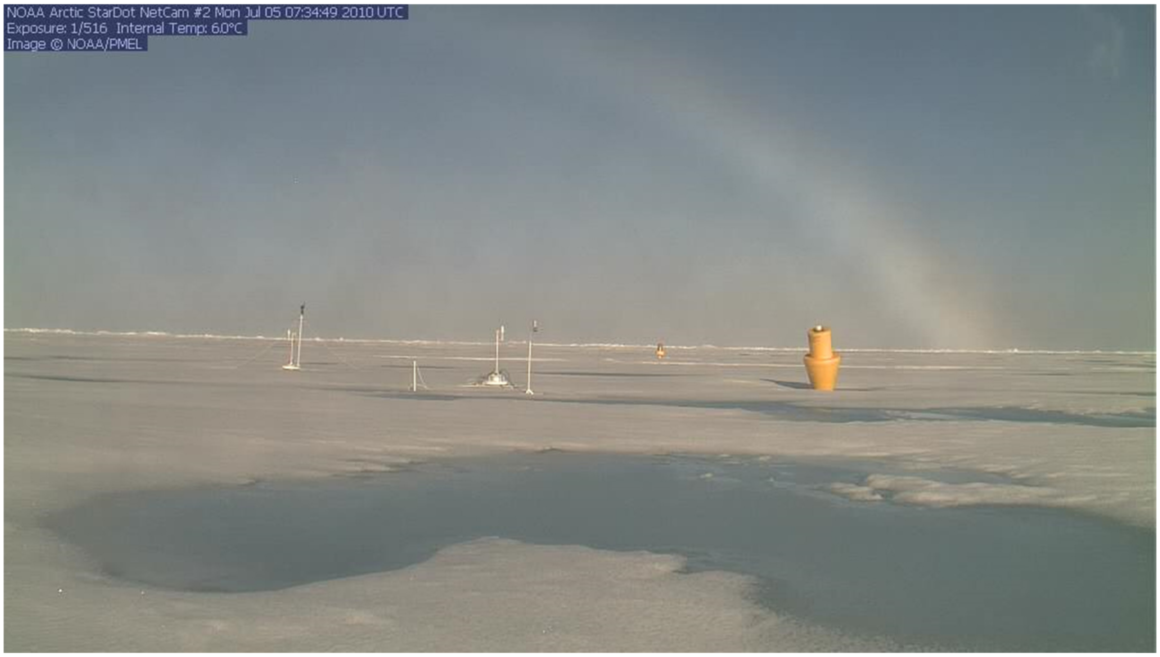


FIGURE 3.17 North Pole webcam image. SOURCE: NOAA.

alerted to where to deploy resources so that we can implement our research programs with this year's situation in hand, not dependent on information from the last time a field program may have been in the area, which can be years to even a decade ago.

Because much of the Arctic has been difficult to access, research has tended in the past to focus on the regions surrounding logistics hubs, with the result that scientific findings are concentrated in these areas. Logistics coordination and sharing can help overcome this obstacle. For example, the Fleet Arctic Operation Game report (Gray et al., 2011) analysis concluded "In order to mitigate these challenges in the short term, the United States Navy should leverage DOD, industry and multinational logistics hubs and platforms. In the long term, the development of permanent infrastructure at the mid-point of a NWP transit capable of providing fuel to maritime assets was recommended."

Creative new ways to crowd-source Arctic monitoring also need support,[14] along the model of Google working with the Centers for Disease Control to collect information on the locations of people conducting online searches for flu symptoms to give hospitals warnings for where the next flu outbreak is likely to be[15]. For example, working with commercial interests, ground truthing data for satellite observations of sea ice conditions in marginal ice zones could be tracked using cruise ships and other ships of opportunity.

Ultimately, the ability to address questions that are as yet unknown will depend on a responsive community, from those identifying priority topics, to those conducting research, to those making funding decisions, to those setting research policies and investing in infrastructure. Trendy new ideas do not diminish the importance of crucial, established research needs. But neither should past practices limit the exploration of what is new or blind us to the possibility of surprise. This chapter presents many compelling and emerging research questions, but it cannot claim to provide a complete guide for new research areas for the next decade or two. Instead, it is a vivid

[14] http://www.nature.com/news/crowdsourcing-may-open-up-ocean-science-1.13341
[15] http://www.google.org/flutrends/us/#US

demonstration of how much remains to be learned, and how often we need to look at the Arctic in a new way.

PRIORITY SETTING

Assigning priorities among the emerging research questions identified in this report inevitably involves a degree of subjectivity. Agencies have specific missions, which will align differently with the questions depending on their particular responsibilities. Depending on one's location in the Arctic, priorities may differ according to specific local economic, environmental, cultural, political, and other conditions. Furthermore, the committee is unwilling to suggest that any of the emerging questions in this report is "low priority," as all have come from extensive input from the research community and lengthy Committee discussion. Addressing each question offers the promise of useful information or significant advances in knowledge. The Committee was tasked "not to provide a literal ranking of research priorities but to provide some scale by which recipients of the report can better judge importance or time-relevance among the identified questions." The committee therefore cannot assign priorities with confidence or rigor, and suggests that such work be undertaken as part of a discussion among agency personnel, researchers, and (where appropriate) policy makers and other stakeholders.

The Committee was also asked to "[e]xplore how agency decision makers might balance their research programs and associated investments (e.g., balancing work done to respond to urgent global change concerns versus work to advance fundamental knowledge and discovery). In other words, what are some of the challenges of trying to do both problem-driven research and curiosity-driven research?" Curiosity-driven research and problem-oriented research are often considered to be competing and even mutually exclusive approaches. This dichotomy is more a reflection of agency funding priorities and mechanisms than a fundamental property of the research enterprise itself.

In practice, our understanding of the Arctic benefits from both approaches, and the ability to act on Arctic matters requires insights from all points on the research spectrum. To demonstrate this, we plotted the emerging questions along time and basic vs. applied axes (Figure 3.18a). The time-relevance axis (x-axis) is the degree to which answers to each question could guide decisions being made now versus those likely to be made later. The other axis (y-axis) is the degree to which the answers will improve our basic understanding of the Arctic versus those that will have direct application to decisions and actions. The result is a fairly even distribution along both time and applications spectra with questions largely falling along a line from "direct application, short-term" to "basic understanding, long-term." This no doubt stems largely from the fact that we know what today's pressing issues are, so can ask pertinent questions to address short-term needs. For the longer term, it is easier to identify key areas of basic understanding that we expect will be relevant to tomorrow's pressing issues.

Because this dichotomy between research on fundamental questions versus that on specific, urgent problems is misleading, we should not seek to identify an "optimal balance". Nor are short-term questions necessarily more pressing than long-term ones, as addressing long-term needs often requires long-term action. It is more productive to think about the ways in which decision makers and communities can draw on the results of all types of research to find appropriate paths for action, and the innovative research that emerges when researchers direct their inquiry toward what decision-makers need to know. Both approaches are necessary, and their respective importance is likely to vary by agency.

Similarly, the Arctic in the Anthropocene requires both natural and social scientific study in order to understand the phenomena and processes that define and shape it, as well as the "sustainability science" called for in the SOT, which informs the decisions that lie ahead. Plotting the emerging questions along time-relevance (x-axis) and natural vs. social science emphasis (y-axis) again reveals a relatively even spectrum in both directions (Figure 3.18b). Many short and medium term questions have a social science component, in part because of the rate of change and in part because investments have not been made in the social sciences to the same degree as the natural sciences. Social science research, including economic, cultural, and behavioral analysis, is clearly needed to provide lines of evidence for making decisions at individual and organizational levels about preparedness and how to live and work in the Arctic. Using the best available information can help improve wellbeing now and enhance our resilience to future shocks.

The emerging questions can also be arranged by spatial scale (y-axis) to highlight geographic scope (Figure 3.18c). As the section on the Connected Arctic demonstrated, what happens in the Arctic does not stay in the Arctic. The reverse is also true. The Arctic is interconnected with global social and economic systems as well as through atmospheric and oceanic transfers and terrestrial migration patterns. And within the Arctic, conditions are not uniform, both in terms of natural and social settings and also with respect to vulnerability to change. As highlighted in the first finding of the Polar Regions chapter of the 2014 IPCC report on Impacts, Adaptation, and Vulnerability, "The impacts of climate change, and the adaptations to it, exhibit strong spatial heterogeneity in the Polar Regions because of the high diversity of social systems, bio-physical regions and associated drivers of change" (IPCC, 2014). Therefore priorities vary by location, discipline, and stakeholder representation.

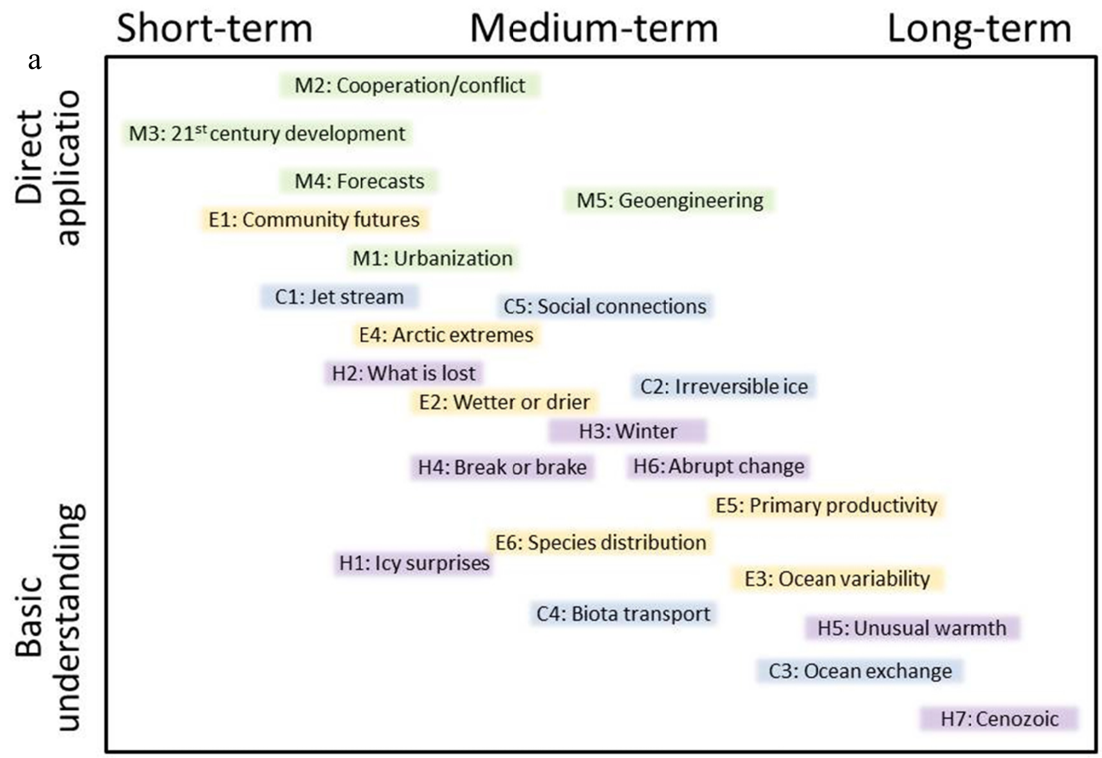
A failure to address emerging questions in a timely fashion and with an appropriate suite of expertise may undermine our ability to mitigate and adapt to change by increasing the risk of:

(1) making decisions based on faulty and/or outdated information (especially for those questions that have direct applications in the short term; Figure 3.18),

(2) pursuing inadequate understanding of important phenomena (especially for questions in the middle area of Figure 3.18), and

(3) laying an insufficient foundation for future research (especially for questions that lead to new basic understanding over the long term; Figure 3.18).

Remaining open to questions and surprises that will emerge in the future enables crucial new insights to the way the Arctic physical, biological, and social systems work, enhancing society's ability to attain the most benefit from Arctic research.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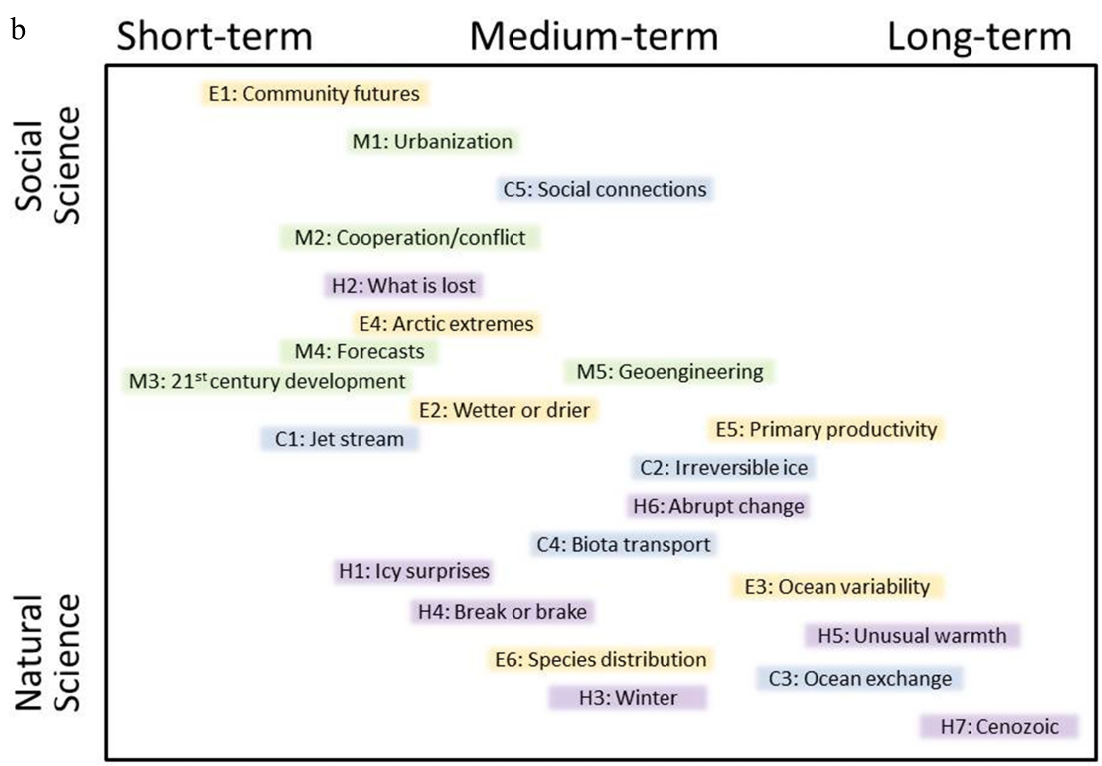
Short-term
Medium-term
Long-term
Direct applicatio
Basic understanding
M2: Cooperation/conflict
M3: 21st century development
M4: Forecasts
M5: Geoengineering
E1: Community futures
M1: Urbanization
C1: Jet stream
C5: Social connections
E4: Arctic extremes
H2: What is lost
C2: Irreversible ice
E2: Wetter or drier
H3: Winter
H4: Break or brake
H6: Abrupt change
E5: Primary productivity
E6: Species distribution
H1: Icy surprises
E3: Ocean variability
C4: Biota transport
H5: Unusual warmth
C3: Ocean exchange
H7: Cenozoic


b
Short-term
Medium-term
Long-term
Social Science
Natural Science
E1: Community futures
M1: Urbanization
C5: Social connections
M2: Cooperation/conflict
H2: What is lost
E4: Arctic extremes
M4: Forecasts
M3: 21st century development
M5: Geoengineering
E2: Wetter or drier
C1: Jet stream
E5: Primary productivity
C2: Irreversible ice
H6: Abrupt change
C4: Biota transport
H1: Icy surprises
E3: Ocean variability
H4: Break or brake
H5: Unusual warmth
E6: Species distribution
C3: Ocean exchange
H3: Winter
H7: Cenozoic

c

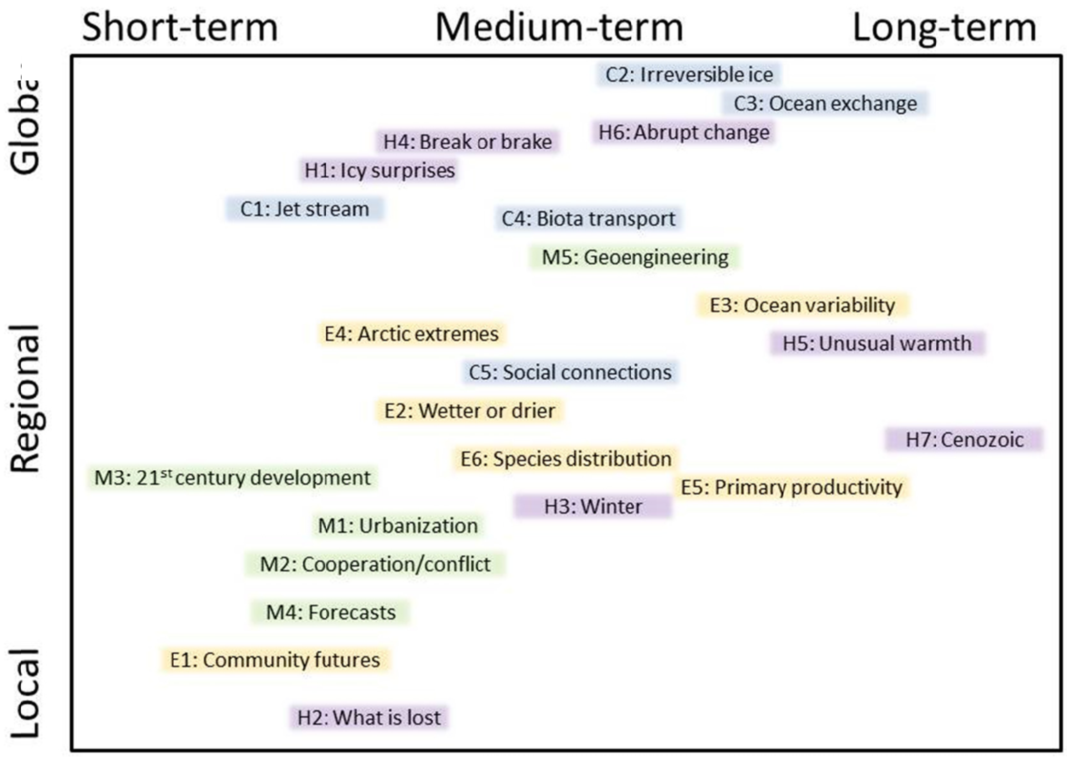


FIGURE 3.18 The emerging research questions are plotted with time relevance on the x-axis and (a) potential for contribution to basic knowledge versus direct application; (b) natural versus social science emphasis; and (c) local versus regional versus global geographic scope on the y-axis.

E1: Community futures. *Will Arctic communities have greater or lesser influence on their futures?*
E2: Wetter or drier. *Will the land be wetter or drier and what are the associated implications for surface water, energy balances, and ecosystems?*
E3: Ocean variability. *How much of the variability of the Arctic system is linked to ocean circulation?*
E4: Arctic extremes. *What are the impacts of extreme events in the new ice-reduced system?*
E5: Primary productivity. *How will primary productivity change with decreasing sea ice and snow cover?*
E6: Species distribution. *How will species distributions and associated ecosystem structure change with the evolving cryosphere?*
H1: Icy surprises. *What surprises are hidden within and beneath the ice?*
H2: What is lost. *What is being irretrievably lost as the Arctic changes?*
H3: Winter. *Why does winter matter?*
H4: Break or brake. *What can "break or brake" glaciers and ice sheets?*
H5: Unusual warmth. *How unusual is the current Arctic warmth?*
H6: Abrupt change. *What is the role of the Arctic in abrupt change?*
H7: Cenozoic. *What has been the Cenozoic evolution of the Arctic Ocean Basin?*
C1: Jet stream. *How will rapid Arctic warming change the jet stream and affect weather patterns in lower latitudes?*
C2: Irreversible ice. *What is the potential for a trajectory of irreversible loss of Arctic land ice and how will its impact vary regionally?*
C3: Ocean exchange. *How will climate change affect exchanges between the Arctic Ocean and sub-polar basins?*
C4: Biota transport. *How will Arctic change affect the long-range transport and persistence of biota?*
C5: Social connections. *How will changing societal connections between the Arctic and the rest of the world affect Arctic communities?*
M1: Urbanization. *How will decreasing populations in rural villages and increasing urbanization affect Arctic peoples and societies?*
M2: Cooperation/Conflict. *Will local, regional, and international relations in the Arctic move toward cooperation or conflict?*
M3: 21st century development. *How can twenty-first century development in the Arctic occur without compromising the environment or indigenous cultures while still benefitting global and Arctic inhabitants?*
M4: Forecasts. *How can we prepare forecasts and scenarios to meet emerging management needs?*
M5: Geoengineering. *What benefits and risks are presented by geoengineering and other large-scale technological interventions to prevent or reduce climate change and associated impacts in the Arctic?*

4
Meeting the Challenges

Southeast coastline of Greenland between 62.5 and 65.5 degrees north   Photo credit: Perry Spector

Studying emerging questions will require a combination of new and traditional approaches and tools. The questions require information at spatial scales ranging from meters for process studies to pan-Arctic and beyond to link high-latitude change to large-scale systems throughout the northern hemisphere. Understanding interactions among changing oceans, terrestrial systems, hydrologic processes, atmospheric dynamics, and social and economic systems will necessitate a broad suite of measurements and observations, obtained at regular time intervals and consistently over decades.

As detailed in this chapter, standard techniques that work in other regions often have deficiencies when applied to the Arctic. For example, remotely sensed data suffers from lack of appropriate validation data and a need for calibration to Arctic conditions. Social indicators often lack specific relevance to the Arctic. Long-term observations, networks of field-based measurements, and remote sensing techniques are needed to understand and quantify the effects of a changing climate and also to inform and validate modeling efforts, which suffer from chronic shortages of appropriate data with which to develop model parameters and to validate model results.

The sections of this chapter describe in more detail various ways research capability can be increased to help address the existing and emerging questions. Many of these improvements will

BOX 4.1
THE CASE FOR ENHANCED COOPERATION

The Department of Defense is increasingly considering the Arctic as a security concern, and recently highlighted the need for cooperation in the Arctic. The 2011 Fleet Arctic Operations Game Report notes, "As risk increased due to extreme climatic conditions and increased operating and support distances, there was a corresponding increase in the need for specialized information and capabilities. As this trend increased, the required information and capabilities became less available in the U.S. Navy and planners were forced to look elsewhere for the capabilities needed to execute their mission tasking. At the low end of the scale, these could be found inside DoD [Department of Defense], but eventually planners needed to rely on industry, international partners, or the whole of U.S. Government. This further reiterates that sustainability in Arctic operations is significantly dependent on strong relationships with international, regional and local partners in government and industry. Mechanisms that strengthen these ties should be prioritized in future planning" (Gray et al., 2011)

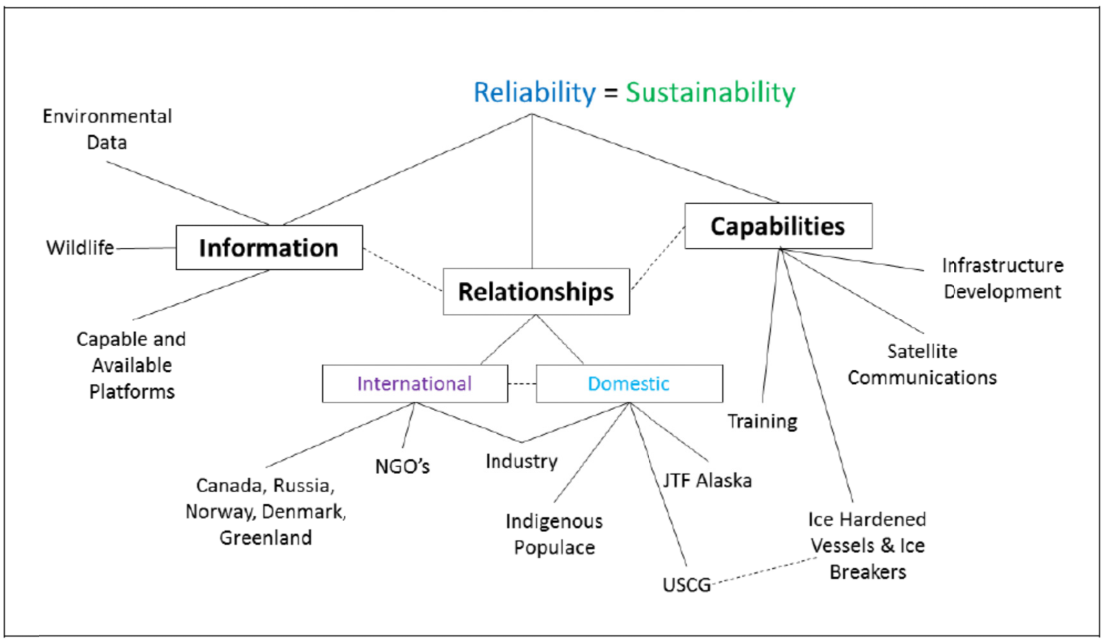


FIGURE This figure illustrates that reliability and sustainability are linked to specialized information and capabilities that are currently enabled by strong relationships. SOURCE: Gray et al. (2011).

require long-term planning, and all stem from the fundamentally collaborative nature of Arctic research. In keeping with the Committee's Statement of Task, we do not suggest specific actions to be taken, but instead raise key topics for consideration by funding agencies and others as they consider how best to address the questions discussed in Chapter 3, as well as how best to continue and improve the strong record of Arctic research described in Chapter 2.

ENHANCING COOPERATION

Effective Arctic research is international and national, interdisciplinary and disciplinary, applied and basic, private and public. Cooperation between and among many individuals, institutions, businesses, agencies, and countries will help to maximize investments in research, synthesis, outreach, and infrastructure (Box 4.1).

Interagency

Since the Arctic Research Policy Act of 1984, an interagency Arctic Research Plan is developed every five years. The Arctic Research Plan for FY2013-2017, released in February 2013, outlines interagency federal initiatives to better understand and predict Arctic environmental change. Following up on this plan was the first ever U.S. National Strategy for the Arctic Region, released in May 2013, calling for each agency to develop a coordinated strategy or implementation plan.

This alignment of effort within and between U.S. agencies, coordinated by IARPC, could have significant implications for the future of Arctic research if there is a concomitant investment in cross-agency sharing of research and infrastructure. The ongoing Study of Environmental Arctic Change (SEARCH) program and the Arctic Science, Engineering, and Education for Sustainability (SEES) competition run by NSF with cooperation from numerous other agencies are examples of what can be done when agencies decide to co-fund initiatives. Nonetheless, there is still a need for commitments to make the most of opportunities for joint studies across agencies. This is especially important when the missions of different agencies result in complementary work, for example in synthesizing findings from different research projects so those findings can be applied to meet the needs of various stakeholders. Some synthesis activities have taken place or are underway, but often as ad hoc efforts after the majority of research is done.

Cooperation across levels of government is as important as interagency cooperation. This exists in some forms, such as the North Slope Science Initiative in Alaska, which involves the federal government, state government, and local (North Slope Borough) government and aims to increase collaboration on monitoring, inventory, and research related to development activities. More can be done, however, to coordinate data collection, share costs, and develop a common basis of understanding regarding key issues affecting the Arctic.

International

Looking beyond the United States, understanding the Arctic is inherently global in nature. The circumpolar North spans the eight nations that constitute the Arctic Council and draws interest from dozens of other countries. Furthermore, changes in the Arctic have global implications. Existing and emerging research questions are often multi-dimensional across international domains. Arctic research and our ability to act on our knowledge benefit from cooperation with those who share an interest in Arctic matters.

One of the most influential developments in scientific discovery in recent decades is the internationalization of science. This is in part a result of the vast improvement in international communication. But it is at least equally a consequence of the nature of key scientific questions, which increasingly view the Earth as a system, within which understanding requires a global perspective. Trends in international scientific mobility (Van Noorden, 2012) document the increased national diversity of the scientific community, and emphasize the benefits of cross-fertilization of ideas and methodologies as we move toward a multicultural and interdisciplinary scientific world.

Much Arctic research is undertaken by U.S. researchers outside of U.S. territories, and by researchers from non-Arctic countries. A variety of formal and informal arrangements exist by which researchers and agencies cooperate with their counterparts in other countries, including the International Arctic Science Committee (IASC) and its associated bodies, the Arctic Council and its working groups, the International Arctic Social Sciences Association (IASSA), and the Association of

Polar Early Career Scholars (APECS). These collaborations help place findings from the U.S. Arctic in a wider context and provide a way to learn from experience elsewhere when it comes to applying science to management, regulation, and governance.

The International Polar Year demonstrated the tremendous value in international cooperation for Arctic research (e.g., NRC, 2012a). Far more was accomplished collaboratively than could have been done by any one country, regardless of Arctic research expenditures. Research under the Arctic Council similarly illustrates what can be accomplished by working together. The scientific community is looking forward to the new Belmont Forum Arctic Collaborative Research Action (CRA) focused on Arctic observing and Arctic sustainability science. The new Scientific Cooperation Task Force (SCTF) of the Arctic Council, co-chaired by Russia, Sweden, and the United States, is a promising step in the right direction. The SCTF will report to ministers in 2015 on ways to improve scientific research cooperation among the eight Arctic States.

There is a great deal of interest in cooperation among individual researchers, among agencies, and among countries engaged in Arctic research. But more could be done to collaboratively address existing and emerging Arctic research questions in a time of rapid change and rapidly expanding human presence. A potential method for fostering international collaboration beyond the level of individual researchers is to explore opportunities for U.S. projects (e.g., SEARCH) to work with international projects (e.g., ACCESS, ICE-ARC). The FY2013-2017 Arctic Research Plan recognizes this with references to the necessity for international partnerships to meet research goals, e.g., "Successful implementation of this five-year research plan will require close coordination among…international partners."

Improved collaboration is needed on both the funding of research that crosses borders (see Investing in Research section later in this chapter) and the logistics of doing international research. Arctic research frequently entails complex logistical arrangements, often international in scope, with long lead times to obtain permission to access remote field sites. But the necessity for international collaboration extends well beyond logistics. Access to the necessary analytical tools and remotely sensed imagery commonly requires international cooperation. Because of the geographically remote nature of much of the Arctic, specialized research platforms and instruments are often necessary to advance regional knowledge and understanding. These needs range from detailed in situ observations to satellite observations and from year-round manned field stations to research vessels. U.S. infrastructure in this regard is finite; international coordination of infrastructure and cost sharing is essential to take advantage of available observing platforms (e.g., ships, aircraft, fixed offshore platforms, coastal research stations). At present, individual projects have the responsibility to navigate these complex issues. A higher level effort to streamline this process would greatly facilitate research and the community is looking forward to the findings from the Arctic Council's SCTF on this issue. Coordination that extends beyond national and international organizations to active participation with the private sector is more likely to result in beneficial new insights. The scientific community also needs to be assured that there are data repositories where data in support of published research can be permanently archived in a format accessible across the international community, and to the public at large (see Managing and Sharing Information later in this chapter).

Interdisciplinary

Interdisciplinary cooperation leads to improved understanding of the complex interactions within and among the physical, biological, and social domains of the Arctic. Researchers often need time to learn to connect the theories, concepts, and language of one discipline to those of another, and for research teams to build a collective understanding of the phenomena they are studying. Interdisciplinary collaboration, however, is often difficult to initiate, and can be difficult to sustain without specific allocation of funding for such research. Yet it is in the connections between research domains that many emerging questions lay. Our ability to tackle these with vigor and success requires considering how interdisciplinary research is encouraged and supported, and what can be done to foster greater efforts in this area. A more strategic approach, with suitable direction from IARPC, will allow us to reap more benefit from our Arctic research efforts and expenditures (see Funding Comprehensive Systems and Synthesis Research later in this chapter).

Intersectoral

Also of substantial importance is the question of intersectoral cooperation, including public-private partnerships. The private sector sponsors a great deal of Arctic research, often related to the prospects for, and the effects of, industrial activity. Too often, such research is questioned or dismissed amid perceptions of bias due to funding source, but it is shortsighted to ignore the data and findings that come from private sector research. Similarly, it is shortsighted for most of this research to be kept proprietary. Findings of commercial value, naturally, belong to those who paid for them. But data concerning basic conditions or research that helps illuminate particular processes or changes is valuable for all, and the greater dissemination and use of such data and research can also help provide quality control, reducing the likelihood and perception of bias. Some efforts have begun in this direction, and after evaluation, effective efforts could be promoted and emulated (see Partnerships with Industry later in this chapter).

Cooperation through Social Media

Looking ahead, we need to explore the use of social media as cooperative sources of information as well as cooperative tools to inform decision making. As recommended in the International Study of Arctic Change report, *Responding to Arctic Environmental Change*, we need "development of an interactive, widely accessible, stakeholder engagement tool that can be used to develop new research priorities and research questions" (Murray et al., 2012). Establishment of issue trackers helps identify concerns emerging from communities. Social networking can then help with collecting knowledge through restructuring expert attention to bring in needed expertise and collaborators for problem solving (e.g., Nielsen, 2011). Regarding responses, social networking can encourage contributions—including through crowdsourcing, fostering local experimentation, disseminating knowledge and best practices, and supporting implementation elsewhere—thus spreading innovation among communities, agencies, and industry. Through these cooperative processes, social media can foster grassroots approaches to proactive management of Arctic change. Might social media also help with the knotty problem of making scientific products more useful for stakeholders? The Sea Ice Outlook along with the Sea Ice for Walrus programs are powerful examples. The SEARCH Sea Ice Outlook (Figure 4.1) synthesizes and publicly posts community estimates of the current state and expected minimum of sea ice. The Sea Ice for Walrus Outlook is a weekly report on sea ice conditions for subsistence hunters, coastal communities, and other interested members of the public. The Canadian Polar Commission recently launched the Polar Knowledge App, intended to expand public access to polar information.[16] In addition, some science blogs are interpreting scientific studies for a lay public and providing broader context.

SUSTAINING LONG-TERM OBSERVATIONS

Science depends on data. Individual projects generate data specific to their questions and hypotheses, but the interpretation of results usually relies on comparison of those results with data from longer periods or over larger areas, to place them in context. In many cases, this means data from long-term observations or monitoring—without which our ability to detect change, constrain models, and analyze the significance of research findings—is greatly diminished if not lost entirely.

[16] http://www.polarcom.gc.ca/eng/content/polar-knowledge-app

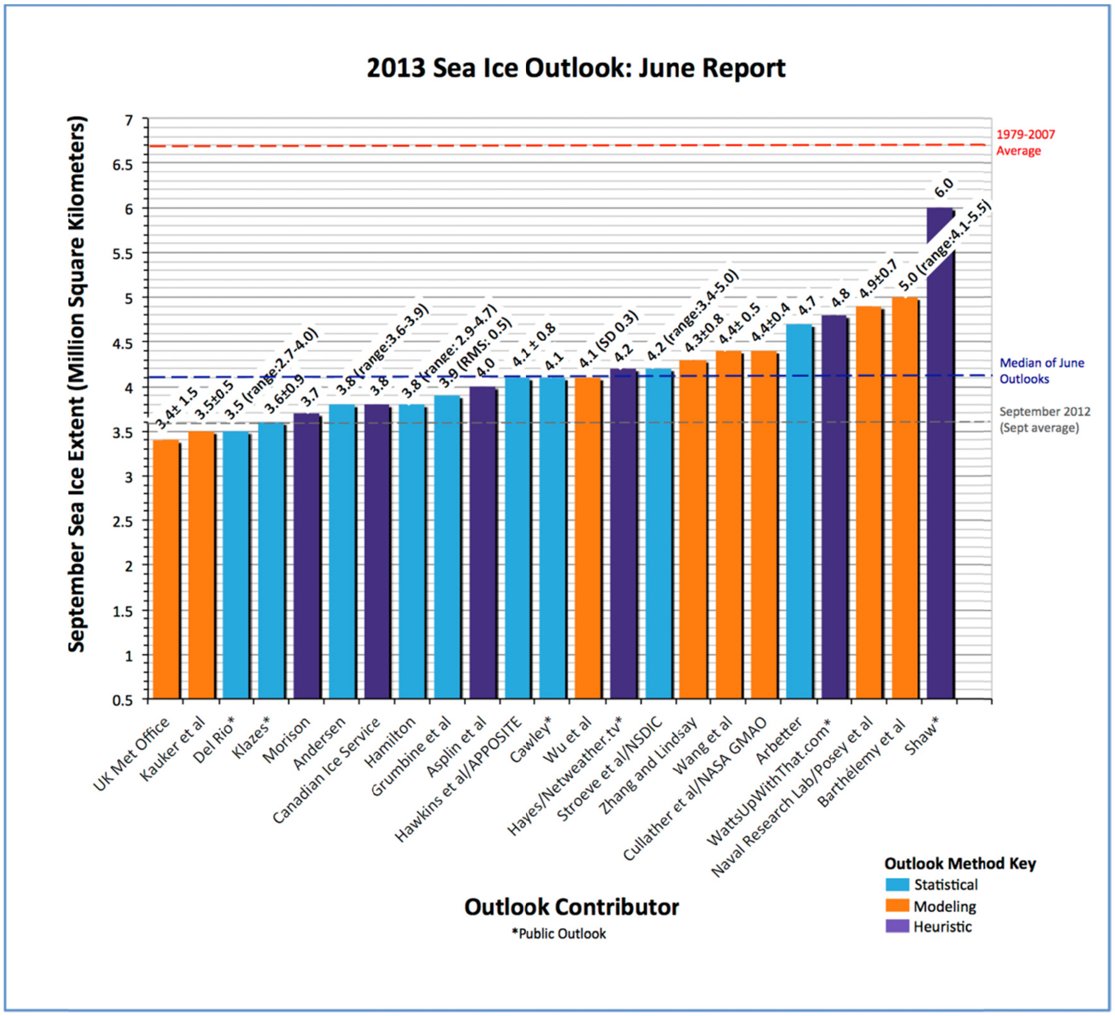


FIGURE 4.1 The Sea Ice Outlook from June 2013. The intent of the Outlook is to summarize all available data rather than issue predictions. SOURCE: ARCUS

Rationale for Long-Term Observations

A major challenge facing society is to ascertain, comprehend, and forecast rates and patterns of change across the Arctic that arise from physical, biological, or human causes. Society can address this challenge through an understanding of the resiliency and vulnerability of the Arctic system. Resiliency is the capacity of a system to withstand disturbances to its structure, function, and feedbacks (Folke et al., 2004; Walker et al., 2004) while vulnerability describes the extent to which a system is harmed due to exposure or sensitivity to stressor(s) and its adaptive capacity to respond to the stressor (Turner et al., 2003). When designed to characterize resiliency and vulnerability, monitoring, the long-term and systematic measurement of appropriate system characteristics, is essential in meeting this societal challenge.

When suitably constructed, monitoring systems serve a variety of purposes for a variety of stakeholders. On one hand, long-term observations enable quantification of the natural variability, over a range of temporal and spatial scales, of complex "noisy" systems. Once the "noise" is defined and quantified, long-term observations enable detection of gradual, systematic changes. On the other hand, because of the non-linear character of many systems, a carefully-developed monitoring scheme may detect abrupt and/or unanticipated changes (e.g., detecting what we *don't* *know we don't know*). In this capacity, long-term observations serve as part of an early warning system (e.g., NRC, 2013), which then allows for a choice of responses. These responses will vary depending upon the nature of the change, but could include collecting focused measurements designed to better understand the emerging phenomenon, development or initiation of mitigating procedures if deemed feasible, or, in the event of a potential catastrophe, appropriate emergency responses. Long-term observations also provide the temporal-spatial context in which shorter-duration, hypothesis-driven, process studies can be undertaken. In this context it allows researchers to determine whether the processes under consideration occurred under typical or atypical conditions. This was, for example, a key ingredient of the U.S. GLOBEC program[17] in which short-term process studies were embedded within the framework of a monitoring program.

Monitoring is a synergistic component in modeling and hypothesis development. It provides data sets necessary for the evaluation and development of models and/or suggests investigations needed to improve model parameterizations and/or processes. Models provide an integrated approach to understanding system behavior and can be used to modify the monitoring program as necessary. Models also augment monitoring efforts by suggesting how unsampled system components may be evolving. Monitoring and model results both contribute to the construction of hypotheses on how the system or parts of it operate.

Much of our recognition and understanding of the dramatic changes occurring in the Arctic has emerged from long-term observations. For example, routine measurements revealed the dramatic warming of the Arctic atmosphere and the accelerating decline in sea ice; both consistent with some of the earliest model predictions of climate response to greenhouse gas warming (Manabe and Stouffer, 1980). Another example is the systematic approach adopted by the Arctic and Bonanza Creek Long-Term Ecological Research (LTER)[18] programs conducted in the tundra and boreal forest biomes of Alaska, respectively. While independently initiated, these LTERs are established along a latitudinal and ecological gradient and each attempts to understand the resiliency and vulnerability of the respective biome to a warming climate. Both LTERs have been in existence for at least 25 years and involve myriad interdisciplinary process studies and modeling activities. Although different investigators are involved in each, there are consistent efforts to compare and contrast the results across biomes.

One important result that has emerged from the integration of plot-scale long-term studies of vegetation dynamics, fire cycles, and their links to climate in the Bonanza Creek LTER (Van Cleve and Vierech, 1981; Van Cleve et al., 1983) and broader scale measurements of a series of wildfire-disturbed boreal forests of interior Alaska, is the likely shift in some Alaskan boreal forests from a spruce- to a broadleaf-dominated landscape due to increased burn severity (Figure 4.2). This transition to more high severity wildfires is occurring in conjunction with thawing of permafrost and the decomposition of previously frozen organic carbon in boreal forest soils. Through large-scale manipulation experiments at the Arctic LTER at Toolik Lake researchers have found that response to heating soil, shading, or altering soil moisture is slow, with responses delayed until 9 or 10 years post initiation of the treatment (Hobbie and Kling, 2014). These experiments are designed to explore future effects of continuing climate change, but at an accelerated rate. The LTER observations and experiments predict increased productivity and biomass of grasses and shrubs by the end of this century, and an eventual shift from tundra to boreal forest with great disruption of fish and wildlife habitats (Hobbie and Kling, 2014). Whole-ecosystem experiments conducted at the Arctic LTER near Toolik Lake, which have been continued for more than two decades, have provided great insight into aboveground production and biomass in moist tussock tundra. They have demonstrated that the vegetation response to marked climate warming is relatively small when compared to annual variation. Linking these longitudinal studies at the LTERs with shorter term, but broader scale studies offers opportunity to improve understanding of the changing Arctic and boreal landscape.

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[17] http://www.usglobec.org/
[18] http://www.lternet.edu/sites/bnz?

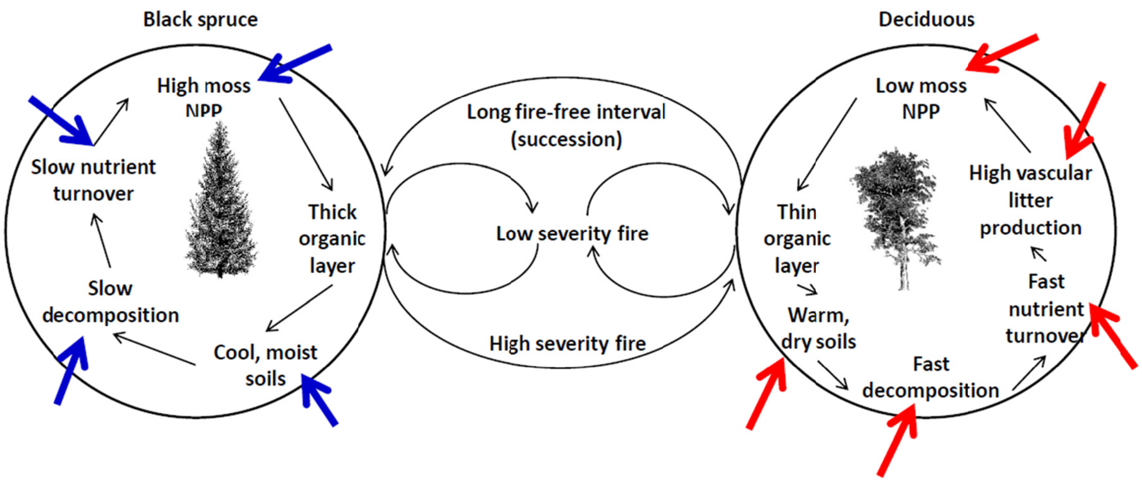

FIGURE 4.2 Conceptual model showing the shift in resilience cycle from a coniferous-dominated (left) to a hardwood-dominated system (right) triggered by an increase in fire severity. High organic matter thickness following low severity fires in black spruce allows for the regeneration of slow-growing woody plants, inhibits hardwood regeneration, and results in rapid reestablishment of a thick moss layer that insulates the soil and permits the return of permafrost. High severity fires remove thick organic layers and allow for the rapid establishment of hardwoods, which store large amounts of C and N in aboveground biomass, and create conditions (high litter quality and warm soils) that accelerate forest floor decomposition rates. SOURCE: Adapted from Johnstone et al. (2010).

Coordinating Long-Term Observation Efforts

As outlined above, the guiding principles behind a monitoring effort seem logical, but the design of a monitoring program in a system as complex and diverse as the Arctic is far from obvious. A number of questions arise immediately. What is the purpose of a particular monitoring activity? How is it integrated into other monitoring efforts, including those in other regions and/or disciplines? Where should the long-term observations occur? How long should the program continue? What are the specific variables to be measured, at what rate, and over what time and space scales should these be sampled? What measurement techniques (including calibration and algorithms used in interpreting the data) should be used? Who should perform the measurements? Who should pay for it? Who evaluates the utility of the measurements? Who interprets and synthesizes results? How do we ensure that the results of individual efforts are blended into a coherent picture of the emerging Arctic that is of use to stakeholders and society? Although this committee recognizes the importance of these questions, it cannot provide definitive answers, and rather suggests that the following issues be considered.

Involvement of northern communities is an important component of monitoring efforts in the Arctic. This includes not only the use of traditional knowledge, but also the involvement of local residents in data collection (e.g., Huntington et al., 2011; Alessa et al., 2013). We expect that a carefully developed approach that involves local residents would provide numerous benefits (see Growing Human Capacity section). Local involvement can enhance cross-cultural communication including ideas about research strategy and interpretation, provide an important degree of ownership by local residents in the measurements being made, stimulate the involvement of decision makers (Danielsen et al., 2010) and schoolchildren within these communities, enhance seasonal coverage, and facilitate overall logistics.

Successful monitoring programs address linkages between different parts of a system (e.g., Alessa et al., 2009; Liu et al., 2013). The Arctic spans a broad latitudinal range that encompasses a number of physical, biological, and social systems. The acquisition of societal data—demographic, infrastructure, health, economic—is essential for many purposes. As such, there are many national and more localized efforts to collect such data, from national censuses to local surveys. The results of these programs are widely used in social science and other research, but they have drawbacks. Some, like the U.S. Census, are only carried out every ten years, providing only coarse temporal resolution. In other cases, different jurisdictions collect information on different aspects of a topic, such as subsistence harvest production versus participation in hunting and fishing. The indicators that are documented are usually chosen for purposes other than scientific research and rarely with the specific context of the Arctic in mind (e.g., AHDR, 2004; Baffrey and Huntington, 2010). The Survey of Living Conditions in the Arctic (SLiCA[19]) has attempted to remedy this shortcoming by developing indicators of specific relevance to Arctic societies and their needs, but cannot gather all that is needed, leaving many gaps in our ability to connect societal trends with each other or with biophysical processes. The Arctic Social Indicators project, which follows up on the activities of the Arctic Human Development Report (AHDR, 2004), offers ideas for indicators of Arctic human development. Other measures of societal factors include adaptive capacity indicators (ACIs), which could be further developed for the Arctic to allow systematic assessment of adapting to change and allow communities and decision makers to weigh trade-offs in adaptation investments (e.g., Fussel, 2009). Efforts such as these, while limited, can yield lessons about the challenges of collecting societal data.

Monitoring efforts that address the physical and biological systems of the Arctic include observations of the atmosphere and cryosphere and their interactions with the boreal forests and the tundra biomes in the terrestrial realm and the broad continental shelves and sub-basins of the marine environment. Each evolves and processes energy and materials in distinctive ways, subject to external forcing. Each also communicates with other systems through energy and material exchanges along a variety of pathways. For example, the marine and terrestrial environments are linked to one another through species migrations, river systems, changing glacial landscapes, and ocean currents. Some of the results from the Bonanza Creek LTER illustrate how addressing linkages within a monitoring program could be considered. That research indicates an increase in carbon export into Arctic river networks as a result of the degradation of permafrost and fire disturbances (Kicklighter et al., 2013). It is also apparent that rivers are the primary pathway by which mercury is entering the Arctic Ocean (Fisher et al., 2012) and that riverine mercury concentrations are likely to increase due to an increase in soil disturbances (Fisher et al., 2012; Leitch et al., 2007). This has implications for the Arctic Ocean's carbon and suspended sediment cycles, trace metal budgets and the Arctic trophic system. An appropriately designed Arctic monitoring system would include measurements of state variables and rates of critical processes within each system and energy and material fluxes along the pathways linking each to the other.

Within the marine environment a similar ecological/latitudinal gradient monitoring approach is evolving in the Bering, Chukchi, and Beaufort Seas under the auspices of the Distributed Biological Observatory (DBO)[20] program (Grebmeier et al., 2010). The DBO program is an international effort involving Canadian, Chinese, Korean, Japanese, Russian, and U.S. scientists collecting data and coordinated through the international Pacific Arctic Group[21] and within the United States, through the IARPC DBO Interagency task team. As conceived, the DBO is a holistic approach to track and understand the effects of changing oceanographic and sea ice conditions on the marine ecosystem. Until recently, bio-physical sampling has occurred at several shelf biological hotspots from research vessels-of-opportunity that transit the region. The biological sampling, which samples water column and benthic organisms, seabirds, and marine mammals, to evaluate species composition, biomass, and the size and condition of key organisms, also includes standard physical oceanographic and nutrient measurements. The shipboard sampling is largely limited to the open

[19] http://www.arcticlivingconditions.org/
[20] http://www.arctic.noaa.gov/dbo/
[21] pag.arcticportal.org

water season but is supplemented by satellite measurements and data from oceanographic moorings (two of the DBO sites have biophysical mooring arrays and two sites have only physical mooring arrays). However, at present many of the moorings are of temporary duration as components of limited-duration process studies being undertaken in the region both nationally and internationally. Although the DBO program provides an emerging opportunity for assessing bio-physical changes over western Arctic shelves, a more concerted effort to coordinate and systematize the sampling over seasonal and interannual scales will be necessary. As a result of western Arctic DBO activities, the Norwegian government is proposing a similar DBO project in the marine waters surrounding Svalbard.

The sampling strategy (duration, sampling rate, spatial extent, locations) of a particular monitoring effort will vary depending upon the process or variable of interest. There will be a need to measure key system attributes at multi-decadal time scales at relevant rates and obvious locations. Other monitoring efforts need to be adaptive, taking into consideration results that emerge from retrospective (including paleoclimatic) studies, models, and other observations. These may suggest a hypothesis-based observation approach, perhaps of shorter duration (3 to 5 years) with a specific focus. If the results are found to address a critical need, then the sampling may transition into a longer-term effort. An adaptive monitoring effort also allows for the findings of an intensive process study to adjust monitoring activities. Statistical approaches or data assimilation models can aid in devising optimal sampling strategies. However, it is almost certain that resources will be inadequate to execute an optimal sampling strategy for many relevant variables. Here again, data assimilation models might clarify the trade-offs in designing options for sub-optimal (from a statistical perspective) sampling designs. Periodic evaluation can be used to determine whether the monitoring efforts need to be modified, augmented, or suspended.

The breadth and complexity of the Arctic system requires that long-term observations be a shared undertaking, involving international partners and coordinated efforts by government agencies, industry, communities, and scientists. We recognize the difficulties inherent in such coordination given the different mission of each potential partner. Nevertheless many or some of the core variables comprising a monitoring program will ideally meet disparate missions. One coordinating approach to consider is a national committee composed of various stakeholders and scientists. The committee's charge would be to: 1) enhance coordination among monitoring activities at both the national and international level; 2) seek opportunities to increase sampling efficiencies and organize responses to "surprises"; 3) address the various needs of the diverse suite of stakeholders that benefit from long-term observations; 4) assist in prioritizing these needs among stakeholders; and 5) communicate monitoring activities and results to policy makers and stakeholders in a coherent manner. Such a committee could be organized by an existing entity like IARPC.

MANAGING AND SHARING INFORMATION

Just as science depends on data, scientific progress depends on access to data. As Arctic research expands, and as datasets grow rapidly in an era of information technology, keeping track of what has happened before is increasingly difficult. Current efforts to coordinate data management and access are commendable, but much remains to be done. Further progress is likely to depend upon concerted and coordinated efforts rather than reliance primarily on individual researchers or funding programs.

Arctic science has a history of large and interdisciplinary programs, so there is some precedent for successful management of complex data sets. The need for interdisciplinary and intersectoral management is not limited to the Arctic, and there is an opportunity for the Arctic research community to become a leader in developing a culture of data management and sharing. Strategies for achieving the greater cooperation necessary for such a culture were addressed earlier in this chapter, and specific suggestions for managing and sharing information are presented in this section.

Preserving the Legacy of Research through Data Preservation and Dissemination

We now understand the Arctic is a tightly coupled, integrated system, where changes in one component will reverberate through the system initiating a cascade of impacts in other components of the system (Roberts et al., 2010). Understanding and quantifying these system interconnections is only possible through simultaneous analyses of extensive and often numerous complex data sets from disparate sources. As scientific urgency drives our research endeavors to collect more observations at greater frequencies and increased numbers of sites, we are compelled to develop new techniques to analyze these massive data sets (Pundsack et al., 2013). Additionally, the realization of the value of well-documented data for application in new and different analyses places utmost priority upon data preservation, stewardship, and access by multiple stakeholders. This not only places great responsibility upon individual scientists and agencies, it elevates the collective responsibility of all engaged in Arctic research to strive to garner the greatest value from our investments in observations and monitoring. The recently published U.S. Arctic Research Plan (Executive Office of the President, 2013) has charged all agencies to "demonstrate new and updated cyberinfrastructure tools to enhance data integration and application and identify opportunities for sharing of technology and tools among interagency partners."

To meet these pressing needs for more efficient utilization of our data resources, it is imperative to establish interoperable data management system(s) that are adequate for academic needs and to assess progress against agency/collaboration goals. Developments in the field of informatics could yield important lessons for managing large amounts of data and creating interoperable systems. Our present system of data submission by researchers and curation by institutions often results in gaps in data awareness, distribution, and quality of metadata. An additional challenge for data management remains achieving interoperability of biophysical and socioeconomic data, as well as how to integrate traditional ecological knowledge. Integrating data management and quality control into network design aids in overcoming such deficiencies. Currently, tremendous amounts of work are required by researchers who compile data from various sources. Prescribed formats to be used by all agencies, with structured data submission, archiving, and delivery would greatly enhance efficiency of analyses by the broader community. One solution would be to create an interagency data management committee (possibly through IARPC) to coordinate structure and dissemination protocols. This committee could identify high-priority data sets and identify responsible agencies to support data collection. Additionally, advances in curation technology will make integration of diverse data sets easier and analysis of disparate data streams seamless.

Creating a Culture of Data Preservation and Sharing

Many advances in Arctic science have resulted from broad scale synthesis of relevant data streams. These advanced analyses have been possible due to technological advancements in computing power and search capabilities. However, we can foresee even greater advances on the horizon with the advent of data archiving and harvesting techniques. Data curation has long been recognized as an essential function of operational agencies, but has only recently been acknowledged as an individual responsibility of every investigator. Moving forward with every scientist accepting a commitment to preserve and share their data will greatly enhance our capabilities. To realize the utopian community of data sharing, it may be necessary to encourage data submission by requiring a portion of each grant be dedicated to data curation. Concurrently, we need to establish a robust method of documenting and crediting data sharing through a formal citation protocol. Also, such magnanimity of data sharing has not always been the standard; support will be necessary to secure older, stranded data sets and rescue those high-quality observations that may provide essential clues to past rates of change.

Infrastructure to Ensure Data Flows from Observation to Users, Stakeholders, and Archives

The service provided by formal data centers is clearly an imperative, however it is quite difficult to secure funding to support such centers. Critical components of our research infrastructure are agency-supported data centers, which are mission- and discipline-specific, yet inter-connected and transparent in terms of data accessibility. Reliable computer systems for storing, accessing, and assessing the quality of data are the crucial backbone of institutional repositories. Compatible architecture using a shared cloud environment as a computer platform would greatly enhance data sharing and transparent accessibility.

Real-time monitoring networks are indispensable for detecting and documenting change, providing validation for model simulations, and elucidating the quantitative relationship among related processes (see Maintaining Long-term Observations section earlier in this Chapter). It is essential that we sustain a commitment to maintain monitoring networks for the long term, but it is also important that we establish a more seamless flow of data from the observations, through quality checking/quality control, into a permanent long-term archive. The flow of data from our observing networks into permanent archives can be disrupted or delayed, limiting our capacity for analyses and syntheses.

A similar challenge arises when working with the traditional knowledge and local observations of Arctic residents. Field scientists have long valued the knowledge and wisdom of local residents. Roald Amundsen spent 1903 to 1905 in what is now known as Gjoa Haven, Nunavut, Canada, collecting magnetic measurements and learning from Inuit (Amundsen, 1908). These lessons in Arctic survival gave him the knowledge required to complete the trek to the South Pole in 1911. The collective experience of local observers and knowledge passed from one generation to the next reveal evidence of the changing climate and environmental and ecosystem responses to those changes, but this information source has not been fully utilized for the potential value for either inquiry-based science or as model validation data (Huntington, 2000; Huntington, 2011. It is incumbent upon the Arctic research community to more fully engage local residents as partners and collaborators to ensure the changes observed today are correctly positioned in historical context and that projections of future change connect environmental and social responses. Such an effort would help address the problem of things we *think we don't know*, as described in Chapter 2. The Exchange for Local Observations and Knowledge in the Arctic (ELOKA) is among those working to address this challenge (Pulsifer et al., 2012).

Data centers need to also serve a dual mission of archive and synthesis, capable on integrating individual projects, real-time data streams, traditional knowledge, and "big data" that are now accessible through a myriad of data mining techniques. We are presently limited in our ability to achieve major scientific advances because of technological limitations in our capacity to efficiently synthesize and analyze big data. The field of bioinformatics, the science of creating an understanding of complex biological systems by leveraging large datasets and computing power, is a mature field. Geoinformatics, using similar techniques in Earth science applications, is by contrast relatively nascent. The big data necessary for such endeavors are emerging from existing sensor networks and geophysical observatories currently placed in the Arctic, and also planned for the future. Such big data processing capability enhances our capacity for integration, synthesis, assimilation, and assessment and lends promise to sweeping advancements in climate, ecosystem, and socioeconomic science. The culture of data sharing and a strong set of data management standards are crucial for the burgeoning field of geoinformatics and deserve high priority.

The goal of an Arctic cyberinfrastructure (CI) is to provide freely and openly accessible quality-controlled data sets to a variety of users, including the public, management agencies, industrial users, educators, and scientists. To achieve this goal, computing infrastructure needs the capability to integrate data from diverse sampling platforms (e.g., including autonomous sensors collecting time-series data, process-oriented, but relatively short-lived field programs, and traditional ecological knowledge) interactively into a coherent architecture. Ideally such a system would permit users to:

- analyze and model Arctic processes;
- develop and test hypotheses;
- adjust measurement strategies to allow for adaptive sampling;
- facilitate responses to environmental events;
- enhance predictive capabilities on both short and long time scales; and
- contribute to the maintenance and reliability of the measurement systems.

At a minimum the Arctic CI requires data preservation and access as has been performed traditionally by centrally managed data archives that ingest and serve metadata and data. More advanced data centers such as the Advanced Cooperative Arctic Data and Information Service (ACADIS) and the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) also provide software and advice on metadata and data submission and facilitate data searches, access, formatting, and visualization. ACADIS is a joint effort by the National Snow and Ice Data Center (NSIDC), the University Corporation for Atmospheric Research (UCAR), UNIDATA, and NCAR that was established to provide data archival, preservation, and access for projects funded by NSF's Arctic Science Program (ARC), including the Arctic Observing Network (AON). ACADIS also links to the EOL holdings and the data archive of the NSIDC. In addition, ACADIS is presently hosting the PacMARS data archive. PacMARS is attempting to link, under one data archive umbrella, the large number of marine-related data sets (including those funded by agencies other than NSF) from the northern Bering, Chukchi, and Beaufort Seas.

Data sources from outside the U.S. academic research community (including those of international scientists and governments, U.S. state and federal resource managers, industry and the military) will also need to be integrated. SAON was established for this purpose with a goal to "support and strengthen the development of multinational engagement for sustained and coordinated pan-Arctic observing and data sharing systems that serve societal needs, particularly related to environmental, social, economic and cultural issues" (SAON, 2011). The challenges of sustaining international observing networks have impeded success in promoting open access to data amongst various national data archives. Additional international partnerships and agreements are necessary to promote truly transparent data access, which will open up new avenues of research and application from a variety of stakeholders. For example, the Department of Defense's first ever Arctic Strategy (2013) stated "DoD will also collaborate with international partners to employ, acquire, share, or develop the means required to improve sensing, data collection and fusion, analysis, and information-sharing to enhance domain awareness appropriately in the Arctic" (DOD, 2013).

The existing Arctic CI facilities allow achieving the goals listed above to varying degrees. However, as Arctic observing and modeling programs become more interdisciplinary and more comprehensive networks of autonomous measurements evolve, a more sophisticated CI system is desirable (Pundsack et al., 2013). Such a system might follow the design criteria and incorporate the various elements of the developing CI components of NSF's Ocean Observing Initiative's (OOI) and NOAA's Integrated Ocean Observing System (IOOS). Both programs ingest and serve data in real time from a large number of autonomous sensors. To take full advantage of such autonomous systems, we need to simultaneously improve our communications capability to enable access to sensor networks in extremely remote locations. Presently, lack of infrastructure and high-power requirements of some communication packages place insurmountable limitations on remote monitoring capabilities. As outlined by Chave et al. (2009), the OOI system includes the capability for operator-to-machine and machine-to-machine control of data collection and analysis, enable model interaction with data acquisition processes, support virtual collaborations of observing system resources among a variety of uses, and provide some degree of automation in the planning and execution of observing system components. In addition, the OOI CI acts as an operating system that provides the messaging, governance, and service frameworks for the system. Meisinger et al. (2009) suggest that this architecture take advantage of the cloud computing environment, which facilitates scalability and flexibility. Scalability addresses users' requirements that may encompass a broad range of time and space scales and information types. Flexibility allows for the incorporation of technological developments in distributed networks, sensor technologies, models, and computing. These developments are well underway and the lessons learned from these activities are likely to prove valuable in guiding improvements to an Arctic CI.

Data Visualization and Analysis

Many gains have been made outside the Arctic science realm that could be brought to bear on problems related to the Arctic. From this, we may find a wealth of what we *think we don't know*.

Visualization technology is highly developed in the computer gaming industry, both in hardware and software and such technology can be applied for scientific use. Additionally, visual analysis in industry has become highly advanced; for example the seismic visualization capability of the oil industry. Leveraging advances like these for the use of Arctic scientists and stakeholders could result in significant gains at modest cost. Many users of data have a need for quick, easy visualization. Steps in this direction have been taken internationally through the Arctic Monitoring and Assessment Program of the Arctic Council[22], the Arctic Portal[23], World Wildlife Fund[24], Conservation of Arctic Flora and Fauna[25], and nationally through NOAA's Arctic Environmental Response Management Application[26] (ERMA), NOAA's Earth Systems Research Laboratory[27] (ESRL), and the emerging Arctic Collaborative Environment[28] (Figure 4.3).

Once databases have the right data in terms of space (e.g., include downscaled model results), time (e.g., real time when possible), and utility (e.g., useful for both basic research and decision support), the visualization challenge posed here is to generate or determine a system that can adapt to differing data formats, dimensions, and other factors as well as to generate products responsive to the spatial and temporal requirements and formats needed by various user communities. Further, the ability to generate quantitative information becomes important. Methods of analysis (such as differencing, statistical tools, and more complex numerical analyses) are integral needs of such visualization packages. Success depends upon an increase in the types and range of visualization data (e.g., completing multi-beam surveys in the Arctic Ocean, improved access to satellite visualizations, development of real-time interactive visualizations so that sensors can be activated based on automated visual analyses).

In addition to visualization technology, the gaming industry has produced hardware that has been co-opted into the scientific community. See, for example, the applications of the Microsoft

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[22] http://www.amap.no/
[23] http://portal.inter-map.com
[24] http://arkgis.org/about-us.aspx
[25] http://www.caff.is/
[26] https://www.erma.unh.edu/arctic/erma.html
[27] http://www.esrl.noaa.gov/psd/data/histdata/
[28] https://ace.arsc.edu/

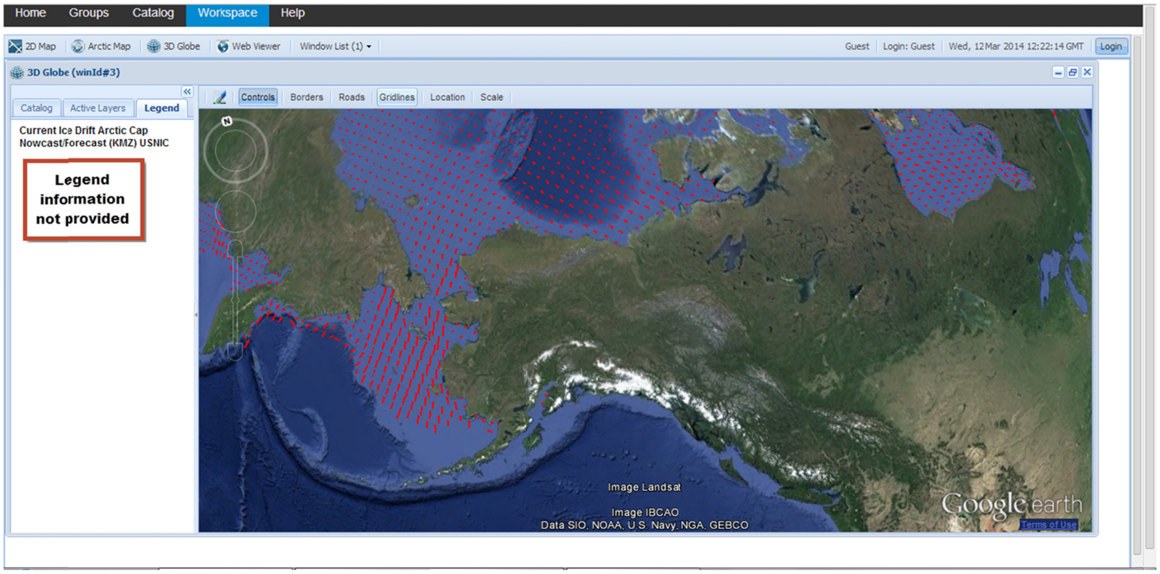

FIGURE 4.3 "Arctic Collaborative Environment (ACE) Joint Capability Technology Demonstration (JCTD) is an internet-based, open-access, Arctic-focused, environmental research and decision support system that integrates data from existing remote sensing assets with products from existing and new environmental models to provide monitoring, analysis, and visualization based on earth observation data and modeling. With an initial focus on the Arctic region, researchers, students, search-and-rescue operators, native hunters, etc. can draw from the open-access data." SOURCE: https://ace.arsc.edu/workspace.

Kinect (Mankoff and Russo, 2013). Another example is the integration of Graphics Processing Units into massively parallel computing architectures.

Miniaturization of data logging and wireless technologies including video is a technology transfer issue. For example, modern smartphones contain vanishingly small cameras that are of increasing quality for both still images and video. In addition, the wireless capability of these devices is impressive. The only (significant) deficiency is robustness. These devices are already being investigated for acquisition and control applications.

Digital photogrammetry from traditional aircraft is an underutilized resource. For example, NASA's Operation IceBridge has flown numerous missions over the Arctic for the past several years, primarily covering targets on land- and sea ice (e.g., Studinger et al., 2010). Each flight carries the Digital Mapping System nadir-viewing camera; from this camera there is sufficient overlap on images to allow stereo photogrammetry.

MAINTAINING AND BUILDING OPERATIONAL CAPACITY

> It's getting harder and harder to find a proper block of ice to sustain one of these stations.
> — Viktor Bovarsky, former polar explorer

It is critically important to establish and maintain consistent networks of measurements and robust infrastructure to detect Arctic changes. There is a general lack of in situ infrastructure across the Arctic, including both mobile and fixed observing systems. Some long-term observatories are being discontinued and some satellite systems are now retired, which has created a gap in observing.

Observations need to be comparable across individual sites, allowing for network-wide analyses and integration. Often there is a need for rapid response. Observations need to be carried through autumn, winter, and spring, not only in the convenient summer season. There is a need for in situ observations along the coast and below the sea surface as well as coastal observing because most remote systems (i.e., satellites) have low resolution in coastal zones and no data are collected below the sea surface. Finally, we need to leverage connections with industry.

Mobile Platforms

Mobile platforms are important for monitoring physical, biological, and chemical oceanographic changes in the Arctic Ocean. Mobile platforms include floats (e.g., Argo), autonomous underwater vehicles (AUVs), ocean gliders, remotely operated vehicles (ROVs), and larger platforms such as ships. Recent advances in miniaturizing sensors have also enabled the use of marine mammals as mobile platforms (e.g., the ocean tracking network), which could be extended to smaller animals in other environments as well.

Submersible Platforms

AUVs, such as buoyancy-driven ocean "gliders", propeller-driven AUVs, and Wavegliders[29] have substantial potential for environmental monitoring, ocean process studies, and inspection of industrial facilities in the Arctic Ocean and its adjoining shelves. Each of these vehicles can collect high resolution data that may be transmitted in near real-time. Mission protocols can either be pre-programmed or adjusted at sea to permit adaptive sampling. These vehicles operate differently from one another and can be used independently or collaboratively. Both gliders and AUVs have been applied extensively in open water settings and now increasingly in the ice-free waters of the Arctic (e.g., Shroyer and Plueddemann, 2012; Timmermans and Winsor, 2013). All of these vehicles come in a range of sizes and capabilities. Deployment and recovery of the smaller vehicles can be done by hand from small vessels (including skiffs) and/or through the ice, while larger vehicles require mechanical aids (hence larger vessels or ice camps).

AUVs are well-suited for mapping missions because their navigational ability is more precise than gliders, especially if guided by transponders. However, their endurance is limited to hours to days because their propulsion systems consume considerably more power than gliders. Under-ice AUV operations have a long history (e.g., Francois and Nodland, 1972) with recent applications including under-ice mapping (Wadhams, 2012), seafloor exploration (Kunz et al., 2009), bathymetric mapping (Crees et al., 2010) and coastal hydrography (Plueddemann et al., 2012).

Gliders move vertically by adjusting buoyancy and use wings and a rudder to control horizontal motion. They have relatively long endurance (weeks to months) and can carry a diversity of sensor packages, although these are limited by size, weight, and power consumption. Under-ice glider operations are a more recent development (Curry et al., 2013). Wavegliders ride the ocean surface and harness wave energy for their propulsion and solar power for recharging their communications and sensor systems. Wavegliders have been used in mid- and low latitudes, but their performance at high latitudes has yet to be evaluated.

Gliders and AUVs can incorporate a variety of sensors, although the sensor configuration (and subsequent mission) may be limited by the size of the vehicle and the power required for the sensor configuration. Nevertheless, gliders and AUVs easily support standard oceanographic sensors (e.g., Conductivity, Temperature, Depth [CTD] instruments, optics), while AUVs can also incorporate Acoustic Doppler Current Profilers (ADCPs), side-scan and/or ice profiling sonars. Each

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[29] manufactured by Liquid Robotics (http://liquidr.com/technology/wave-glider.html)

vehicle has the potential to incorporate passive acoustic recorders for marine mammal detection. As new ocean sensors evolve, many of these are likely to be easily adaptable to one or more of these vehicles. Sensor packages for Wavegliders are more limited given their size and that their propulsion mechanism limits the depth to which sensors can be deployed. Nevertheless, Wavegliders could be useful in sampling the uppermost 5 to 10 m in ice-free conditions during the summer months.

There are several hurdles to overcome to expand the use of gliders and AUVs in the Arctic. For example, gliders have difficulties navigating under ice, although the under ice navigation approach of Curry et al. (2013) is promising. Those approaches will be further refined as outlined in the Office of Naval Research's Marginal Ice Zone Program (Lee et al., 2012). In some regions of the Arctic, swift currents may result in glider loss or prevent the glider from conducting or completing its mission. Depending on the capacity of its buoyancy engine, strongly stratified waters (associated with ice melt and/or river outflows) may prevent the glider from surfacing. Larger buoyancy engines such as used in the Exocetus Coastal Glider (Imlach and Mahr, 2012), could overcome the impediments associated with swift currents and stratification. Through-ice glider deployments and recoveries also deserve further exploration. Necessary glider improvements include incorporating inertial and acoustic navigation systems and a glider propulsion mechanism that would be used intermittently to enable gliders to navigate precisely to an ice hole for recovery.

A variety of short-duration, attended AUV deployments under ice have been demonstrated. Extended, unattended operations beneath the ice in the high Arctic will require substantial new developments for navigating, providing power, and communications. This includes an autonomous on-ice power and communication system that drifts with the ice and includes a through-ice docking port by which the AUV can re-charge its batteries, transfer data to the surface, and receive new mission guidelines. It will also require the distribution of an acoustic transponder network (drifting with the ice or fixed on moorings or on the ocean floor) and acoustic modems for passing the position of drifting beacons to the vehicle. Improvements in decision-making software for docking and for choosing the appropriate set of transponders by which to navigate are also needed. An alternative docking scenario may be feasible in the event that offshore hydrocarbon development occurs and subsea pipelines extend onshore. It may be possible to incorporate fixed AUV docking ports and communication and power cables with the pipeline.

While these are formidable hurdles, many of the necessary elements are currently being developed. A specific challenge is to merge these capabilities into an integrated system for use in the Arctic. Substantial advancement is anticipated over the next three to five years driven by scientific research as well as interest in seafloor mapping and subsea resources. For example, the OOI is addressing unattended AUV power and re-charge systems, data storage and communications, and two-way command and control issues. A prudent course of action would be to allow successful resolution of these issues by the AUV community, while simultaneously planning how to adapt AUVs for the unique conditions of the Arctic. It is nevertheless conceivable that such a system may be feasible and applicable to the Arctic within the next 10 years.

In addition to autonomous vehicles, there is a variety of drifting sensor platforms (buoys) that have been developed for Arctic Ocean applications. These buoys are either installed into and drift with the ice or drift in the ocean below the ice. These include Ice Mass Balance (IMB) buoys (Jackson et al., 2013; Richter Richter-Menge et al., 2006) designed to determine rates of ice and snow accretion and ablation, autonomous ocean flux buoys (AOFB) that measure the turbulent fluxes of heat, salt, and momentum between the upper ocean mixed layer and the ice, ice-tethered profilers (ITP; Krishfield et al., 2008) that sample the upper ocean hydrography and, depending on configuration, a variety of other parameters including fluorescence, irradiance, oxygen, and velocity (from within ~5 m of the ice to 250 to 800 meters, depending upon application). The IMBs, AOFBs, and ITP use GPS for positioning and transmit data via Iridium. Polar profiling floats (PPF) are analogous to the profiling floats used in the Argo float program. Specifically, the floats drift at a fixed depth but periodically rise to the surface, profiling the temperature and salinity structure of the water column. Once at the surface they transmit the data via satellite, receive a GPS fix, and then descend again. PPFs do not break through the ice, but will surface if open water is present, and then transmit their data and obtain a GPS fix. For periods of extended under-ice operations, the PPFs use fixed sound sources for geopositioning but store their data until they reach open water. While most of these devices have been developed for ice and ocean physics applications, it is feasible that other sensors can be adapted to these as well.

Argo floats currently span all oceans except the Arctic because of the limitation of access to sea surface communications. Enabling them to be used in the Arctic Ocean would greatly advance our understanding of physical changes within this ocean's deeper water masses. A technology proposed by Sagen et al. (2011) would enable this technology to be deployed in the Arctic Ocean by the installation of a basin-wide undersea navigation and communication system.

Research Vessels

Numerous reports have discussed the continued needs for ships capable of working in the Arctic Ocean (e.g., Dunbar et al., 2012; NRC, 2003; NRC, 2007; NRC, 2011; USCG, 2013; U.S. Navy, 2009). All have identified research questions that can only be suitably addressed with the access provided by research, icebreaker, and drilling ships (rather than autonomous or remote instrumentation). Sustained use of ships is also envisioned for deployment/recovery of stationary or mobile installations equipped with autonomous samplers (e.g., moorings, AUVs/gliders). With the diminished summer sea-ice extent, and the new availability of the ice-capable research vessel *R/V Sikuliaq*, as well as other non-ice capable research vessels, access to a larger portion of the Arctic Ocean during ice-free months can be achieved using the assets at hand.

However, access to some regions of the Arctic will still require the use of a medium or heavy icebreaker. A number of emerging research questions in the Arctic can only be addressed through shipboard access during all times of the year. This can be achieved by expanding the capabilities of ice-capable ships and icebreakers to deploy and support traditional and new equipment, instrumentation, and technologies in ice-covered seas. Research questions pertaining to oceanic gateway, sea surface temperatures, long-term climate excursions, gas hydrates, oceanic-crust architecture, and tectonic as well as magmatic evolution of the Arctic Ocean basin require access to deep drilling capability with riser and blowout preventer systems. Drilling of the seafloor could be accomplished through management of ship and sea-ice movements using both a moon pool and sophisticated ship-handling technology. Advanced ice clearing capabilities are also necessary for deployment of AUVs and ROVs in sea ice. UAVs will also be increasingly utilized in the Arctic and research vessels and icebreakers need to be capable of supporting the deployment of UAVs.

Present U.S. icebreaker capability for medium-to-heavy ice is minimal. The *USCGC Healy*, a medium icebreaker with a primary mission of science (Figure 4.4), is at mid-life (commissioned in 2000) and will need to be replaced, under normal ship life length, in ~15 to 20 years. Furthermore, the Healy crew is rotated approximately every 2 years, diminishing institutional memory and science experience in the operation of the ship. Retaining crews for longer periods of time would improve the operational capacity of the Healy, resulting in more efficient use of science resources. The heavy icebreaker *USCGC Polar Star* has recently returned to service after extensive refurbishment and will primarily serve national security interests in the Arctic and McMurdo Station in Antarctica. The science mission requirements for a new polar icebreaker were recently updated at the request of the National Science Foundation (Dunbar et al., 2012). That report identified the need for a medium icebreaker research vessel to address current and future research questions while being reasonably economical to operate (in lieu of a heavy icebreaker). Still, it is important to identify a means to increase heavy ice-breaking capability, either through new construction or by leasing a vessel that can be used either for science or to provide escort services for a less ice-capable research icebreaker.

FIGURE 4.4 Scientists obtain samples on the sea ice during a cruise to the northern Chukchi Sea using the USCGC Healy (background). SOURCE: Steve Roberts.

It is also important to retain and increase access to non-icebreaking research vessels in the Arctic through increased funding for Arctic research, increased coordination of research activities to maximize use of available assets, greater use of private sector assets (including research vessels as well as platforms of opportunity), and the development of large, multi-investigator, multi-disciplinary research programs and by operating research icebreaking assets as efficiently as possible. At present, research vessel time is available primarily on the *USCGC Healy* or non-UNOLS vessels. Due to downsizing of the UNOLS fleet, availability of platforms in the U.S. research fleet for Arctic work is inadequate. Additionally, the perception that inclusion of ship time in research proposals diminishes the likelihood of funding has driven a decline in the number of proposals requesting ship time across all oceanographic disciplines (UNOLS, 2013).

Fixed Platforms and Systems

A range of stationary marine platforms already exists. Some types are used routinely (e.g., moorings), while others are relatively rare or absent in the Arctic, although commonly deployed in other oceanic regions (e.g., shore-based installations, cabled marine observatories). There is still much room for improvement in the capabilities and deployment of both stationary (sea-floor deployment) and semi-stationary (sea-ice deployment) platforms from which to monitor a range of ocean and atmosphere characteristics over all seasons. The platform types include bottom-moored and ice-tethered profilers equipped with a range of physical, meteorological, biological, and chemical sensors; free-floating and ice embedded buoys; cabled marine observatories; and shoreline instrumentation such as tide gauges, meteorological packages, and coastal ocean dynamics applications radar (CODAR) in remote locations. It is also desirable to network data collected from these remote installations into a common location.

In addition to these marine-based fixed observatories, there already exist many terrestrial observatories that need to be sustained in order to address critical Arctic research questions. An example is Summit Station in central Greenland, where atmospheric and snow chemistry measurements have been made for decades, making it an important node in the network of Arctic climate observatories. Similarly, Toolik Field Station in Alaska provides an important observational platform.

Efforts to combine these in situ observations with local community and traditional knowledge, so that local residents' priorities with respect to climate change can be monitored and assessed, are critical. It is also important to integrate local and community-based observing into operational and research activities. We need to empower local residents to monitor their own environments and assist in the coordination of these community-based monitoring observations (Pulsifer et al., 2014). These locally-based observing platforms require strong partnerships between communities and scientists to capture the knowledge of community members. One particular aspect of these observatories is the ability to place current observations in a local historical context. Local involvement is discussed further in the section on Community Engagement later in this chapter.

Remote Sensing

Satellite and airborne observations provide the greatest spatial coverage of the Arctic and have proven to be important tools for detecting the impacts of climate change. For example, satellite remote sensing data have allowed the quantification of sea-ice loss, and the mass loss of ice sheets that contribute to sea-level rise; surface temperature changes; atmospheric changes; shrub expansion northward; changing wetlands and lakes on the north slope; and coastal shoreline changes. Remote sensing makes it possible to scale what is observed on the ground at plot scales up to landscape scales for improved broadscale understanding of patterns of change and for extrapolating that knowledge to grid cells for modeling. Satellite remote sensing has and will continue to play a major role in monitoring and detection of change in the Arctic.

Satellites

Arctic conditions present many challenges to the interpretation of satellite remote sensing data. The Arctic is characterized by low solar illumination, low vegetation biomass, low primary productivity, perennial snow and sea ice, prolonged darkness, persistent low clouds, and frequent temperature inversions, all of which severely limit radiometer accuracy and monitoring capabilities. Much progress has been made in recent decades in remote sensing applications, but many obstacles remain in retrieving useful information from high latitudes. For example, some satellite systems fly in orbits that simply do not provide Arctic coverage. In addition, many remote sensing products and calibration algorithms are developed for temperate or tropical systems, and thus may be inappropriate for the Arctic. The standard atmospheric correction algorithms such as those used by the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) do not work well in the tundra due to changing solar angle variation across the scene. In addition, standard image products from sensors such as NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) or the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) are developed primarily for temperate or tropical systems; the MODIS net and gross primary productivity products overestimate low productivity sites such as tundra ecosystems (Turner et al., 2006). Cloud detection over snow- and ice-covered scenes also remains a challenge for imagers and sounders, and the frequent temperature inversions over Arctic regions are problematic for retrieving vertical profiles.

At an Arctic remote sensing workshop in October 2013, participants cited the lack of calibration of remote sensing products to the Arctic as the number one current concern for effectively observing changes in the Arctic.[30]

For airborne and satellite remote sensing collections, field data are important for training and validation; these data require collection over an area representative of the spatial resolution or minimum mapping unit of the remote sensing platform. In this regard, distributed measurements may be collected across a somewhat "homogeneous" area and averaged to relate to the image observation resolution. For example, for mapping vegetation cover to a minimum mapping unit of 0.2 hectares, field characterization data requires collection in a representative 40 m x 50 m area. For coarse resolution satellite platforms (1 km or greater) typically the observed landscape is not homogeneous for a sufficient number of coincident field measurements to be made. In this case, an intermediate remote sensing product (~ 30 m resolution) may be employed, where the field data are used to train or validate the intermediate product across a range of "homogeneous" cover types within the coarse resolution cell of the targeted sensor (Liang et al., 2002), and then these intermediate data are upscaled to the coarse resolution sensor. In some cases this intermediary step is not an option and a network of field measurements are necessary across the resolution cell (e.g., soil moisture from passive microwave; Jackson et al., 2010). The types of data necessary for addressing the existing and emerging questions in Chapter 3 that have the potential to become available from satellite sensors include:

Lake depth (bathymetry), precipitation, and evapotranspiration (ET) Remote sensing has/is being used to map where the water is (MODIS - lakes, AMSRE – fractional wetness), but characterization of the impact of climate on surface water and hydrology cannot be attained without information on lake depth and other hydrology parameters (e.g. precipitation, ET). NASA's Global Precipitation Measurement (GPM) mission is scheduled for 2014 launch and will address the precipitation needs.

Sea-ice and land-ice thickness. These data have been successfully retrieved from NASA's Geoscience Laser Altimeter System/Ice, cloud, and land Elevation Satellite (ICESat/GLAS). Together with aerial surveys from the IceBridge program, a continuous record of ice and snow thickness estimates is being collected and will be extended by ICESat2 (scheduled for launch in 2015). These data will assist in addressing emerging questions related to changes in ocean/ice/atmosphere energy exchange, ocean currents, and sea-level rise.

Snow depth on ice surfaces. The /ICESat/GLAS and other laser altimeters are able to estimate the thickness of snow and ice as a freeboard measurement. The laser altimeters reflect from the snow air interface, thus to obtain snow depth on ice, radar altimetry is also needed which reflects from the snow ice interface. Others have used passive microwave data to estimate snow depth. More consistent measurements are needed with better spatial coverage. Snow information is essential to answer questions related to surface energy exchange and for sea-ice thickness.

Permafrost, soil moisture, active layer depth, and soil organic carbon stocks. Satellites are beginning to provide estimates of changes in high-latitude vegetation, freeze-thaw processes, soil moisture, and burn severity. However, these are limited by calibration of the systems and algorithms developed for temperate systems. For example, standard burn severity mapping algorithms do not work well in the tundra, but scientists are developing algorithms specific for the Arctic (e.g., Loboda et al., 2013). Also, many of these systems are of coarse spatial resolution (e.g., Soil Moisture Active Passive-SMAP has 3 to 9 km resolution). While SMAP will provide data on freeze-thaw processes and soil moisture, its relative utility for defining active-layer depth is uncertain. The resolution of SMAP is also still too coarse to define landscape heterogeneity in conditions influencing permafrost

[30] NSSI Remote Sensing-Derived Monitoring Products for the Arctic Workshop (http://www.northslope.org /event/products2013/)

and soil organic carbon distributions (ideally resolution needs to be closer to 30m than 3km). Synthetic Aperture Radar (SAR) satellite systems are of high spatial resolution (~30 m) and widely used for ice monitoring, but are underutilized in the Arctic for land applications. Use of SAR and/or InSAR techniques for soil moisture and active layer retrieval, assessment of carbon stocks, permafrost deformation, and other needs in the Arctic have been demonstrated to have great potential but require further research and development for widespread application. Changes in the Arctic terrestrial ecosystem will be assessed in the Next-Generation Ecosystem Experiment (NGEE): Arctic Landscapes project, in which data from satellite-based laser altimeters will be combined with biogeochemical models. Monitoring and changes in the high northern latitudes will also be assessed in NASA's Arctic Boreal Vulnerability Experiment (ABoVE), a major field campaign scheduled to begin in 2015 and run for 5 to 7 years over Western Canada and Alaska. For a more detailed discussion of remote sensing tools for understanding permafrost, see (2014 2014a).

Atmospheric boundary layer. The strong near-surface inversions under a frequently overcast sky cover present a particularly difficult challenge to satellite sounding systems, yet knowledge of boundary-layer stratification is essential for determining surface-atmosphere exchanges. Higher spectral resolution systems such as NASA's Atmospheric Infrared Radiation Sounder (AIRS) combined with the Advanced Microwave Sounding Unit (AMSU) have the potential to provide more accurate retrievals of profiles and cloud information in the critical Arctic boundary layer.

Cloud properties. Estimates of cloud optical thickness, phase, and base height—particularly over ice- and snow-covered surfaces—require additional detail and accuracy. Improved retrievals may be possible from AIRS/AMSU, MISR, GLAS/ICESat, ICESat-2/ATLAS, and instruments in NASA's A-Train constellation. Cloud information is essential for determining the surface energy balance and atmospheric chemical processes.

Sea ice motion. A near-real-time, high-resolution product is needed for assimilation into dynamical models to provide more accurate sea-ice predictions. Coverage for such a product is a challenge, particularly for optical systems and may require a constellation of satellites. The new Sentinel-1 SAR satellite mission will provide high repeat coverage of the Arctic allowing more frequent information on sea ice including ice motion.

Repeatable landcover mapping techniques at high spatial resolution. High resolution (30 m or less) circumpolar land cover maps are needed as baseline, to detect changes and to aid modeling. Current maps are either geographically limited, are of low spatial resolution or lack accuracy due to limited ground control. The National Geospatial-Intelligence Agency (NGA) high resolution database may be useful for this purpose, as well as multi-sensor approaches that include Landsat, SAR, Lidar, hyperspectral observations, and other satellite data sources.

Digital Elevation Models, ground surface height and geodetic control. Arctic land areas (including ice-covered) currently have poor resolution Digital Elevation Models (DEMs; 60 to 90 m). High resolution DEMs are necessary for improved modeling, geospatial analysis, and remote sensing analysis. In Alaska, the State Digital Mapping Initiative (SDMI) is a program using airborne interferometric SAR to produce high resolution DEMs and imagery (e.g. SPOT) to produce ortho images for mapping[31] (Figure 4.5). The NGA provides access to data at no charge to civilian agencies. For example, 2.5 million scenes over the Arctic and Antarctic of commercial submeter imagery have been collected by NGA, and are currently being used by the Polar Geospatial Center in Minnesota to create DEMs at 2 to10 m resolution for portions of Antarctica. Such data could be used to map the pan-Arctic.

Measurements relative to a stable datum would enable measurement of seasonal variations of surface elevation dynamics and long-term subsidence associated with degradation of ground ice. This could possibly be incorporated with NOAA's National Geodetic Survey (NGS) of the national Continuously Operating Reference Station (CORS) network. These are highly accurate Global

[31] http://www.alaskamapped.org

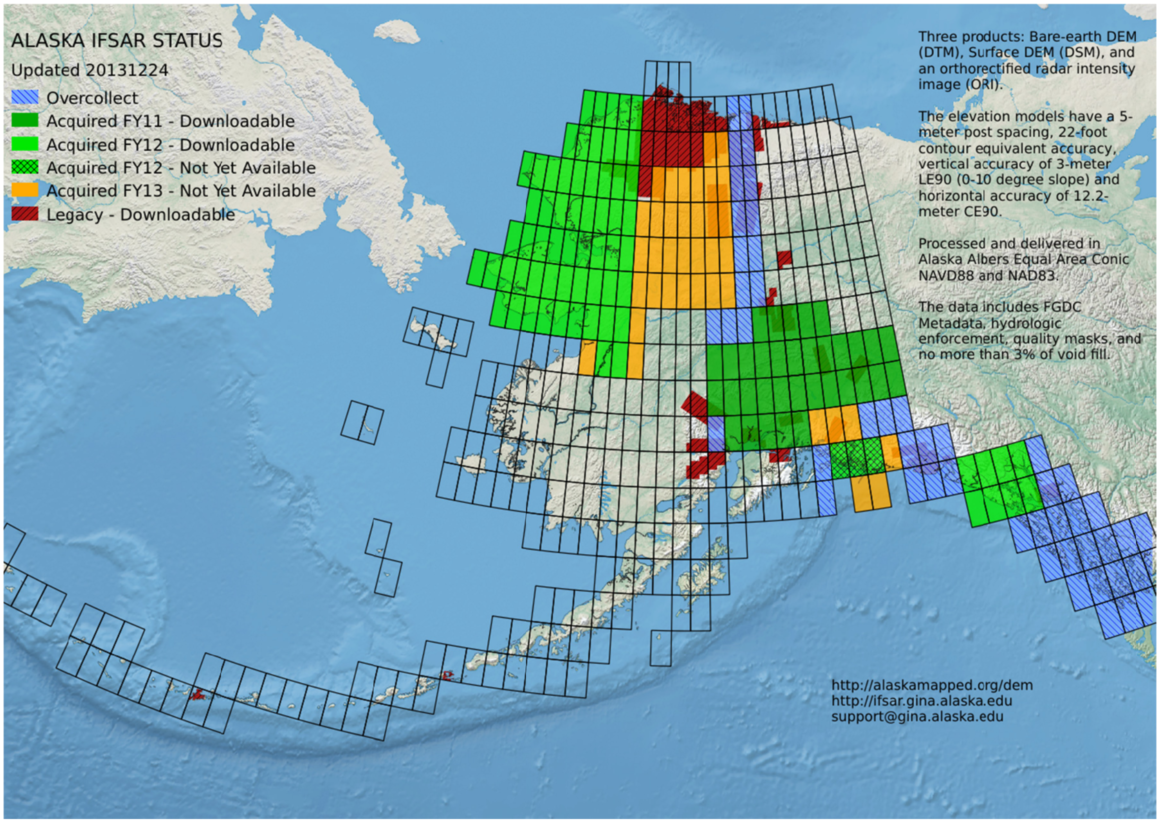

FIGURE 4.5 Alaska Mapped digital elevation model. SOURCE: alaskamapped.org

Navigation Satellite System (GNSS, formerly GPS) receivers. Installation of a small subset of foundation CORS in the Arctic is needed to supplement the network. The foundation CORS will improve the accuracy of the International Terrestrial Reference Frame.

The Gravity for the Redefinition of the American Vertical Datum, or GRAV-D, is a program initiated by NGS to redefine the vertical datum of the United States. NGS is prioritizing collection of airborne gravity data in Alaska. This is the most cost-effective way to establish geodetic control in these areas and will allow the increase of elevation measurement accuracy from one meter (or worse) to two centimeters. Less than 10 percent of Alaska has contemporary shoreline data, and less than 1 percent is mapped annually. This program needs to be expanded to the pan-Arctic.

Improved weather and sea condition forecasts. New observing technologies (in situ, airborne, and satellite) could help to fill existing gaps in meteorological and oceanographic datasets and improve weather forecasts. Beyond approximately 60 to 72 hours, forecasts of weather and sea conditions lack sufficient detail. The resolution of the observational fields that support both meteorological and oceanographic modeling exacerbates this discrepancy (see Managed Arctic question 4).

In addition, there are some infrastructure needs to aid in sharing and dissemination of imagery and sensor data. An autonomous network to uplink and disseminate multi-sensor information about sea ice and other Arctic data is needed.

There is also a need to improve access to satellite imagery including access to foreign satellite observations and commercial data.

Unmanned Aerial Vehicles

In gathering community input for this study, a frequently identified technology that would facilitate Arctic research was unmanned aerial vehicles (UAVs), or drone aircraft. The Arctic is a remote and challenging region to conduct research. In addition to extreme weather/sea conditions and transportation obstacles during much of the year, the Arctic consists of large expanses of sparsely populated areas with limited access that combine to make environmental observations difficult at best. As a result, aircraft ranging from balloons to transport airplanes have long been an important tool for the collection of observations on the physical, chemical, and biological systems of the Arctic.

Although manned aircraft have the capacity to afford access to broad and remote areas of the Arctic, this access is not without significant peril. With extremely limited infrastructure for emergency alternatives or rescue in the case of failure, manned aerial operations are rightly approached with caution. In recent years, reduced tolerance for risk on the part of investigative agencies and the private sector have increasingly restricted aerial access to remote areas and limited the scope and scale of data acquired.

During the late 1990s and early 2000s the rapid development and utilization of UAVs by the military provided the possibility of new capabilities for aerial operations in remote areas with challenging flying conditions. The UAV industry now includes options ranging from small hand-launched line-of-sight operated craft to large airframes that are capable of extensive periods aloft and long-distance operation.

Emerging UAV capability has the potential to greatly expand and extend our ability to collect information in the challenging and remote conditions of the Arctic. To date the use of UAVs in U.S. airspace, including the Arctic onshore and offshore, has been somewhat limited as the Federal Aviation Administration (FAA) works to maintain the safety of airspace and resolve the potential for interactions between manned and unmanned air traffic. In addition to obtaining certification for the specific aircraft to be used, operators of UAVs are required to obtain a certificate of authorization (COA) from the FAA that establishes the airspace and operating parameters under which the vehicle can be operated. Generally, the airspace available to UAV operation has been limited to designated areas of controlled airspace, as in military reserves or testing ranges. COAs have not been broadly available to the private sector and have been limited to governmental entities with aviation responsibilities, including a handful of universities with established aviation research programs. In the relatively rare cases where private sector use of a UAV has been possible, it has been through the establishment of a relationship with and sponsorship by one of the governmental bodies or universities. Acquisition of COAs over the last five years has required as much as 10 to 12 months from the initiation of the process. More recently, processing times have trended toward six months.

Despite these obstacles, the use of UAVs for data acquisition in the Arctic has been advancing. In 2008 a UAV was tested for the purpose of making observations of marine mammals in the Arctic by being launched and recovered from a vessel at sea. In 2012 small UAVs assisted an ice breaker in its effort to provide access for the delivery of fuel to the village of Nome, AK. In 2013 experimental UAVs were successfully launched and operated from controlled airspace near Pt. Oliktok, AK and were tested successfully in the Chukchi Sea.

On December 30, 2013 the FAA announced an initiative to greatly increase the level of access to experimental use of UAVs.[32] Though this initiative will not immediately provide access to the national airspace for commercial and civil purposes, the program will generate data and information related to safe operation of UAVs. Six investigative entities have been selected to operate UAV test sites. These include University of Alaska, State of Nevada, New York's Griffiss International Airport, North Dakota Department of Commerce, Texas A&M University, and Virginia

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[32] http://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=15575

Polytechnic Institute and State University (Virginia Tech). Through this program, the agency has set in motion a process that will result in the establishment of operational standards and capacities within the coming years.

Sensors

Observing platforms are only effective when equipped with sensors that measure critical variables. It is particularly important to measure parameters that describe feedbacks among system components (e.g., albedo and ocean temperature).

Improvements in sensor technology would (1) increase the numbers and types of autonomous measurements, particularly biological and chemical characteristics, (2) miniaturize sensors and sensor vehicles, (3) increase data transfer capabilities from remote installations to the laboratory, (4) enable deployment of sensors that can collect high-quality data during all seasons (including winter), and (5) decrease sensor power consumption.

Examples of new sensor types and technologies that need improvement for Arctic deployment include:

- Underwater, airborne, and terrestrial still and video cameras;
- Chemical sensors for nutrients, pH, pCO2, CH_4, and other dissolved gases;
- Bottom-pressure recorders for tides, storm surges, and tsunamis;
- Sensors to measure sea-ice thickness;
- Sensors for identifying organisms using molecular techniques; and
- Telemetry instruments (low power, small, inexpensive, fast).

Integrated suites of new instruments would allow sensors to be programmed for event detection, responses to seasonal changes, or alterations of data capture rates based on ecosystem processes. Integrative technologies use smart sensors that can react to external communication. A network of smart sensors could be autonomously coordinated over a wide range of platforms, for example among fixed, ocean drifting, and autonomous underwater and unmanned aerial vehicles.

Accurate and reliable monitoring of key variables in remote locations and under harsh environmental conditions requires development of robust and inexpensive new sensor technology to provide the density of measurements needed to validate spatially distributed models. It is important to ensure that instrumentation to be deployed for operation at remote field sites has passed a thorough pre-deployment testing process, including environmental testing, and has been developed to enable module-level serviceability and remote calibration. It may be necessary to adopt more formal approaches such as those practiced by industry and other agencies for testing and evaluation of new systems and technologies and to formalize the assessment of technological readiness of new equipment and processes. Sensors need to be easy to use and install, autonomous and with remote data transfer to cover vast parts of the Arctic where no data currently exist. Maximizing the value of independent sensor data distributed across a wide geographic area in a range of terrains (oceans, land, coast, continental ice, and sea ice), requires robust data capture, archive, access, visualization, and integration. Sensor data collection is an area of increasing innovation. For example, most cars and smartphones are now miniature weather stations. Most new cars have temperature sensors and windshield wiper speed can be a crude measure of precipitation rate (NRC, 2009). In the data sparse Arctic, accessing data from these sources could make a large contribution, and cars and smartphones provide an example of how we need to be open to new and unusual methods of data collection. New and emerging sensor data can be fused with visual sensors data (e.g., acoustics, video imagery, photogrammetry, satellite imagery) to yield data products that can enable profoundly new insights about this rapidly changing region.

Additionally, at present there are many important components of the Arctic system that are under-measured due to logistical or technical constraints (e.g., Executive Office of the President, 2013). These include:

- Coordinated measurements of full energy and mass budgets on scales that resolve seasonality and synoptic variability, including development of new methods to measure radiation fluxes, monitor upper ocean heat, mass balance changes while integrating over spatio-temporal variability;
- Long-term observations of key outlet glaciers and tidewater glaciers;
- Monitoring of the biological and physical state of the Arctic environment in concert with quantitative measurements of human interactions with the environment;
- Assessing the effects of clouds and atmospheric constituents on surface radiation balance;
- Quantifying the impact of terrestrial warming and permafrost thawing on the carbon cycle.

Power and Communication

All of the technologies—existing and envisioned, mobile and fixed—for remote measurement of changes in Arctic systems, require some source of energy, and power is still a limiting factor in many cases. In addition, the large quantities of data generated by these remote instruments and systems will need robust and inexpensive telemetry systems for transmission of data. Preparing for the transmission of big data is necessary as we move into the most intensive observational period the Arctic has ever seen, including high-bandwidth observations such as real-time video feeds.

Power

There are several excellent examples of solutions to the remote power problem already in existence. For smaller power requirements the Ch2MHill polar power website[33] has been funded by NSF to be a clearinghouse for information on polar power systems in remote environments. For lower-power requirements, UNAVCO has developed a small (5-W continuous power) system based on photovoltaic (PV) panels and an optional wind-turbine[34]. For the larger power requirements, such as for a shore-based High Frequency Radar, Statscewich et al. (2012) developed a Remote Power Module (RPM), integrating PV, wind turbines, and a diesel generator, along with batteries for storage and the required control and switching circuitry. At the largest scale of operation, for example Summit Station at the center of the GrIS or Toolik Field Station in Alaska, diesel generators are still needed to produce the necessary 80 to 170 kW.

Two key challenges remain in developing systems for future research questions:

- Developing cleaner solutions for the large-power-requirement stations.
- Distributing power from where it can be generated cleanly to where it is needed.

More robust and affordable clean energy sources and improved energy storage systems are essential to meet the data collection and transmission needs discussed elsewhere in this chapter.

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33 http://www.polarpower.org/
34 http://facility.unavco.org/project_support/polar/remote/remote.html

This is evidenced, particularly at Summit Station, Greenland. Ironically, one of the most pristine sites in the Polar Regions, a location used largely for its clean atmospheric conditions, is powered primarily by a diesel generator running continuously. Major enhancements to the value of Summit as a facility could be realized by effectively replacing the diesel generator power with renewable, clean energy sources. It is likely that the technology for overcoming this challenge already exists, and the major impediment is cost.

Many locations in the Arctic are ideal for using renewable energy, and distributing that power is a key way to realize the benefits of these conditions. Related to the idea of power distribution hubs is the idea of using power where it is generated, and moving the products of that power (perhaps manufactured goods, or energy-dense material such as hydrogen), as opposed to moving the energy itself.

Another idea is reducing the energy consumption of the instruments themselves, many of which were designed for laboratories where power is not an issue. These instruments are often now deployed in remote locations, where power consumption is one of the biggest limiting factors. Moving forward, large gains may be made by focusing effort on designing instruments to consume less power, as an alternative to developing higher-output power systems.

Broadband Communication

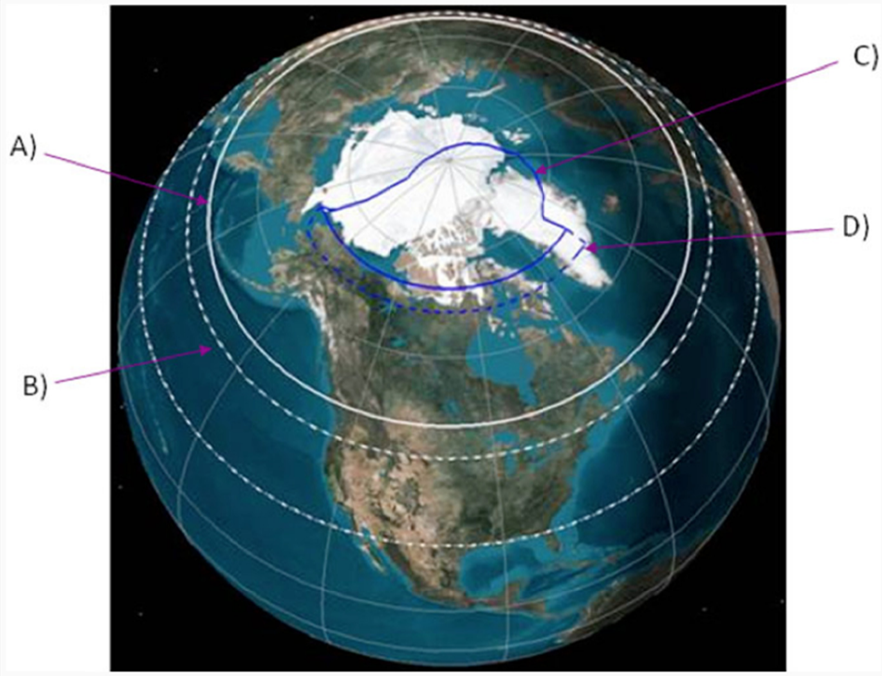
Broadband communication systems are vital for research activities (e.g., delivery of sensor network data and environmental monitoring) in the Arctic, are central to northern communities' ability to adapt to climate change, and are important for monitoring and managing the expected increase in economic and industrial activity in the Arctic region. For example, it is well recognized that a robust and reliable high-bandwidth network is essential for fisheries management, weather forecasting, energy exploration and production, search and rescue, and expanding ship traffic. Broadband communication would also contribute to a paradigm shift in education and telemedicine in the Arctic region.

The coverage of geostationary satellites, which provide a robust marine communication system, is limited to approximately seventy degrees north. An example of technology that could provide communications is being proposed by Canada. The Government of Canada is currently developing a polar communications and weather mission (PCW) with international collaborations that currently includes Denmark, Finland, Norway, Sweden and the United States (Figure 4.6). The proposed mission comprises two satellites operating in highly elliptical orbits with a weather payload (spectroradiometer), space weather instruments, and Ka-and X-band telecommunications.

Partially in response to the 2011 Arctic Communications Infrastructure Assessment Report,[35] commercial endeavors have been proposed to install a high bandwidth telecommunications cable from London to Tokyo through the Northwest Passage and along the Alaska coast. The proposal includes thirteen spur cables that would connect to Arctic Ocean coastal communities in Alaska and Canada.

This committee cannot and does not endorse any specific proposal, but because of the urgent need for communications in the Arctic as well as the challenges and resources involved, it would be prudent to pursue a partnership model including other Arctic nations and industry to enable the implementation of these technologies.

[35] www.aciareport.ca



Picture of the Areas of Interest for the PCW mission located in the arctic region of the earth

a) Meteorological coverage: 50° north latitude (minimum requirement) white line
b) Meteorological coverage: 45° north latitude (goal) white dotted line
c) Communications coverage: 70° north latitude (minimum requirement) blue line
d) Communications coverage: 66° north latitude (goal) blue dotted line

(Credit: Canadian Space Agency)

FIGURE 4.6 This image illustrates the areas of interest for the PCW mission in the Arctic. SOURCE: Canadian Space Agency.

Models in Prediction, Projection, and ReAnalyses

Computational approaches to understanding the Arctic system remain central to developing capacity in understanding mechanisms, diagnosing change, ensuring safe field operations, and improving climate change projections. In all of these aspects, the Arctic presents unique challenges. For example, large biases in simulations of the Arctic climate by global climate system models, particularly at high elevations, over ice sheets, and in the marginal sea-ice zone, illustrate the fact that modeling capability in this region lags behind that in lower latitudes. Some of these challenges can be ascribed to limitations in our observational capacity. Some problems can be understood as biases originating from inadequately understood processes in lower latitudes. However, in most respects, we face a combination of sparse and noisy data with inadequate understanding of Arctic processes for the purposes of simulation (Kattsov et al., 2010). Further, the difficulties described above in maintaining robust, continuous, high quality, distributed observations increases our reliance on models of all kinds as tools for understanding the Arctic.

At present, the capability to reproduce observed Arctic amplification and project its effects into the coming decades, continues to elude us. This is manifest in the biases in integrative signals such as regional and temporal variability on a range of scales in the atmosphere, sea ice, ocean, and land (e.g., Notz et al., 2013; Stroeve et al., 2012). Specific challenges include the simulation of critical processes, including for example the interaction between liquid- and ice-phase microphysics (Klein et al., 2009), precipitation amount and phase (de Boer et al., 2014), glacial melt

(Irvine-Fynn et al., 2014), sea-ice albedo (Karlsson and Svensson, 2013) and soil freeze/thaw dynamics (Rawlins et al., 2013). These challenges present opportunities for detailed analysis of field observations in concert with targeted simulation (e.g., single column models, cloud resolving models, sea ice models, watershed models) that enhance our understanding of these key processes (e.g., Luo et al., 2008; Morrison et al., 2005). The benefits to climate model improvement arising from coordinated field programs (e.g., DOE ARM, the Surface Heat Balance of the Arctic [SHEBA] program) that include the measurement of key parameters for simulation cannot be overstated. Atmospheric reanalyses (e.g., Dee et al., 2011; Onogi et al., 2007; Saha et al., 2010) are an important tool for a range of Arctic research activities, including applications as diverse as detection of climate change to impacts assessment to component model development. However, in the context of both data scarcity and model bias, the ability of data assimilation techniques to provide a resource for these activities is limited. Even the current generation of reanalysis products reveal large inter-model differences, particularly in surface meteorology, clouds, and radiation (Jakobson et al., 2012). Quality operational weather forecasts are critical for safe operations in the Arctic. Generally these models are adapted from national operational weather prediction models of Arctic nations, but research has demonstrated that these models require substantial modification to reduce bias (e.g., Bromwich et al., 2009; Schroder et al., 2011). Enhancement of the reanalysis process (including specialized Arctic regional re-analyses) and operational weather prediction rely on the continuing improvement in understanding Arctic atmospheric processes and their interactions with other Arctic systems.

The ongoing development of limited area climate system models in the Arctic represents a critical gap in our modeling infrastructure (Proshutinsky et al., 2008). These models allow the testing of our simulation understanding in a framework that has high spatial resolution, uses Arctic-specific physical representations, and ensures that lower-latitude biases are minimized. While this approach is one that enjoyed considerable advances in earlier decades (e.g., Dethloff et al., 1996; Lynch et al., 1995), development slowed until recently (e.g., Cassano et al., 2011; Dorn et al., 2009; Glisan et al., 2013). These models provide an important platform for testing approaches prior to implementation in global models, as well as providing additional infrastructure for impacts assessment, downscaling, and field campaign support.

Partnerships with Industry

Building the operational capacity necessary to address emerging research questions requires a mix of approaches, including partnering to leverage resources. With increased accessibility comes increased activity on the part of tourism, shipping, oil and gas, and other extractive industries. In many cases these industries operate extensive investigative and infrastructure development programs. Frequently, the information needs for industry have much in common with the needs of regulatory agencies and curiosity-driven science. When industry operates in remote locations it also tends to establish or create infrastructure to support safe operations, including housing, transportation, communications, and crisis response capabilities (e.g., search and rescue). Establishing partnerships with these organizations could allow for collection of information that would, in turn, facilitate robust decision-making and extend capacities for scientific investigations in the Arctic.

There are many ways collaborations with industry can generate mutual benefits and synergies with the science community. At the most basic level, instrumentation of existing industry platforms (i.e., ships, platforms, and facilities) operating in the Arctic can allow for collection of data. Industry is often open to allowing investigators to utilize logistical assets provided the investigative work is consistent with the mission of these assets and can be conducted in full compliance with industry standards. The private sector is also beginning to lead funding for scientific investigation in the Arctic (see Investing in Research later in this chapter). While a portion of these funded studies is directly operated by, or on behalf of, industry, opportunities exist to co-fund investigative efforts through matching funds or the inclusion of industry in such programs as the National Ocean Partnership Program (NOPP).

Industry-funded science can also be a rich source of information that could be more effectively tapped by the scientific or regulatory communities. Recognition of the utility of scientific information as a business driver is increasing the extent and quality of industry investment and willingness to participate in greater public-private sector collaboration. While industry science may be focused on specific impacts-related questions or project-specific areas, data from these studies can inform a broad array of research inquiries. Measures that increase transparency and inclusion in the planning and implementation of industry studies, the peer review and validation of results and reports, and broad sharing and utilization of industry data, all increase the value of this science both to the scientific community and to industry itself.

Examples of effective public-private collaboration on Arctic science are increasing. An excellent example of utilizing industry assets as observation platforms is the Smart Ocean Smart Industries program under the World Ocean Council (WOC). Through this program the WOC, which is an international, cross-sectoral industry leadership alliance, works with the scientific community to identify data needs and mechanisms through which these data may be collected either directly by vessel crews or through the deployment of instrumentation onto industry assets. NOAA also operates the Volunteer Observing Ship[36] program for collecting a standard set of weather observations daily from more than 1,000 ships and platforms globally for incorporation in weather forecasting models.

A 2010 agreement on data sharing between three international oil companies (Shell, ConocoPhillips, and Statoil) and NOAA has made the results of nearly $100 million investment in data on the U.S. Arctic offshore available to the agency and, more broadly, to the scientific community. Under this agreement, data from meteorology/oceanography observing buoys are served directly to the National Data Buoy Center and are utilized to improve forecasting in the Arctic. Data from integrated ecological studies and monitoring programs are made available through the Alaska Ocean Observing System.[37]

Investigators frequently establish ad hoc public-private collaborations by soliciting matching funds, or by combining privately-funded opportunities with publicly-funded initiatives. Such informal pooling of funding can increase the scope and utility of publicly funded projects by accommodating the utilization of a larger, more capable vessel or adding scientists to the program. Formal public-private collaborations are becoming more common as both communities find new strategies for co-planning investigative efforts and for co-funding research.

GROWING HUMAN CAPACITY

An essential element of ensuring that the nation has sufficient research capacity is an adequate supply of people with a unique combination of the necessary skills and knowledge. Arctic questions span many disciplines across the natural and social sciences and thus require some researchers who work at the intersections, crossing and connecting fields, and collaborating across international boundaries. Also, research capacity in the Arctic is particularly important because climate change and its impacts are occurring at an accelerated rate. Thus, our capacity to observe and conduct research to understand the observations, and develop appropriate response strategies, needs to keep apace. Building human research capacity includes both training of the next generation, as well as engagement and professional development of the existing community so that we are better prepared to address current and future challenges.

[36] http://www.vos.noaa.gov
[37] http://www.aoos.org/

Human research capacity building was a major component of the IPY. The National Academy of Sciences study on *Lessons and Legacies of the International Polar Year (IPY) 2007-2008* showed that there were measurable increases in the number of scientists conducting polar research (NRC, 2012a). This increase was not only attributed to the climate change-driven need for more polar researchers, but also IPY's efforts that enabled international research teams to closely coordinate their activities. Two specific human capacity building activities deemed successful during IPY were the Association of Polar Early Career Scientists (APECS) and the growth in student participation in the University of the Arctic.

The APECS coordination office is currently funded by three Norwegian organizations. Other organizations that work with APECS formed to support early career scientists in specific disciplines including:

- Permafrost Young Researcher Network (PYRN)
- Young Earth Scientists (YES) Network
- ArcticNet Student Association (ASA)
- Young European Associated Researchers (YEAR)
- Young Earth System Scientists (YESS)
- World Association of Young Scientists (WAYS)
- European Geography Association for students and young geographers EGEA

Increased support and funding agency incentives for U.S. young scientists to engage in APECS's activities would contribute to growing Arctic research capacity.

The University of the Arctic has a range of programs distributed among and coordinated with member higher education institutions that enable building of Arctic human research capacity with important emphasis on the recruitment and involvement of Arctic peoples. As of 2013, the United States had the lowest student involvement in their northern engagement program. Supporting U.S. students (including recruits from northern communities) in the University of the Arctic has the potential to increase human capacity through their established and well-recognized programs. Another key aspect of human capacity building is training young scientists, particularly social scientists, in the linguistic and cultural competency skills to work across the Arctic. Training centers in other parts of the Arctic could serve as models for North America.

Other IPY human capacity-building successes were related to funding agency incentives for researchers to incorporate northern community engagement in research and as public outreach. Some of these success stories included expansion from academic-based outreach to include informal education venues (e.g., museums, science fairs, online broadcasts). Continuing funding agency mechanisms that encourage these activities would provide young Arctic residents an opportunity to see research career opportunities directly linked to the future of their own communities.

Community Engagement

Arctic residents have played important roles in research for over a century, and their involvement continues to increase. From providing logistical support and safety in the field, to offering insights from generations of observations and experience, Arctic peoples have a great deal to offer. They also have a great deal to gain from sound scientific research, which can address many challenges of rapid environmental and social change in the region. Effective research partnerships have led to major advances in marine mammalogy (e.g., Noongwook et al., 2007; Thewissen et al.,

2011) and meteorology (e.g., Weatherhead et al., 2010), the emergence of traditional knowledge as an important topic of study (e.g., Huntington, 2011), and an increase in the number of scientists and scholars who come from Arctic communities. Arctic researchers, similarly, are increasingly interested in making connections with Arctic residents to incorporate traditional knowledge and observations and also to share the results of their work (Figure 4.7).

These trends are encouraging, and yet the Arctic research community has only begun to tap the potential for involving Arctic residents as well as citizen science practitioners who do not live in the Arctic but are still interested in Arctic topics. Arctic residents are alone in observing their environment throughout the entire year, year after year. Each has a lifetime of knowledge from their own observations as well as what has been passed down by older relatives, a chain that extends back countless generations in indigenous communities. Few of these contemporary and traditional observations and insights are recorded or made available to others, leaving many potential connections unrealized. The power of entraining large numbers of people in addressing research questions or data analyses (e.g., crowd sourcing) has yet to be applied to Arctic research to any substantial degree. There are promising developments in all these areas (e.g., Alessa et al., 2013), but the wider application of successful approaches has not yet occurred.

Three areas are particularly ripe for further attention to increase meaningful engagement of Arctic communities. First, communities themselves need to determine how they want to be engaged. The research burden on Arctic residents can be high, for example being interviewed again and again in the course of different studies with similar objectives. The return of scientific information back to the communities is not always effective. And communities are not always involved in all phases of research, reducing the value of their participation as well as their ownership and/or partnership. At the same time, few individual research projects have the resources to address all aspects of community interest and opportunity, creating a need for other mechanisms to support community engagement on the community's own terms.

Second, the infrastructure to support community engagement is only now being developed on a larger scale than that of individual projects or, in a few cases, regions of the Arctic. Such infrastructure includes data management, to capture and make available the results of community efforts, as well as communication procedures that can help researchers connect with communities as they plan, conduct, and disseminate the results of their research. Ad hoc approaches have worked for some projects and individuals, but many opportunities have also been missed, especially for building beyond the activities of a single project. The same principle applies to enhancing the capacity of communities to engage in Arctic research. Various Alaska Native organizations have played important roles in this regard, but greater continuity of effort and connections among projects and practitioners can yield even better results.

Third, there has simply been too little experience to date with the various approaches that have been and can be used, limiting the utility of an evaluation of what works and what doesn't. More needs to be done, engaging more communities on more topics, to build up a better body of practice and experience, from which relevant lessons can be drawn. More experience will also help community aspirations and capacity grow and mature, likely creating greater demand for community engagement along with a greater sophistication in how to make use of research activities and results.

INVESTING IN RESEARCH

Research requires funding. Funding involves making decisions, which includes considering what is needed, what is likely to work, and what trade-offs are entailed. Most Arctic research funding in the United States comes from government agencies, ranging from studies intended to address the needs of regulatory and other decisions, to curiosity-driven research within broad areas of scientific interest. Additional research, typically addressing specific needs or goals, is funded by

FIGURE 4.7 Warren Matumeak (left) and Andy Mahoney (right) discussing sea ice conditions near Barrow while examining a satellite image. SOURCE: Henry Huntington.

the private sector, including industry as well as philanthropic groups. Decisions about what is funded therefore occur at many levels in many places. Nonetheless, some general patterns are evident, and society's ability to address emerging research questions in the Arctic is closely tied to the way research funding is organized.

Evaluating the strengths and drawbacks of current funding mechanisms for Arctic science in the United States is beyond the scope of this report. Instead, we draw attention to certain features of research funding and suggest a closer look at whether the current approach is optimal for addressing society's needs. We focus our discussion in five areas: comprehensive systems and synthesis research, funding non-steady-state research, stakeholder-initiated research, international, and long-term observations. We consider cooperation among countries, among agencies, across disciplines, and with the private sector.

Comprehensive Systems and Synthesis Research

Research is often proposed in response to a request for proposals and then carried out over a three to five year time frame. Successful research may lead to subsequent projects that build on the results from the initial project, but there is no guarantee of further funding. Most projects are proposed and run independently, only rarely with support for coordination with related initiatives. This system provides flexibility, in that funding streams are committed for a relatively short period, and that researchers have the ability to pursue topics they deem important and, often, to adjust their research as circumstances and preliminary findings warrant. At the same time, implementation of full programs, deep engagement with, and the ability to explore the wider connections or ramifications of, a particular topic are often limited within a five-year project. Similarly, the ability to coordinate and cooperate across projects may be curtailed by time as well as by the demands of producing individual project results and then the competitive aspects of seeking further funding.

These drawbacks are especially apparent when trying to grapple with a comprehensive view of the Arctic, encompassing its myriad components, each with its own complexity. The challenges of "systems" research and interdisciplinary collaborations are well known. How those challenges can be overcome is less apparent, but continuity, coordination and leadership are likely to play major roles. Other funding approaches are used in other countries, and some innovative approaches have been tried in the United States in recent years. For example, long-term projects under the leadership of scientists with strong records of accomplishment and collaboration have been funded elsewhere. The part of the Bering Sea Project (Wiese et al., 2012) that was funded by the North Pacific Research Board was organized as a single project with one principal investigator (PI), rather than as a collection of individual projects, in order to emphasize interdisciplinary collaboration and a high degree of integration of ecosystem understanding. Integrated and cross-disciplinary proposals could also be developed through the National Science Foundation's new option for program managers to handle proposals through an "Ideas Lab" model[38]. A request for participation in the Ideas Lab is announced. Interested participants are invited to submit an application that outlines their ideas on a specific Ideas Lab topic. Selected participants will attend an interactive, multi-day program of collaborative discussion to construct new ideas and approaches. Sub-sets of teams will then submit full integrated proposals. Another way to integrate projects is to announce at the outset that the intent is to support a balanced suite and also support a coordinating office, as NSF did with the Climate Change Education Partnership program.

Synthesis activities, similarly, are often challenging in that they lack the allure of new field research. In some cases, the rationale for investing in synthesis is not readily articulated before the synthesis activity has started, but only emerges from the interactions of those involved and the interpretation of the various streams of data and insight that are to be connected in the course of the synthesis. Some examples exist, such as efforts under the Outer Continental Shelf Environmental Assessment Program (OCSEAP) in the 1970s and 1980s, synthesis workshops undertaken by NSF's Arctic System Science Program (e.g., Overpeck et al., 2005), the NSF's and the North Pacific Research Board's Bering Sea Project (Wiese et al., 2012), NSF's Arctic Freshwater Integration project,[39] and recent efforts for U.S. Arctic waters (e.g., the Pacific Marine Arctic Regional Synthesis [PacMARS] and the Synthesis of Arctic Research [SOAR] programs), but these are the exceptions rather than the norm.

Because of the funding structures and norms, there is currently an imbalance, with most research initiated by individuals and small groups, and few resources devoted towards larger-scale synthetic thinking and study. Other countries have different ways of handling synthesis research, including making large scale and longer term investments. Some invest in training of reviewers, so that they are better able to handle interdisciplinary and integrative proposals. The extent to which various approaches work and the trade-offs that they entail (e.g., opportunities for young researchers vs. continuation for established researchers) require careful evaluation to determine whether they do in fact produce a better comprehensive understanding of the research area in question, and at what cost. If so, then new funding approaches could be considered by U.S. agencies in light of their specific missions for Arctic research, to ensure the maximum benefit for society from its investment.

Non-Steady-State Research

Understanding an Arctic in transition may require greater risk on the part of funding agencies, and a greater acceptance of uncertainty on the part of reviewers to make headway against an uncertain future. Funding non-steady-state research will be necessary to better understand the dynamics of thresholds, resilience, and transformation in a rapidly changing Arctic. Obtaining funding for research into steady-state processes can sometimes be more straightforward than

[38] http://www.nsf.gov/pubs/2014/nsf14033/nsf14033.jsp?WT.mc_id=USNSF_179
[39] http://www.arcus.org/witness-the-arctic/2010/1/article/896

funding non-steady-state research, as steady-state proposals can provide convincing evidence of feasibility. However, given the potential for nonlinear change, tipping points, and emergent properties, it is important to ensure that investigations of emerging, non-steady-state research questions are funded as well, even if that means greater willingness on behalf of the funding agencies to take risks. Alternative approaches to proposal review and decision-making could be utilized, along with locally-inspired social-ecological experiments.

Social Sciences and Human Capacity

In titling this report "The Arctic in the Anthropocene" the committee intended to draw attention to the central role of humans in the emerging research questions. There are pressing needs for both social science research as identified in Chapter 3, as well as recognition of the role people play in research infrastructure discussed earlier in this Chapter.

Support for the social sciences, including economic, behavioral, and decision research, has lagged behind that of the natural sciences. As we attempt to prepare ourselves, our communities, and our country for a more rapidly changing future (IPCC, 2014), investments in social science are more critical than ever. Many of the questions we have identified in this report have at least some connection with the social sciences (Figure 3.18b).

In addition to conducting the research, ultimately it is people who are central in enhancing cooperation and coordination, sustaining long-term observations, managing and sharing information, building and maintaining operational capacity, and providing the capacity to meet the challenges. The committee heard from many in the community who had stepped in to fill gaps, but were not supported to do so and were stretched thin in responding to multiple demands forced by the rapid pace of change. To do this, people have to be engaged, trained, re-trained and supported so that we have the requisite expertise, provide for follow-through in research infrastructure, operations, and administration, and can rapidly respond to new ideas and fresh perspectives.

Stakeholder-Initiated Research

Critical questions are emerging from stakeholders, including decision-makers and communities, which are not traditionally participants in federal research (thing *we think we don't know*). There is not currently a consensus within the research community that this type of research is important, therefore it is less likely to rise to the top during proposal reviews and funding decisions—what we *know we need to know* will often take precedence over what *we think we don't know*.

An evaluation of how current funding mechanisms affect the ability of non-traditional research organizations to participate in Arctic research is needed (see also Intersectoral Cooperation and the section on Growing Human Capacity earlier in this chapter). Approaches used by other agencies, regions, and countries that are worth considering applying to the Arctic.

International Funding Cooperation

A major barrier to international collaboration is the nature of the present framework for funding basic research. International collaborations can by stymied by failure to obtain funding approval from agencies in more than one country. Most nations have a national funding organization that is constrained by unique rules and guidelines that rarely accommodate multinational proposals. This somewhat arbitrary limitation impedes true international collaboration. Peer review of proposals also lacks consistent guidelines internationally, and proposal target dates are not synchronized. There are few official channels (e.g., Belmont Forum[40]) for program managers to communicate internationally to set common research goals. Removing these barriers to efficient international collaboration requires long-term, sustained commitments from national funding agencies, and the development of policies that serve the interests of both national funding agencies and the scientific community. An Arctic activity is forthcoming from the Belmont Forum, which is a welcome first step, but a long term sustained program supporting international collaboration would yield many additional benefits.

Global leaders are beginning to recognize the importance of cooperation in the Arctic. For example, in August 2013, the Russian news agency ITAR-TASS reported that:

> "Japan believes there is a strong need to conduct continuous monitoring and research in the Arctic, in particular, in connection with global climate change," Hakubun Shimomura [minister of education, culture, sports, science and technology] continued. "In view of the fact that Russia is a country to which the largest territory in the Arctic belongs, we consider cooperation with it as absolutely necessary. In particular, we need to work together in the sphere of creating monitoring stations in the Arctic, the use of the icebreaker fleet, exchange of experts and the general expansion of research in this sphere." The minister said that a regular meeting of the Japanese-Russian Joint Commission on Scientific and Technological Cooperation will be held in Tokyo this September. "It will exactly discuss further prospects for the development of interaction and cooperation between the two countries in this part of the world…We plan to put forward a concrete proposal on Arctic research cooperation, in particular, with regard to cooperation in the sphere of observation and personnel exchange," said the minister.

Long-Term Observations

Change can only be detected by observations over time. The precision by which change can be measured depends on the consistency, frequency, and breadth of those observations. At present, there are relatively few consistent, frequent, spatially extensive datasets for the Arctic. Instead, we have a smattering of ad hoc stations, incomplete time series, and varying methods. The Undetermined Arctic section in Chapter 3 addressed the rationale for better long-term observations. Here we address the implications for funding.

Consistent, system-wide observations over time require sustained support. Long-term funding commitments, however, are rare. Furthermore, the payoff from long-term observations is typically time-delayed, making it easy to justify spending money on relatively short-term research efforts that produce results in a few years rather than over the course of decades. The result on the funding side is a patchwork of efforts that have little coordination and thus exhibit little synergy, in

[40] The Belmont Forum was established to overcome some funding challenges by advancing international collaboration in research through joint announcement of targeted programs: "(1) strengthening engagement between the research funding agencies and the academic research community as represented by ICSU and (2) improving coordination of early phase engagement on GCR strategies and priorities in order to improve co-design, co-alignment, and co-funding of major research programs." http://www.igfagcr.org/index.php/challenge "The Forum requires each Collaborative Research Action to address the Belmont Challenge: To deliver knowledge needed for action to avoid and adapt to detrimental environmental change including extreme hazardous events. Belmont further requires consideration of human and natural systems in each proposal, and a minimum of three nations involved in each project." http://www.climate-cryosphere.org/news/clic-news/521-update-on-international-research-funding-from-the-belmont-forum

that the monitoring of one component in one location does not readily lend itself to detecting the connections between that component and other parts of the system, or to evaluating the relationship among trends observed in different locations. Complicating matters in the Arctic is the fact that processes interconnect across national borders, requiring cooperative, long-term international observations.

One alternative is the development of a coordinated program of long-term observations, designed not from individual interest or based on what proposal happened to get funding, but rather from a vision of understanding the system as a whole, and with a sustained commitment to funding. Such an approach is the idea behind the international Sustaining Arctic Observing Networks (SAON) initiative and other efforts such as the Circumpolar Biodiversity Monitoring Program. While meritorious, these efforts are still largely a collection of ad hoc efforts with funding dependent on those responsible for each separate component of the overall network.

Our ability to detect change and to determine what new features of the Arctic system are emerging is thus compromised and will remain so until there is a lasting commitment to long-term observations. Because agency interests will always be focused on specific missions or mandates, we need to explore how to put in place a network backbone that provides continuity as well as disciplinary and regional breadth. This backbone would serve to explore promising scientific approaches and generate new findings while at the same time keeping track of key variables and indicators of change. Other activities, such as more focused agency programs would benefit because they could plug into this network.

5
Building Knowledge and Solving Problems

Photo credit: Matt Kennedy, Earth Vision Trust

We want to understand the wonder of the world around us. We want to use what we learn to improve our circumstances, to support human wellbeing and dignity. We want to mitigate harmful impacts where possible and adapt as best we can to changing conditions. We want to anticipate what lies over the horizon so that we are better prepared to meet future challenges (Box 5.1). All of these motivations apply to Arctic research, as scientists study the inherent fascination of a rapidly changing region dominated by ice in many forms, and as society figures out how best to face the challenges and pursue the opportunities emerging there.

Curiosity-driven research and problem-oriented research are often held up as competing and even mutually exclusive approaches. This dichotomy is a reflection more of agency funding priorities and mechanisms and less a fundamental property of the research enterprise itself. In practice, and as demonstrated by the many examples described in this report, our understanding of the Arctic benefits from both approaches, and the ability to act on Arctic matters requires insights from all points on the research spectrum. Because this dichotomy is misleading, we should not seek to identify an "optimal balance" between research on fundamental questions versus that on specific, urgent problems. It is more productive to think about the ways in which decision makers and communities can draw on the results of all types of research to find appropriate paths for action, and the innovative research that emerges when researchers direct their inquiry toward what decision-makers need to know.

Natural and social scientific study can provide an objective basis for developing a common understanding of the phenomena and processes that define and shape the Arctic. It has the potential to provide lines of evidence for making decisions about how to live and work in the Arctic, recognizing that our knowledge will never be complete, but that using the best available information can support decisions that meet our goals now while leaving us better prepared for, and resilient to, future shocks.

For all regions of the planet where accelerated impacts of climate change are occurring, it is well recognized that if action had been taken earlier to tackle global warming using the science available at that time, the results would likely have been different with more positive environmental outcomes. This lack of action strongly suggests that the science-policy-practice link is broken (Weichselgartner and Marandino, 2012). These authors point to a need to improve the ways in which science is used to develop policies and other tools for managing marine environments, but this need also applies to the Arctic. They also suggest that, in general, improving how science is translated to knowledge, synthesizing existing local knowledge, and engaging regional communities to develop decision support systems are some of the important ways in which this broken link can be repaired.

Arctic research is already an important underpinning of U.S. investments in resource exploration, wildlife management, and social services (e.g., Huntington et al., 2011; Meek et al., 2011; Shanley et al., 2013). Alaska provides half the nation's commercial fish catch by weight (NMFS, 2012), holds vast reserves of oil and natural gas, is home to indigenous peoples who continue traditional practices on land and sea that are critical to culture and community, serves as a bellwether for rapid environmental change and its impacts, and has a critical role in the regulation of global climate (Euskirchen et al., 2013). The management of Alaska's fisheries is recognized around the world for its commitment to sound stewardship based on sound science. The regulation of oil and gas activities relies on scientific understanding to uphold the high standards needed to meet the nation's commitment to conservation of wildlife and ecosystems. Natural and social scientific research supports the pursuit of sustainable futures for Arctic communities.

At the same time, research designs in general are not crafted with decision support for practitioners in mind, and many scientists are ill-prepared to engage substantively and ethically with these processes (e.g., Johnson et al., 2013; Sutherland et al., 2013; Tyler, 2013). The role of research leading to action with knowledge is complex. Knapp and Trainor (2013) compiled results from a wide range of stakeholders on ways to improve this science-policy-link. They found that there is strong decision-maker support for making improvements. Their results are consistent with this report: among other recommendations, they suggest improvements to broad access to data, knowledge sharing and mobilization, regional scale and community-engaged science, and interdisciplinary research training.

Because of the interdisciplinary nature and the geographic focus of Arctic research, the scientific community is well poised to improve knowledge mobilization and its integration in governance and institutions. It is critical in this time of rapid change, as opportunities for economic development, capacity building, and ecological conservation interact, that Arctic research seeks and implements best practices in supporting knowledge integration in governance. These practices need to address the boundaries between policy-relevant science and policy making (Turnpenny et al., 2013), actively consider the timescales on which decisions are made (Tyler, 2013), and produce knowledge that is, and is perceived as, salient, credible, and legitimate (Cash et al., 2003). In times of rapid change, all of these characteristics can be challenging and thereby prevent scientific knowledge integration or delay policy implementation (Tonn et al., 2001).

Providing useful information for Arctic communities is a good example of the importance and difficulty of connecting research to action (e.g., Gerlach and Loring, 2013). The current and future well-being of those communities depends on, among other things, the ability to respond effectively to the myriad social and environmental changes taking place. Information is one part of this equation. Human capacity to act on that information is also required, from individual ability to systems of governance that foster adaptation and learning. Collaborations with researchers have great potential to help, but community ownership of both the process and the results is essential. Communication with other communities can share ideas and successes, building a network of support. These outcomes require understanding of the ways communities operate, and also need input beyond that which researchers provide. In other words, research and researchers can be part of the solution, together with supporting and expanding the community's capacity to learn and act (Audla, 2014).

The bottom line is: How can we do a better job of initiating, supporting, and conducting research that seeks to incorporate salient, legitimate, and timely scientific advice into Arctic decision-making? Funding agencies that collaborate to produce opportunities that incentivize the integration of curiosity-driven and problem-oriented research will motivate such research.

Second, how can we help to promote incorporation of decision support in the broader research community? In the United States "many public agencies still advocate the traditional approach best characterized by the phrase 'invite, inform, and ignore'" (Karl et al., 2007). There is growing awareness that consultative processes are more effective, particularly in the Arctic context of high costs of field programs and a mobilized and knowledgeable resident community. To maximize opportunities for knowledge integration in decisions while ameliorating the potential for conflict and violations of intellectual property, research programs require decision maker participation, support for local research capacities, and investments in education and capacity building.

Decision-making based on scientific knowledge tends to be more effective when the stakeholders and researchers communicate at all phases of the process: from planning to knowledge generation to assessments of the effectiveness of the decision. Funding of this sort of work, therefore, should include activities that foster engagement among the various entities involved.

Connecting research with decisions is in many respects beyond the capacity of an individual researcher or project. More support both from agencies that fund research and from agencies that make decisions that could benefit from the results of such research. While short-term decision needs cannot drive all aspects of Arctic research, neither can they be ignored. While scientific results are not the only factor considered in decisions (e.g., Tyler, 2013), they are an important component and the Arctic research community as a whole needs to acknowledge the importance of communicating and working with decision makers. We urge scientists and decision makers to look for models to emulate and to work together to find new ways of understanding one another, for the long-term benefit of the Arctic and its inhabitants.

Addressing the challenges that stem from what is happening in the Arctic in the Anthropocene requires a greater degree of cooperation, both among researchers from different disciplines and between researchers and decision makers. In other words, getting more from Arctic research may best be pursued by enhancing the ways in which we make use of that research. We need to support more collaboration among scientists and among nations. We need to improve the application of results by society by creating more ways to interact and fostering a sense of shared purpose to manage change to the best of our abilities. The United States has the resources to invest in such a range of research undertakings throughout the entire Arctic. A will to apply the results of research is needed, as is a continued commitment to studying what exists, what is emerging, and what awaits us in the Arctic.

BOX 5.1
LAST SEA ICE REFUGE

The record-setting losses of sea ice in 2007 and 2012 resulted in widespread attention to the question of when the Arctic will be ice free in summer. But a closer look at the model results leads to an important finding: after most of the ice is lost, many projections show some sea-ice cover extending far into the latter half of this century. The modeled ice distributions (Figure 5.2) project that this last remaining summer sea ice will be located north of Greenland and the Canadian Archipelago, in a region known as the last sea-ice refuge or the last ice area (Pfirman et al., 2009; Wang and Overland, 2009; WWF, 2012). Because winds drive winter ice into this region, it is expected to continue having contiguous ice cover in summer for decades after sea ice is lost throughout the rest of the Arctic. This means that polar bears, ringed seals, and other species dependent on sea ice will likely find supportive habitat in this region throughout much of the 21st century (Durner et al., 2009; Kelly et al., 2010).

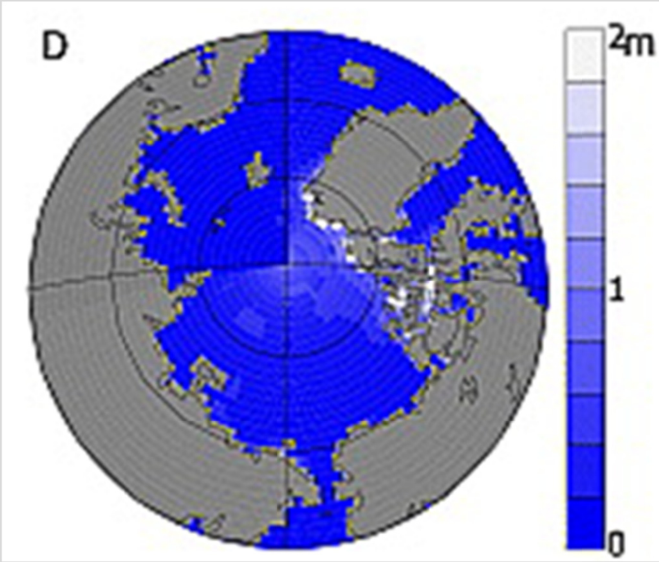


FIGURE Model projections of sea ice thickness when the Arctic is nearly ice free in September, within 30 years. Units for sea ice thickness are meters. SOURCE: Wang and Overland 2009.

Knowing that there will be a region with persistent summer sea ice poses many challenges: As there is less and less ice, forecasting the location of the sensitive region will become more important (Lovecraft and Meek, 2010; Meek and Lovecraft, 2011). How large will it be, and for how long? How will the ice characteristics change over time (i.e., from multiyear ice to mixed multiyear and first-year ice, to largely first-year ice)? How much and what types of ice are needed to support key species, such as polar bears and ringed seals? While projections indicate that the refuge will be located largely within the exclusive economic zones of Canada and Greenland, research indicates that the ice supplying it will come from the central Arctic, and with increasing ice speeds (Kwok et al., 2013; Rampal et al., 2009), from the Siberian continental shelf (Pfirman et al., 2009). Given the dynamic nature of the ice cover, what issues are raised by oil development, commercial shipping, and tourism? What would be needed to manage this special region -- at local, national, and international scales—so that the quality of habitat is maintained for as long as possible? Will this become a region of cooperation, for example, designated internationally as a special area (Lovecraft and Meek, 2010; Meek and Lovecraft, 2011; Pfirman et al., 2008) or will it become a region of conflict (Chapter 3)? Establishment of public-private partnerships (see Chapter 4) may be the key to co-management of this region.

This is not the only region in the Arctic that is special – other refugia for cold-dependent species and hotspots are important because of either their vulnerability or their resilience in the face of change, and need to be managed carefully. How do we predict and then set research and management priorities for regions of high ecological and cultural importance?

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Appendixes

A
Acronyms and Abbreviations

ABoVE	Arctic Boreal Vulnerability Experiment
ACADIS	Advanced Cooperative Arctic Data and Information Service
ACIA	Arctic Climate Impact Assessment
AIRS	Atmospheric Infrared Radiation Sounder
AMOC	Atlantic Meridional Overturning Circulation
AMSR-E	Advanced Microwave Scanning Radiometer – Earth Observing System
AMSU	Advanced Microwave Sounding Unit
AOFB	autonomous ocean flux buoys
AON	Arctic Observing Network
APECS	Association of Polar Early Career Scientists
ARM	Atmospheric Radiation Measurement
AUV	autonomous underwater vehicles
CDR	carbon dioxide removal
CI	cyberinfrastructure
CMIP5	Coupled Model Intercomparison Project Phase 5
CODAR	coastal ocean dynamics applications radar
CORS	Continuously Operating Reference Station
CRA	Collaborative Research Action
DoD	Department of Defense
ELOKA	Exchange for Local Observations and Knowledge in the Arctic
EOL	Earth Observing Laboratory
ET	evapotranspiration
GAO	Government Accountability Office
GCM	global climate model
GrIS	Greenland Ice Sheet
GNSS	Global Navigation Satellite System
GPM	Global Precipitation Measurement

GPS	Global Positioning Satellite
GRAV-D	Gravity for the Redefinition of the American Vertical Datum
HALIP	High Arctic Large Igneous Province
IARPC	Interagency Arctic Research Policy Committee
IASC	International Arctic Science Committee
IASSA	International Arctic Social Sciences Association
InSAR	Interferometric Synthetic Aperature Radar
IOOS	Integrated Ocean Observing System
IMB	Ice Mass Balance
IPY	International Polar Year
ITP	ice-tethered profilers
LEDAPS	Landsat Ecosystem Disturbance Adaptive Processing System
LIP	Large igneous province
LTER	Long-Term Ecological Research
MIS	Marine Isotope Stage
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NGA	National Geospatial-Intelligence Agency
NGEE	Next-Generation Ecosystem Experiment
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
NSSI	North Slope Science Initiative
OOI	Ocean Observing Initiative
PacMARS	Pacific Marine Arctic Regional Synthesis
PETM	Paleocene-Eocene Thermal Maximum (PETM)

PI	principal investigator
PPF	polar profiling floats
ROV	remotely operated vehicles
SAON	Sustaining Arctic Observing Networks
SAR	Synthetic Aperture Radar
SCTF	Scientific Cooperation Task Force
SEARCH	Study of Environmental ARctic CHange
SEES	Science, Engineering, and Education for Sustainability
SHEBA	Surface Heat Budget of the Arctic Ocean
SMAP	Soil Moisture Active Passive
SOAR	Synthesis of Arctic Research
SRM	solar radiation management
UAV	unmanned aerial vehicles
UCAR	University Corporation for Atmospheric Research
USARC	U.S. Arctic Research Commission
UV	ultraviolet

B

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C
Summary of Questionnaire Responses

The committee carefully considered multiple forms of community input (see also Appendix B). One of these was an informal online questionnaire[41], distributed to a wide audience via newsletters and listservs. The questionnaire was distributed to various NRC boards and committees (including the Polar Research Board, Ocean Studies Board, Board on Atmospheric Sciences and Climate, Space Studies Board, Board on Environmental Change and Society, and Marine Board); email distribution lists such as ArcticInfo, Arctic Monitor, IASSA, CLIMLIST, CRYOLIST, Paleoclimate List, APECS, and USARC Arctic Update; the US IASC Delegation; and other groups, blogs, and online networks. The input collected was not used in a statistical or quantitative analysis. Rather, the comments provided insights into whether the committee had overlooked some aspects of emerging research. Multiple sources of information were considered in the drafting of this report.

Each respondent was asked to answer a few background questions about career stage, scientific discipline, and sector. Respondents were then asked to address the following questions about the future of Arctic research:

- Within your own discipline, please list up to 3 emerging scientific questions that will enhance our understanding of the Arctic over the next 20 years.
- Please list up to 3 ideas or needed improvements for technology, infrastructure, or innovative logistics that you believe will play a major role in Arctic Research over the next 20 years.
- Please share any additional comments or information you wish the committee to consider.

A total of 330 complete responses were received from a wide range of disciplines, expertise, and geographical locations (Figures C.1 through C.4). The following figures show that there was a range of response types, but this should not be viewed as a systematic survey of the community.

[41] The committee used SurveyGizmo (http://www.surveygizmo.com/).

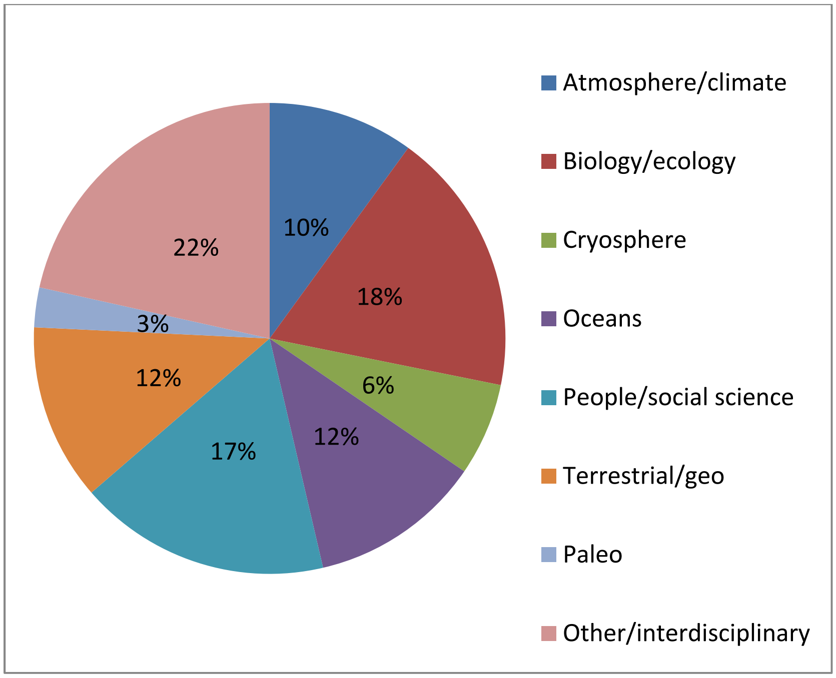

FIGURE C.1 Respondents were asked to briefly describe their discipline. They were sorted into eight categories: atmosphere/climate, biology/ecology, cryosphere, oceans, people/social science, terrestrial/geo, paleo, and other/interdisciplinary. A variety of disciplines and expertise were represented.

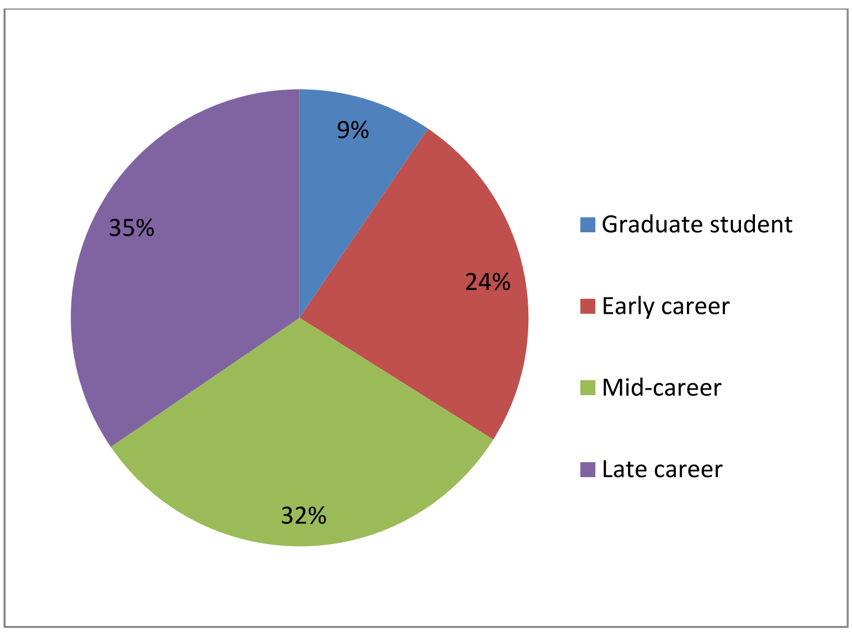

FIGURE C.2 Most respondents considered themselves to be late career (25+ years post terminal degree), but a large number of responses were received from graduate students as well as early and mid-career scientists.

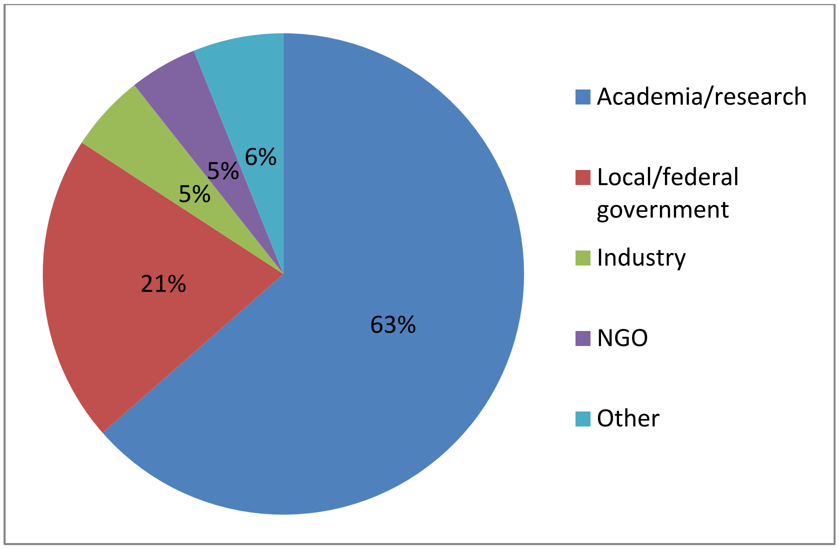

FIGURE C.3 When asked to describe their primary sector, a large number of questionnaire respondents indicated that they are in academia and research. Smaller percentages of respondents represented local and federal government, industry, NGOs, and others.

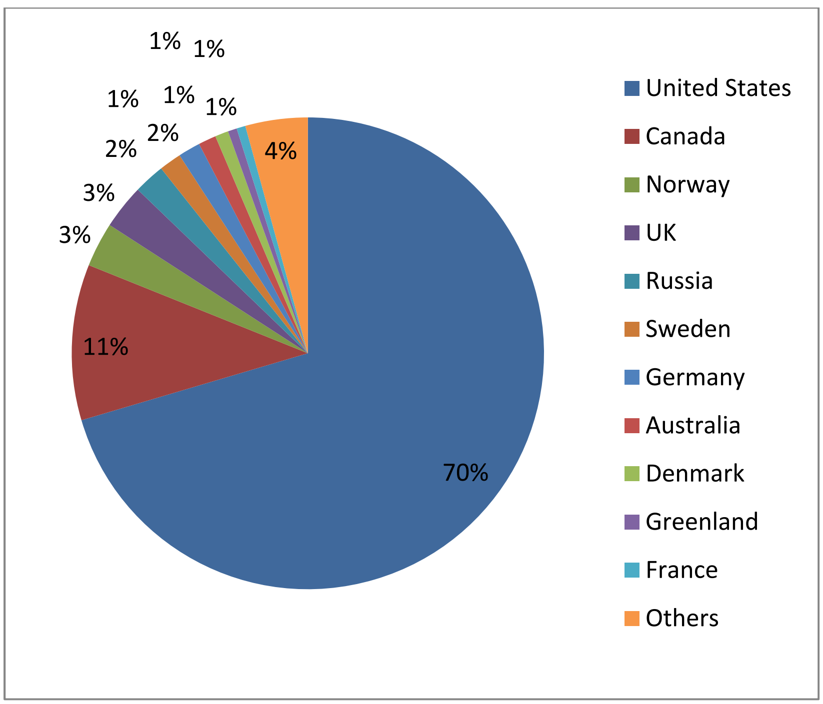

FIGURE C.4 By far, most questionnaire respondents were from the United States, although a number of other countries are also represented. Canada has the second largest representation in this questionnaire.

The questionnaire asked respondents to identify, within their own discipline, up to three emerging research questions that will enhance understanding of the Arctic over the next 20 years. Responses to this question were grouped into the following categories:

- Biological systems
- Physical systems
- Human-environmental systems
- Arctic system/feedbacks/cascading effects
- Rapid change/thresholds
- Management/governance
- Other (including technology ideas)

Respondents were then asked to list up to three ideas or needed improvements for technology, infrastructure, or innovative logistics that they believe will play a major role in Arctic Research over the next 20 years. They were also asked to select the category or categories that best describe their response:

- Existing but not yet deployed
- New technology with a high potential for deployment in the next 20 years
- Emerging technology that requires further development but is critical even if its likelihood of deployment in 20 years is uncertain

Finally, respondents were asked to share any additional comments. These could include, for example, emerging questions in cross cutting realms such as integrated systems science, sustainability science, and applying knowledge for decision support. Some themes emerged from this open-ended question:

- Interconnections (e.g., international, interagency, intergovernmental, and interdisciplinary connections)
- Human and ecosystem connections and community involvement (including indigenous knowledge and citizen science)
- Infrastructure needs
- Arctic system and linkages with the Earth system (including climate change and Arctic impacts as well as feedbacks)
- Data coordination and management (particularly open access)
- Communication (with the public, media, local communities, and other scientists, for example)
- Sustainability

The committee found that it was useful to have some insight into the research questions, science ideas, and general concerns of the Arctic community (across a broad range of disciplines and expertise), but this was not a systematic survey. The committee did not consider the responses to be a complete or official statement for the scientific community, and generalizing based on the responses received should be avoided. The individual responses are available in the Public Access File for this study. The committee considered them in their deliberations and used their expert judgment, as well as other community input, into the development of the questions presented in Chapter 3.

D
Biographical Sketches of Committee Members

Henry Huntington (Co-Chair) is a Senior Officer with the International Arctic campaign at the Pew Charitable Trusts. Before this, Dr. Huntington worked independently in environmental research and policy, reviewing the regulation of subsistence hunting in northern Alaska, documenting traditional ecological knowledge of beluga and bowhead whales, studying Inupiat Eskimo and Inuit knowledge and use of sea ice, and assessing the impacts of climate change on Arctic communities and marine mammals. Dr. Huntington has also worked as a researcher and writer on a number of international research programs, among them the Arctic Monitoring and Assessment Program, the Program for the Conservation of Arctic Flora and Fauna, the Arctic Climate Impact Assessment, the Arctic Marine Shipping Assessment, and the Arctic Biodiversity Assessment. He has written three books and numerous articles, and has been published in journals such as Arctic, Polar Research, Marine Policy, Ecological Applications, and Nature. Dr. Huntington holds a Bachelor's Degree in English from Princeton University and Master's and Doctoral Degrees in polar studies from the University of Cambridge.

Stephanie Pfirman (Co-Chair) is Alena Wels Hirschorn and Martin Hirschorn Professor of Environmental and Applied Sciences at Barnard College. Dr. Pfirman has been a faculty member at Barnard since 1993 and currently serves as a Co-Chair of Barnard's Department of Environmental Science. She holds a joint appointment with Columbia University as a member of the faculties of the Earth Institute and the Department of Earth and Environmental Sciences, and Adjunct Research Scientist at the Lamont-Doherty Earth Observatory at Columbia University. Before accepting her position at Barnard, Dr. Pfirman was a Senior Scientist at the Environmental Defense Fund as well as a co-developer of the award-winning exhibition, "Global Warming: Understanding the Forecast," produced jointly with the American Museum of Natural History. Her research focuses on the Arctic environment, specifically the nature and dynamics of the Arctic Sea under changing climate. Dr. Pfirman is a Fellow of the American Association for the Advancement of Science and a member of the National Science Foundation's advisory committee for Environmental Research and Education.

Carin Ashjian is a Senior Scientist in the Department of Biology at the Woods Hole Oceanographic Institution (WHOI). She graduated with a Ph.D. in Oceanography from the University of Rhode Island in 1991. She did postdoctoral work at Brookhaven National Laboratory, the University of Miami, and Woods Hole Oceanographic Institution before joining the scientific staff at WHOI in 1996. Her research has focused on oceanography, zooplankton ecology, and biological-physical interactions in a range of the world's oceans. Her recent work focuses on the impact of climate change on polar ecosystems and the greater Arctic system, including the human dimension. She has served on numerous national committees focusing on polar research and logistics, including the North Pacific Research Board Science Panel, the Bering Sea Program Science Advisory Board, and the SEARCH Observing Change Panel, and she is a past chair of UNOLS Arctic Icebreaker Coordinating Committee.

Laura Bourgeau-Chavez is a Principal Investigator at MTRI and an Adjunct Assistant Professor at the School of Forest Resources and Environmental Science at Michigan Technological University. She has over 20 years of experience in the application of remote sensing to characterize and measure landscape ecosystems. Her work has focused on SAR and the fusion of SAR and Multispectral data for mapping and monitoring wetlands and monitoring soil moisture for fire danger prediction in boreal regions. Dr. Bourgeau-Chavez holds a Bachelor of Science and a Master of Science in Forest Ecology from the University of Michigan, and received her PhD from the School of Forestry and Environmental Science of the University of New Brunswick.

Jennifer A. Francis is a Research Professor at the Institute of Marine and Coastal Sciences and the Graduate Program in Atmospheric Sciences at Rutgers University. She studies the Arctic climate system, causes for rapid change, and linkages between the Arctic and the global climate system. Her work is funded primarily by the National Science Foundation and the National Aeronautics and Space Administration. She has served on several national committees in the National Science Foundation, the American Meteorological Society, and the science steering committee for the Study of Arctic Environmental Change (SEARCH). Dr. Francis received her Ph.D. in Atmospheric Sciences from the University of Washington in 1994. Dr. Francis is currently a member of the Polar Research Board.

Sven Haakanson was born and raised in the rural Kodiak Island community of Old Harbor, Alaska, and is a member of the Old Harbor Alutiiq Tribe. He holds a B.A. in English from the University of Alaska Fairbanks, and a Ph.D. in Anthropology from Harvard University. Since 2000, Dr. Haakanson has worked to share Native American perspectives with museums as well as museum practices with Native people. Dr. Haakanson is the former Executive Director of the nationally acclaimed Alutiiq Museum, a Native cultural center in Kodiak, Alaska. He is currently at the University of Washington. He has made collections more accessible to Native communities by researching objects in the world's museums and developing traveling exhibits and educational resources around the information they hold. In 2007 his work was honored with a MacArthur Foundation Fellowship. Dr. Haakanson serves on many cultural organizations and maintains an active research program. He is systematically documenting Kodiak's prehistoric petroglyphs and continues to publish his research on the Nenets culture of Siberia.

Robert Hawley is an Assistant Professor of Earth Sciences at Dartmouth College. He studies the physics of firn densification, mass balance of large ice sheets, and interpretation of ice core records, using field programs, numerical analysis, and remote sensing. He has worked primarily in East and West Antarctica and Greenland. He started working as a glaciologist in 1995, as an undergraduate at the University of Washington, through the National Science Foundation 'Research Experience for Undergraduates' (REU) Program. Following the completion of his B.S. degree, he continued in glaciological research by participating in the inaugural winter-over at Summit camp, Greenland, during the 1997-1998 boreal winter. In 2005, Dr. Hawley earned a Ph.D. in geophysics from the University of Washington. He then served as a post-doctoral research associate at Cambridge University from 2005-2008 before joining the faculty at Dartmouth in 2008.

Taqulik Hepa was born and raised in Barrow, Alaska. She grew up living a subsistence-based lifestyle and has great respect for her traditional and cultural way of life. Participating in subsistence hunting activities with her family has taught her many valuable lessons in subsistence survival skills. Currently, Ms. Hepa serves as the Director for the Department of Wildlife Management for the North Slope Borough. In this capacity, she is in contact with many local people and outside agencies dealing with subsistence related issues. She is a member to the following boards and commissions; Gates of the Arctic National Park and Preserve Subsistence Resource Commission, Indigenous People's Council of Marine Mammals, Alaska Migratory Bird Co-management Council, Barrow Arctic Science Consortium, and Ukpeagvik Inupiat Corporation. Taqulik cares deeply for the protection of her environment and subsistence resources and wishes to expand her opportunities to participate in the advancement of research programs in the Arctic.

David Hik is a Professor in the Department of Biological Sciences at the University of Alberta. He received a Ph.D. from the University of British Columbia, and since 1984 his research interests have focused primarily on the ecology of plant-animal interactions in northern, alpine, and arid environments. He currently serves as President of the International Arctic Science Committee (IASC) and Vice-Chair of the Arctic Council–led 'Sustaining Arctic Observing Networks (SAON)' initiative. He is also a member of several advisory boards, including the Canadian Polar Commission, the Arctic Institute of North America, the Polar Continental Shelf Program, and the NSERC CREATE Program in Arctic Atmosphere Science. Previously, he held the Canada Research Chair in Northern Ecology (2002-2012) and was Executive Director of the Canadian International Polar Year (IPY) Secretariat (2004-2009).

Larry Hinzman is the Director of the International Arctic Research Center and is Professor of Civil and Environmental Engineering at the University of Alaska Fairbanks. Professor Hinzman's primary research interests involve permafrost hydrology. He has conducted hydrological and meteorological field studies in the Alaskan Arctic continuously for over 30 years while frequently collaborating on complementary research in the Russian and Canadian Arctic. His research efforts have involved characterizing and quantifying hydrological processes and their inter-dependence with climate and ecosystem dynamics. Dr. Hinzman's academic degrees were earned from South Dakota State University, Purdue University and the University of Alaska Fairbanks in Chemistry, Soil Science, Agronomy and Soil Physics. He is strongly committed to facilitating international partnerships to advance our understanding of the Arctic system.

Amanda Lynch is a Professor of Geological Sciences at Brown University. She obtained her Ph.D. in Meteorology in 1993 from the University of Melbourne. From 1992-2003 she was in the United States, most recently at the University of Colorado. She was a Fellow of the NOAA Cooperative Institute for Research in Environmental Science, a Visiting Scientist at the National Center for Atmospheric Research (NCAR), and a consultant to Los Alamos National Laboratory. She returned to Australia in 2004 to take up a Federation Fellowship and head the Monash University Climate program. She was admitted as a Fellow of the Australian Academy of Technological Sciences and Engineering in 2008, and returned to the U.S. in 2011. Dr. Lynch's interests lie in the application of climate and meteorological research to concrete problems of policy relevance. Her approaches include regional and global climate models of the contemporary and past climates, weather prediction models, statistical models, and quantitative and qualitative analysis. She has a strong interest in working with under-represented minorities, particularly indigenous people.

A. Michael Macrander currently serves as Chief Scientist for Shell Alaska. In this role he is responsible for planning, directing, and implementing a diverse portfolio of scientific investigations and monitoring in the Alaskan Arctic. This portfolio includes both onshore and offshore studies programs and is directed at understanding broad baseline environmental /ecological conditions, monitoring and assessing interactions between industry activities and the environment, and assessing impacts of an overall changing Arctic. In addition to directing the Shell Alaska science program, Dr. Macrander serves as a subject matter expert on Arctic sciences within Shell, advising on Arctic and subarctic projects for the company. He serves on the Advisory Panel for the North Pacific Research Board (NPRB) and the Science and Technical Advisory Panel for the North Slope Advisory Panel. Through his more than 30 year career, Dr. Macrander has focused his investigative efforts on multiple aspects of environmental ecology, management, and regulation including wetlands, threatened and endangered species protection, ecological risk evaluation, and evaluation of the impacts of oil spills.

Gifford Miller is a Professor of Geological Sciences as well as a Fellow and Associate Director of the Institute of Arctic and Alpine Research at the University of Colorado Boulder. Dr. Miller earned his Ph.D. from the University of Colorado Boulder in 1975 and specializes in quaternary stratigraphy, geochronology, and paleoclimatology. His main scholarly interests focus on gaining an improved understanding of how the physical earth system operates with particular interest in using the Quaternary as a means to reconstruct the coupled ocean/atmospheric/ice climate system. Current research includes quaternary stratigraphy and dating methods; amino acid geochronology and cosmogenic exposure dating; and glacial history of the Arctic, focusing on glacial chronology and ice-sheet dynamics using direct field evidence and quantitative estimates of the timing and magnitude of warm times in the Arctic. Among his distinctions, Dr. Miller is an Elected Fellow of the Geological Society of America and an Elected Fellow of the American Geophysical Union.

Kate Moran is the Director of Ocean Networks Canada. She formerly served a two-year term as Assistant Director in the White House Office of Science and Technology Policy in Washington, DC. In her White House role, Moran advised the Obama administration on the oceans, the Arctic, and global warming. She was seconded to the position from a faculty appointment at the University of Rhode Island where she was a Professor of Oceanography and Associate Dean of the Graduate School of Oceanography. Dr. Moran holds degrees in marine science and engineering from the University of Pittsburgh, the University of Rhode Island and Dalhousie University. Her research focuses on marine geotechnics and its application to the study of paleoceanography, tectonics, and seafloor stability. She has authored more than 45 publications.

Ellen Mosley-Thompson (NAS) is a Distinguished University Professor in the Department of Geography and Director of the Byrd Polar Research Center at The Ohio State University. She was elected to the National Academy of Sciences in 2009 and currently serves as a member of both the Polar Research Board and the U.S. National Committee for the International Union for Quarternary Research. Dr. Mosley-Thompson has made significant contributions to understanding Earth's climate history using the chemical constituents and physical properties preserved in its glaciers and ice sheets. These records provide a critical historical context for assessment of contemporary climate changes and rigorous constraints on regional and global forcing mechanisms. Her areas of expertise include paleoclimatology, abrupt climate changes, glacier retreat, Holocene climate variability and contemporary climate change.

Samuel Mukasa has been the Eric J. Essene Professor of Geochemistry and Dean of the College of Engineering and Physical Sciences at the University of New Hampshire since January 2011. Previously, he was a faculty member at University of Michigan since 1989, where he also served as Department Chair for the Department of Geological Sciences in 2007-2010. He holds a Ph.D. in geochemistry from the University of California, Santa Barbara, an M.S. degree in geology from Ohio State University, and a B.S. in geology from the University of New Hampshire. Dr. Mukasa received an Honorary Doctor of Science degree from Nkumba University in Uganda in 2008. Dr. Mukasa's fields of interests include geochemistry, geochronology, and petrology.

Tom Weingartner is a Physical Oceanographer and Professor of Marine Science in the School of Fisheries and Ocean Sciences at the University of Alaska Fairbanks (UAF). He has been affiliated with UAF since 1989. Dr. Weingartner holds a Ph.D. in Oceanography from North Carolina State

University. He is an observational physical oceanographer interested in continental shelf dynamics and how these processes affect marine ecosystems. He is also interested in how high-latitude shelf systems are influenced by changing climate and how these shelf processes may affect the Arctic Ocean. Dr. Weingartner uses a variety of observational tools (oceanographic moorings, satellite-tracked drifters, shipboard measurements, shore-based, surface current mapping radars, autonomous underwater vehicles, and remote sensing tools) to investigate shelf processes in the Gulf of Alaska, and the Bering, Chukchi, and Beaufort seas.