Future Science Opportunities in Antarctica and the Southern Ocean

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FUTURE SCIENCE OPPORTUNITIES IN ANTARCTICA AND THE SOUTHERN OCEAN

Committee on Future Science Opportunities in
Antarctica and the Southern Ocean

Polar Research Board

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Preface

The purpose of science, in the broadest sense, is to expand the frontier of human understanding. Antarctica and the Southern Ocean have always been, and remain, a frontier—both an unexplored place and an untapped library of knowledge. In the past 50 years, scientists have made tremendous progress in Antarctic and Southern Ocean science. But there are still many frontiers to explore in the coming decades.

Scientific inquiry in Antarctica and the Southern Ocean is helping to answer questions that are important to understanding the planet: its history, its processes, and how it is changing. The gas inside of a tiny bubble of air trapped in the Antarctic ice miles below the surface can help us understand how the climate of the whole planet is changing. A temperature sensor strapped to a seal swimming deep in the ocean under sea ice in the Southern Ocean can ultimately help us understand how sea levels might rise in Washington, DC. There are also mysteries to be solved about how the world and the universe work. Light from earliest seconds of the formation of the universe that is collected at telescopes at the South Pole can help unlock the mysteries of dark matter.

In this report, the Committee on Future Science Opportunities in Antarctica and the Southern Ocean was asked to identify the important questions that will drive scientific research in Antarctica and the Southern Ocean over the next two decades. This report is intended to inform the work of the National Science Foundation's (NSF's) Office of Polar Programs and in particular a Blue Ribbon Panel that is reviewing the logistical support of NSF's U.S. Antarctic Program. In doing its work, the committee has tried to highlight important areas of research by encapsulating each in an overarching question. The questions fall into two themes—observing and understanding global change and fundamental discovery. Research support in the South requires considerable resources, so the committee has also attempted to identify key opportunities to be leveraged in the effort to enhance scientific research in the Antarctic region. In looking forward, the committee has identified a need for new initiatives to further develop an observing network and improve scientific modeling capabilities.

Through the process of gathering information for this report, the committee heard from many people in the Antarctic and Southern Ocean science community and we thank everyone for their thoughts (see Acknowledgments section). The committee relied upon a large number of reports from the community, and we would like to thank the community at large for all of its work in these efforts over the years. In addition, we want to thank the Office of Polar Programs for providing information as we needed it, and for being open to receiving advice. Finally, this report would not have been possible without the dedication and contributions of the National Research Council staff: Edward Dunlea, Lauren Brown, Amanda Purcell, and Chris Elfring.

The Office of Polar Programs has a big job to do in supporting and enhancing scientific research in Antarctica and the Southern Ocean, and it is very important for understanding our world. We hope that this report offers advice to guide their efforts in the coming decades.

Warren M. Zapol, *Chair*
Committee on Future Science Opportunities
in Antarctica and the Southern Ocean

Acknowledgments

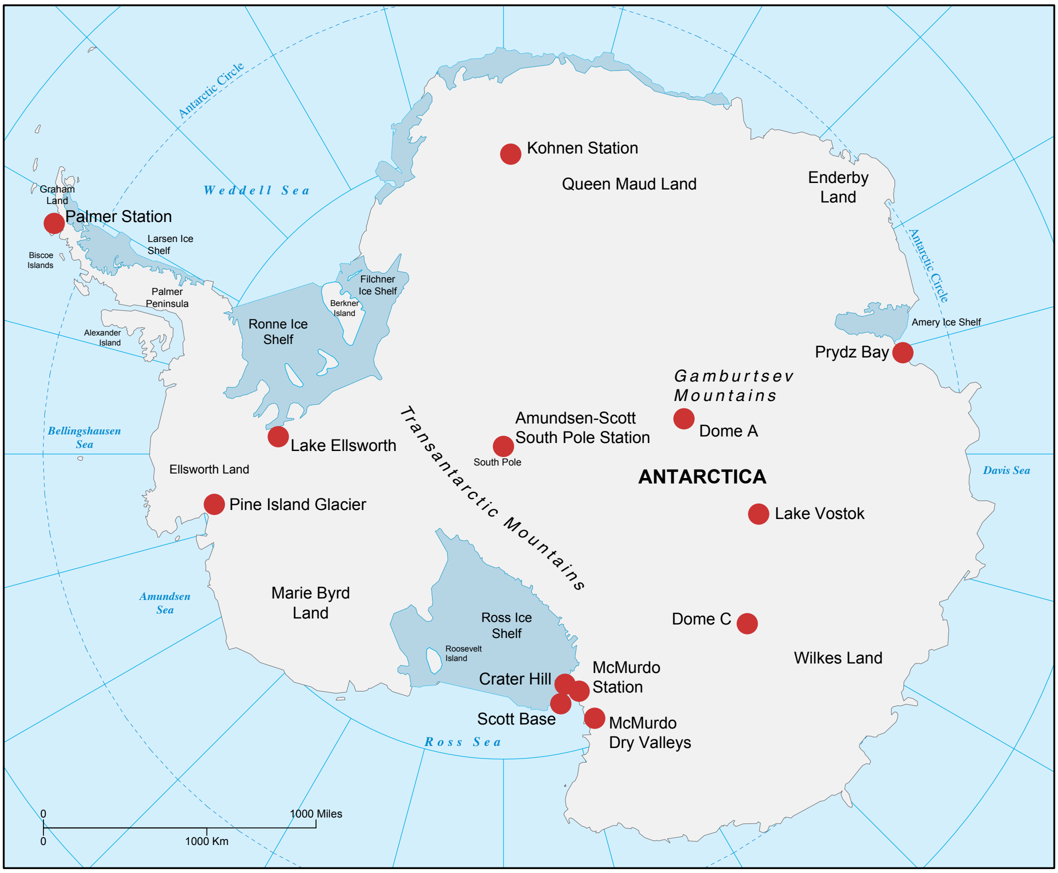
This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical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

Sridhar Anandakrishnan, Pennsylvania State University
Gerald T. Garvey, Los Alamos National Laboratory
Thom J. Hodgson, North Carolina State University
Gretchen E. Hofmann, University of California, Santa Barbara
Barbara Methe, The Institute for Genomic Research
Ellen S. Mosley-Thompson, Ohio State University
Claire L. Parkinson, NASA Goddard Space Flight Center
Steve Rintoul, CSIRO
Colin P. Summerhayes, University of Cambridge

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

In addition, the committee would like to thank in particular for their contributions during the study process: Karl Erb, Scott Borg, Brian Stone, Kate Moran, Joel Parriott, John Calder, Waleed Abdalati, Tom Wagner, Jerry Mullins, Larry Hothem, LCDR Michael Krause, Mahlon (Chuck) Kennicutt, Meredith Hooper, John Goodge, Helen Fricker, Eric Rignot, Sarah Gille, Jim Bishop, Donal Manahan, Alton Romig, Scott Doney, Allan

Weatherwax, Lawson Brigham, Alexandra Isern, and George Denton. The committee would also like to thank the numerous scientists spoken to throughout the study process, in particular all of the online questionnaire respondents who provided their thoughts on the future of science in Antarctica and the Southern Ocean.



Map of selected locations in Antarctica referenced in this report.

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Icebergs near the Antarctic Peninsula. SOURCE: Jeffrey Kietzmann/NSF.

Summary

Antarctica and the surrounding Southern Ocean remains one of the world's last frontiers. Covering nearly 14 million km^2 (an area approximately 1.4 times the size of the United States), Antarctica is the coldest, driest, highest, and windiest continent on Earth. While it is challenging to live and work in this extreme environment, this region offers many opportunities for scientific research.

The icy landscape of Antarctica and the Southern Ocean may seem distant, but the natural processes that occur there are intimately linked to those on the rest of the planet. For example, the Southern Ocean is an extremely important region of the globe for air-sea exchange of carbon dioxide, second only to the northern North Atlantic. To understand the effects of increasing emissions of carbon dioxide on the climate, it is vitally important to understand the processes that occur in the Antarctic region.

Ever since the first humans set foot on Antarctica a little more than a century ago, the discoveries made there have advanced our scientific knowledge of the region, the world, and the universe—but there is still much more to learn. Recent findings in the region have included enormous lakes and mountain ranges buried beneath ice and entire ecosystems of never-seen-before life forms. The rocks, sediments, and ice of Antarctica hold a trove of information about the past history of Earth's climate, continents, and life forms. The remarkable clarity and stability of the atmosphere above Antarctica allows scientists to look out to the upper reaches of the atmosphere and into the universe beyond—observations that could contribute to understanding of the origins of the universe and the nature of the solar system.

However, conducting scientific research in the harsh environmental conditions of Antarctica is profoundly challenging. Substantial resources are needed to establish and maintain the infrastructure needed to provide heat, light, transportation, and drinking water, while at the same time minimizing pollution of the environment and ensuring the safety of researchers.

The U.S. Antarctic Program (USAP) within the National Science Foundation (NSF) is the primary U.S. agency responsible for supporting science in Antarctica and the Southern Ocean. In 2010, the NSF Office of Polar Programs, in coordination with the Office of Science Technology Policy, initiated two activities to provide guidance to the USAP program. This report, authored by the National Research Council's Committee on Future Science Opportunities in Antarctica and the Southern Ocean, represents the first

TABLE S.1 Important Areas of Research in Antarctica and the Southern Ocean

Global Change	Discovery
How will Antarctica contribute to changes in global sea level?	What can records preserved in Antarctica and the Southern Ocean reveal about past and future climates?
What is the role of Antarctica and the Southern Ocean in the global climate system?	How has life adapted to the Antarctic and Southern Ocean environments?
What is the response of Antarctic biota and ecosystems to change?	What can the Antarctic platform reveal about the interactions between Earth and the space environment?
What role has Antarctica played in changing the planet in the past?	How did the universe begin, what is it made of, and what determines its evolution?

activity; the committee's task was to identify and summarize the changes to important science conducted on Antarctica and the surrounding Southern Ocean that will demand attention over the next two decades. The second activity is an NSF-organized Blue Ribbon Panel intended to assist in making strategic decisions to improve the logistical support of the U.S. science program in Antarctica and the Southern Ocean over the next two decades.

In response to its charge, the committee has highlighted important areas of research by encapsulating each into a single, overarching question (see Table S.1). The questions fall into two broad themes: (1) those related to global change and (2) those related to fundamental discoveries. In addition, the committee also identified several opportunities to be leveraged to sustain and improve the science program in Antarctica and the Southern Ocean in the coming two decades.

GLOBAL CHANGE

Over the past century, temperatures on land and in the ocean have been increasing. Sea level is rising, global weather patterns are shifting, and the chemical and biological processes of the planet are changing. The poles are particularly susceptible to climate change, with the Arctic already displaying large temperature changes. The situation in Antarctica and the Southern Ocean is complicated by the influence of the Antarctic ozone hole, another human-induced change that has uniquely affected this region. Thus, the Antarctic region provides an unparalleled natural laboratory in which to study these changing conditions.

How Will Antarctica Contribute to Changes in Global Sea Level?

Antarctica's ice sheets exist in a state of dynamic equilibrium: snow and ice accumulate over the continent and flow to the coasts with the movement of glaciers. When the ice comes into contact with the relatively warm ocean, it melts, or chunks of it break off and are lost to the sea in a process called calving.

Rising global temperatures now threaten to push the equilibrium out of balance. As more of the Antarctic ice sheets melt, the volume of the world's oceans will increase—and so too will global sea level. The Antarctic ice sheets hold about 90 percent of the world's ice; if all of this ice were to melt, it would raise global sea levels by more than 60 meters. Therefore, it is critical that scientists understand how rapidly the world will warm, if ice loss will accelerate, and how quickly sea level will rise. Key to improving this understanding in the next 20 years is increased observations and model development to learn more about the interactions of ice sheets at the ice-ocean and ice-bedrock boundaries.

What Is the Role of Antarctica and the Southern Ocean in the Global Climate System?

The climate system of the Antarctic region is inextricably linked to that of the rest of the planet. The strong westerly winds that circle the Antarctic continent influence global atmospheric circulation. To improve projections of future changes in atmospheric circulation, enhanced observations and modeling capacity are needed to understand the role of the Antarctic ozone hole and the influence of global climate change.

Similarly, the Southern Ocean circulation is central to the global ocean circulation, affecting not only the Southern Hemisphere but also the circulation of the North Atlantic Ocean, with impacts on the climate of Europe and North America. In addition, understanding the carbon dioxide exchange between the Southern Ocean and the atmosphere is a fundamental part of understanding the global carbon cycle and climate change. Again, improved observational and modeling capabilities are needed to improve the understanding of the role of the Southern Ocean in the global ocean system.

Changes in the patterns of sea ice in the Southern Ocean strongly affect atmospheric and oceanic circulations as well as carbon dioxide uptake; therefore, improved monitoring and modeling of sea ice will be important in the next two decades. There is also an urgent need to better understand the dynamics of the ocean-glacial ice interaction beneath floating ice shelves, which will contribute to better projections of future sea level rise caused by melting of glacial ice in Antarctica.

More information on Antarctica's influence over globally interacting systems will allow scientists to better understand the global climate system and predict how it will change in the future. A systems approach, with increased observations and improved modeling, is critical to further the understanding of all aspects of the climate system over the next 20 years.

What Is the Response of Antarctic Biota and Ecosystems to Change?

Although recent research has revealed a surprising diversity of life forms in Antarctica, even in habitats once considered lifeless, Antarctic ecosystems are relatively simple compared to those in other areas of the globe. This makes it easier to detect the impacts of global climate change and other environmental changes in Antarctic ecosystems than elsewhere on the planet.

Furthermore, Antarctic ecosystems are particularly vulnerable to change. The marine and land-based ecosystems of this region evolved in isolation from the rest of the planet, but now factors such as the global transport of pollutants, the introduction of invasive species, and increases in ultraviolet radiation are altering these communities. Increasing human presence, due to tourism and research, has brought concerns about habitat destruction, overfishing, pollution, and other toxic effects on the environment.

Of all the human influences, the impact of human-induced climate change may prove to be the largest. On land and sea, warming and ice melt will increase the area of surfaces exposed to the elements, providing new habitats for colonization by organisms—with the potential to change the functioning and structure of ecosystems. As warming continues, biotic factors such as predation, competition, and pathogens will likely have a greater influence on ecosystem functioning than the physical processes that have, until now, dominated the region's ecosystems. Changes in the ecosystems of the Antarctic region may be a harbinger of larger changes to come, and therefore monitoring Antarctic change could allow scientists to predict future ecosystem change elsewhere.

What Role Has Antarctica Played in Changing the Planet in the Past?

The movement, fragmentation, and collision of tectonic plates can have dramatic consequences on the planet, including causing earthquakes and volcanoes, constructing new mountain ranges, opening gateways between vast oceans, and triggering global climate shifts.

About 180 million years ago, the movement of tectonic plates caused Gondwana, a massive supercontinent consisting of Antarctica, India, Australia, South America, and Africa, to begin to break apart. Antarctica—which at that time was covered with dense forests inhabited by dinosaurs and mammals—started to move toward its present polar position, opening up new ocean passages and causing great shifts in the circulation of the ocean and atmosphere. These shifts reduced the amount of heat brought to the region and caused glaciation to begin, turning the lush, green continent into a white continent encased in ice. Understanding the opening of the Southern Ocean as Gondwana fragmented is critical to understanding how Antarctica became glaciated, and how global climate came to be in its present state.

DISCOVERY

Antarctica and the Southern Ocean provide a natural laboratory for scientific discovery. The tiny air bubbles trapped within the ice hold a record of the planet's atmosphere through time; the living things in the ocean and on land can teach scientists about survival strategies in extreme environments; and Antarctica provides an excellent platform for looking out to the solar system and the universe beyond. The committee highlighted several areas of science that will be important in discovery-driven scientific research in Antarctica and the Southern Ocean over the next two decades.

What Can Records Preserved in Antarctica and the Southern Ocean Reveal About Past and Future Climates?

Records of the Antarctic region's past conditions come from drilling into rocks, sediments, and ice, and from examining geological features. This information has allowed scientists to reconstruct past climatic conditions, an important step toward understanding present climate and predicting future climate change.

The fossil records in rocks and sediments can tell scientists the geographical range of an organism's habitat and the timeline of its existence. Physical and chemical analyses of cores drilled into the sediments at the bottom of the Southern Ocean can provide records of ocean temperatures, salinity, circulation, and biological productivity through time. Studying the composition of ice cores and the impurities and gases trapped in ice sheets has yielded information on past climate conditions and atmospheric greenhouse gas concentrations. Better understanding of the regular cycles and processes that affect Earth's climate will continue to accumulate from these analyses, and details of abrupt climate change events in Earth's history may provide insight on how rapidly Earth's climate could change in the future.

How Has Life Adapted to the Antarctic and Southern Ocean Environments?

Organisms native to Antarctica have evolved characteristics that allow them to thrive in the region's harsh conditions. These adaptations include changes in body shape, cardiovascular control, and metabolism that allow organisms to avoid hypothermia or hypoxia (low oxygen levels). For example, because prey is available at great depths in the Southern Ocean, many of the mammal and bird species able to survive in the harsh climate of the Antarctic region have developed the ability to dive deeply, swim under water for long periods, and resurface without suffering damage from low oxygen levels or getting the bends. More information about these specialized biochemical and physiological adaptations could hold the key to understanding and preventing a host of pathological problems that plague humans, such as heart attacks, strokes, and decompression sickness. In addition, learning how life tolerates the extremes of Antarctica could help scientists engineer frost-resistant plants and develop an array of temperature-stable products, from ice cream to vaccines. New tools are emerging that will allow scientists to study the genomics, metagenomics, and proteomics of how life has adapted to survive and prosper in the frigid and inhospitable Antarctic and Southern Ocean environments.

What Can the Antarctic Platform Reveal About the Interactions Between the Earth and the Space Environment?

As society becomes more dependent on space-based technologies such as satellites for communications and navigation, it is becoming more vulnerable to severe space weather events—magnetic storms on the Sun that can spew high-energy particles toward Earth. Space weather can disrupt the proper functioning of Global Positioning System satellites, as well as electrical power distribution at the surface.

In 1859, the most powerful solar storm in recorded history caused visible auroras all over the globe and made telegraph systems all over Europe and the United States fail, spark, and catch fire. If such an event were to occur today, it could cause trillions of dollars worth of damage, and many areas of the United States and the rest of the world could be left without electrical power and communications for several months.

The alignment of Earth's magnetic field places the planet's poles in an optimal position to monitor space weather. The region around the South Pole is an ideal location to monitor changes in space weather, as compared to the North Pole, where shifting sea ice makes building a permanent research station impractical. Increased space weather observations in Antarctica over the next 20 years can improve our ability to predict potentially catastrophic space weather events.

How Did the Universe Begin, What Is It Made of, and What Determines Its Evolution?

Antarctica's atmospheric conditions of cold temperatures, low levels of water vapor, high altitude, and stable temperatures allow scientists to view far out into the cosmos. Measurements from Antarctica of cosmic microwave background radiation can be used to test theories of how the universe formed (the Big Bang) and how it evolves (the accelerating expansion of the universe, or "inflation"). Ordinary matter makes up less than 5 percent of the universe, and very little is known about the "dark matter" and "dark energy" that constitutes the rest. Astrophysical measurements from Antarctica can provide insight into the fundamental question—of what is our universe made?

In addition, Antarctica's vast supply of homogeneous and transparent ice has allowed scientists to build a detector for neutrinos—high-energy, nearly massless particles that are very difficult to detect. Scientists have embedded photodetectors into a cubic kilometer of clear ice located deep below the surface at the South Pole research station. Understanding neutrinos could provide insights into the long-standing mystery of the origin of ultra-high-energy cosmic rays, a key piece of understanding how the universe works.

OPPORTUNITIES TO ENHANCE RESEARCH IN ANTARCTICA AND THE SOUTHERN OCEAN

The committee identified several opportunities to be leveraged to ensure a strong and efficient U.S. Antarctic Program into the future—collaboration; energy, technology, and infrastructure; and education—and identified two new initiatives—expansion of an observing network with data integration and improvements in scientific modeling capabilities—that are critical to achieving rapid and meaningful advances in science in Antarctica and the Southern Ocean in the coming 10-20 years.

Collaboration

Scientific research in Antarctica has thrived and grown over the past half century, largely because of collaboration—across national borders, across disciplinary boundaries, between public- and private-sector entities, and between scientists and the providers of logistical support. This report examines opportunities to enhance each of these types of collaboration, with the overall conclusion that, by working together, scientists can reach their goals more quickly and more affordably.

Energy, Technology, and Infrastructure

Advances related to energy and technology have the potential to facilitate scientific research in Antarctica, making the endeavor more cost effective and allowing a greater proportion of funds to support research directly, instead of to establish and maintain infrastructure. As one example, most of the energy required to power the research stations and field camps, as well as transport people and materials, comes from the burning of fossil fuels. In addition to the cost of the fuel, the combustion of fossil fuels pollutes the air, and fuel leaks during storage and transport have the potential to contaminate the surrounding environment. Innovations such as new, more cost-effective overland transportation systems for fuel, or the use of wind power generators, promise to reduce the cost and pollution associated with fuel transport. Antarctica has been and can continue to be an important testing ground for energy innovations.

One important area for development is the access to fully and partially ice-covered seas provided by surface ships and, in particular, icebreakers. There is a critical shortage of U.S. icebreaking capacity in Antarctica and the Southern Ocean at this time. Options to address this shortage include the purchase of any new polar class icebreaker by the United States either alone or in partnership with other countries and the leasing of icebreakers flagged by other countries. Based on the scientific research needs outlined in this report, the committee strongly supports the conclusion from previous reports that the United States should develop sufficient icebreaking capacity, either on a national or international basis. Any arrangement should ensure that the scientific needs in Antarctica and the Southern Ocean, both for research and for the annual break-in done to supply the McMurdo Research Station with fuel and materials, can be met by secure and reliable icebreaking capacity.

Education

Antarctica and the Southern Ocean offer great opportunities for inspiring popular interest in science in much the same way that space exploration did in the latter half of the 20th century. NSF has supported a broad range of educational efforts to spark interest in polar science, including television specials, radio programs, and a multimedia presentation that toured U.S. science centers, museums, and schools. These efforts can both increase public awareness and understanding of the research taking place in Antarctica, and help to inspire the future generations of polar scientists needed to implement the research studies described in this report. Current educational efforts related to Antarctic and Southern Ocean science at NSF could benefit from a more coordinated program of activities.

Observing Network with Data Integration and Scientific Modeling

A common theme throughout the scientific research questions described in this report is the importance of integrated and sustained observations for answering these questions. In particular, achieving rapid and meaningful advances in science in Antarctica and the Southern Ocean in the coming 10-20 years will require an expanded observing network with data integration. The committee identifies an overarching need for NSF to develop and lead a coordinated international Antarctic observing system network encompassing the atmosphere, land, ocean, ice, and ecosystems, as well as their interfaces. Based on previous examples such as the Arctic Observing Network and the proposed Pan-Antarctic Observation System, this initiative would provide the framework for intensive data collection, management, dissemination, and synthesis across projects and across disciplines; lay the foundation for many future Antarctic and Southern Ocean observations; utilize models to evaluate and plan the optimal locations for observations; and maximize the scientific output from the deployment of resource-intensive observing platforms.

Any observing system would be incomplete without the simultaneous development of new models that can assimilate the observational data and provide sophisticated tools for data analysis and synthesis. Improved data reanalysis of new and existing data sets could benefit modeling efforts internationally. Earth system models for Antarctica and the Southern Ocean depend on component models (atmosphere, ice sheets, etc.) that are unique to the Antarctic region.

RECOMMENDATIONS

The committee identified key science questions that will drive research in Antarctica and the Southern Ocean in coming decades, and highlighted opportunities to be leveraged to sustain and improve the U.S. research efforts in the region. Here, the committee suggests actions for the United States to achieve success for the next generation of Antarctic and Southern Ocean science.

Lead the development of a large-scale, interdisciplinary observing network and support a new generation of robust Earth system models

To record the ongoing changes in the Antarctic atmosphere, ice sheets, oceans, and ecosystems, scientists need observing systems that can collect the necessary data. This network should be able to measure and record ongoing changes, develop an advanced understanding of the drivers of change, and provide input for models that will enable the United States to better project and adapt to the global impacts of the changing Antarctic environment. Improvements in scientific models of the Antarctic region are urgently needed to strengthen the simulation and prediction of global climate patterns. These initiatives will require interdisciplinary approaches at the system scale that would be best addressed with a coordinated, long-term, international effort. Given the scope of its research program and support infrastructure in the Antarctic region, the United States has the opportunity to play a leading role in this effort.

Continue to support a wide variety of basic scientific research in Antarctica and the Southern Ocean, which will yield a new generation of discoveries

Basic science in Antarctica and the Southern Ocean covers a wide breadth of research questions, including the climatic shifts that Earth has undergone in its history, the

RECOMMENDATIONS

Lead the development of a large-scale, interdisciplinary observing network and support a new generation of robust Earth system models.

Continue to support a wide variety of basic scientific research in Antarctica and the Southern Ocean, which will yield a new generation of discoveries.

Design and implement improved mechanisms for international collaboration.

Exploit the host of emerging technologies.

Coordinate an integrated polar educational program.

Continue strong logistical support for Antarctic science.

adaptation of polar species to the rigors of life in Antarctica, the predictability of space weather, and the origins of the universe. This research is expected to lead to remarkable new insights into our planet and the universe over the next two decades.

Design and implement improved mechanisms for international collaboration

The vast size of the Antarctic continent and the logistical challenges of working in the region mean that international teamwork is needed to reach the goals set out in this report. The International Polar Year, held from 2007 to 2008, demonstrated how successful international collaboration can facilitate research that no nation could complete alone. The United States can best retain its leadership role in global science by taking the lead in future international activities. Mechanisms to ensure timely and integrated international collaborative research would greatly enhance this effort.

Exploit the host of emerging technologies

Conditions in Antarctica and the Southern Ocean are often challenging for observers and instruments alike. The advancement of technology, both in the instruments that make measurements and in the platforms that support those instruments, can help to overcome those challenges and open up new capabilities. Continued efforts to adopt new technologies including cyberinfrastructure and novel and robust sensors could facilitate research and monitoring of the Antarctic region and would promote the efficiency of U.S. scientific research efforts.

Coordinate an integrated polar educational program

The polar regions have a powerful appeal to people of all ages. Antarctica and the Southern Ocean could be used as focal points to help recruit, train, and retain a diverse and skilled scientific workforce. The committee envisions building upon existing educational activities to develop a more integrated polar educational program, which would encompass all learners including K-12, undergraduates, graduate students, early career investigators, and lifelong learners. The goal of this effort is to engage the next generation of scientists and engineers required to support an economically competitive nation and foster a scientifically literate U.S. public.

Continue strong logistical support for Antarctic science

Because conducting the far-reaching and innovative work recommended in this report will continue to require extensive logistical support, the committee encourages the NSF-led Blue Ribbon Panel to develop a plan to support Antarctic science in the next two decades with the following goals:

- Improve the efficiency of the support provided by the contractors, and enhance the oversight and management of the contractors by the scientific community.
- Increase the flexibility and mobility of the support system to work in a continent-wide and ocean-wide manner, utilizing as much of the year and continent as possible, and fostering innovative "cutting-edge" science.
- Maintain and enhance the unique logistical assets of the United States, including the research stations, aircraft, and research vessels with increased icebreaking capabilities, and heavy icebreakers for reliable resupply of the U.S. Antarctic Program.

CLOSING THOUGHTS

Despite the challenges of working in the harsh environment of Antarctica and the Southern Ocean, the region offers great insight into the changing planet and is an invaluable and unique platform for scientists to make new discoveries. Preserving the unique environment of the Antarctic region for new observations and experimental science requires a continued commitment to stewardship.

Making use of international and multidisciplinary collaboration, emerging technologies and sensors, and educational opportunities, the next 20 years of Antarctic research have the potential to advance understanding of this planet and beyond. A robust and efficient U.S. Antarctic Program is needed to realize this potential.

Emperor penguins are the largest of all penguins, standing up to 42 inches (115 cm) tall and weighing 84 lb (38 kg). SOURCE: Glenn Grant/NSF.

CHAPTER ONE

Introduction

Mention of Antarctica and the Southern Ocean conjures up images of vast, icy, remote spaces, and it can be hard to imagine how these southernmost reaches of the planet are connected to daily life. But this very large region of the world is tightly linked to the global system in ways that scientists are only beginning to understand and fully appreciate. Antarctica and the Southern Ocean are unique vantage points from which to observe major environmental changes happening on the planet, and they offer unparalleled platforms from which to discover new and exciting things about the world and universe.

Large changes are happening to the planet, and, simultaneously, scientists are developing the capability to observe and understand the world in new ways (IPCC, 2007; National Research Council, 2010b). There are large global questions at hand that are vitally important for society. How much will global sea levels rise in the coming decades? How quickly is the acidity of the global oceans changing, and how will ocean food chains be affected? To what extent will changes in Southern Ocean temperature and saltiness influence global climate? How will global climate change affect life forms in the ocean and on land? Understanding the processes that occur in this region is crucial to answering these questions. Antarctica and the Southern Ocean are simultaneously intimately involved in the global changes that are occurring and unique places from which to witness those changes.

Historically, Antarctica and the Southern Ocean have always been places of fundamentally new discoveries. This region was one of the last to be explored: the first person reached the South Pole just 100 years ago. As such, there has been much mystery surrounding this region. Indeed, there are still sections of the Antarctic continent and Southern Ocean where direct observations have not yet been made. New discoveries occur on a continual basis—scientists have found enormous lakes and mountain ranges completely covered underneath the ice, as well as entire ecosystems of never-before-seen life forms under the ice shelves, in the frozen lakes, and in the ice-free areas of the continent. Ice core records continue to reveal new insights into the history of Earth's climate. Scientists are continually learning more about how life survives in extreme environments with impacts and implications for everyday life. In addition, Antarctica is a platform for observations of the upper reaches of the atmosphere and into the universe beyond. Scientists are able to examine fundamental questions about the origins of the universe and the nature of the solar system owing in part to the remarkable clarity and stability of the atmosphere above the high Antarctic plateau. In the coming decades, Antarctica and the Southern Ocean will continue to be a place where new discoveries are made.

The types of research questions that are studied in Antarctica and the Southern Ocean are often broad and multifaceted, which necessitate collaborations among scientists from differing disciplines, backgrounds, and nations. In addition, because of the harsh environmental conditions and remoteness of the region (see Box 1.1), conducting science in Antarctica and the Southern Ocean presents special logistical challenges. Overcoming these challenges has led nations to collaborate with one another in their support of science in this region. Technological innovations have always aided in the support of science in the Antarctic environment, and it will be important to continue to take advantage of new technologies as they emerge in the future. Last, it takes specific training on how to do scientific research in Antarctica and the Southern Ocean, and the education of the next generation of Antarctic scientists will continue to be a critical issue. Choices that are made about these issues—collaborations, technology, and education—will have a large influence on the capacity to conduct scientific research in this part of the world in the future. If opportunities are exploited wisely, they have the ability to extend the reach and the quality of the scientific work conducted in this region.

In the United States, the U.S. Antarctic Program (USAP) within the National Science Foundation (NSF) holds the primary responsibility for supporting science in Antarctica and the Southern Ocean. USAP is also at a unique time in its history. The last review of this program was 15 years ago (Augustine et al., 1997; Executive Office of the President, 1996). A major outcome from that review process was the reconstruction of the South Pole Station, which has solidified the U.S. presence on the continent. That reconstruction of the South Pole Station, which required a major investment of resources, has recently been completed. Now is the time to examine the program and look forward to the future directions for science in Antarctica and the Southern Ocean.

1.1 CONTENT AND PURPOSE OF THE REPORT

At the request of the NSF Office of Polar Programs, in coordination with the Office of Science Technology Policy and the Office of Management and Budget and under the auspices of the National Research Council, the Committee on Future Science Opportunities in the Antarctic and Southern Ocean was asked to identify the important scientific issues that will drive research in Antarctica and the surrounding Southern Ocean over the next two decades. The committee was neither expected to set priorities among scientific research areas nor asked to discuss budgetary issues. The full Statement of Task can be found in Appendix A. The information in this report is intended to inform a subsequent NSF Blue Ribbon Panel that is examining logistical operations in Antarctica. The goal is for the combination of these two studies to ensure that logistical operations are capable of supporting important forefront scientific research in Antarctica over the coming two decades.

In gathering information for this report, the committee relied upon previous work by other organizations (e.g., the International Council for Science, the Scientific Committee on Antarctic Research, etc.) and drew upon recent scientific achievements in Antarctica and the Southern Ocean including those reported during the 2007-2008 International Polar Year (IPY). Numerous workshops and reports were considered during this process; a selection of the important documents used is listed in Box 1.2.

In identifying future science requirements, the committee gathered input from a large portion of the U.S. polar research community through an online questionnaire (see Appendix B). More than 200 scientists responded to this questionnaire and that information has broadly informed the conclusions in this report. The science priorities identified by questionnaire respondents correspond closely to the science drivers the committee highlighted in this report.

In understanding the needs of the other federal agencies that depend on the USAP for infrastructure and logistics, the committee heard directly from a number of speakers and conducted interviews with various key personnel in those agencies, including the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the U.S. Geological Survey, the Department of Energy, the Environmental Protection Agency, the Smithsonian Institution, and the U.S. Coast Guard. Several members of the committee who had not previously traveled to Antarctica had the opportunity to visit McMurdo Station, a field research camp, and the Amundsen-Scott South Pole Station during the report process to see many U.S. activities firsthand and interact with scientists in the field.

This report is structured around major themes and supporting activities identified by the committee. Chapter 2 describes how Antarctica and the Southern Ocean are keystones in the mechanisms by which global change occurs and unique vantage points from which to observe climate and environmental change. Chapter 3 describes how Antarctica and the Southern Ocean are unique places to discover new things about the world and the universe. Chapter 4 explores several opportunities that could

BOX 1.1 QUICK FACTS ABOUT ANTARCTICA AND THE SOUTHERN OCEAN

Antarctica (Figure 1) is an extraordinary place—it is the coldest, driest, and windiest continent. In fact, the coldest recorded temperature on Earth (–89.2°C or –128.6°F) was measured at Vostok Station in 1983. Antarctica covers nearly 14 million km^2 (5.4 million mi^2), which is approximately 1.4 times the size of the United States. Despite much of the continent receiving little enough annual precipitation to be classified as a desert, approximately 90 percent of all the ice on the planet is located in Antarctica and the continent holds substantial amounts of the world's freshwater (SCAR, 2010). In the middle of the continent, the Antarctic ice sheet is more than 2 miles thick. Indeed, less than 0.5 percent of Antarctica is not covered by ice (British Antarctic Survey, 2005). But the ice is not static; it moves in large glaciers, sometimes at speeds that can cover more than 9 m (30 ft) in a day. If Antarctica's ice sheets melt, the world's oceans would rise by at least 60 m (200 ft) or more (Huybrechts et al., 2000). One of the biggest icebergs ever seen broke free from the Ross Ice Shelf in Antarctica in 2000; it was the size of Connecticut and approximately 250 m (800 ft) thick, holding enough water to sustain total world consumption for more than a year.

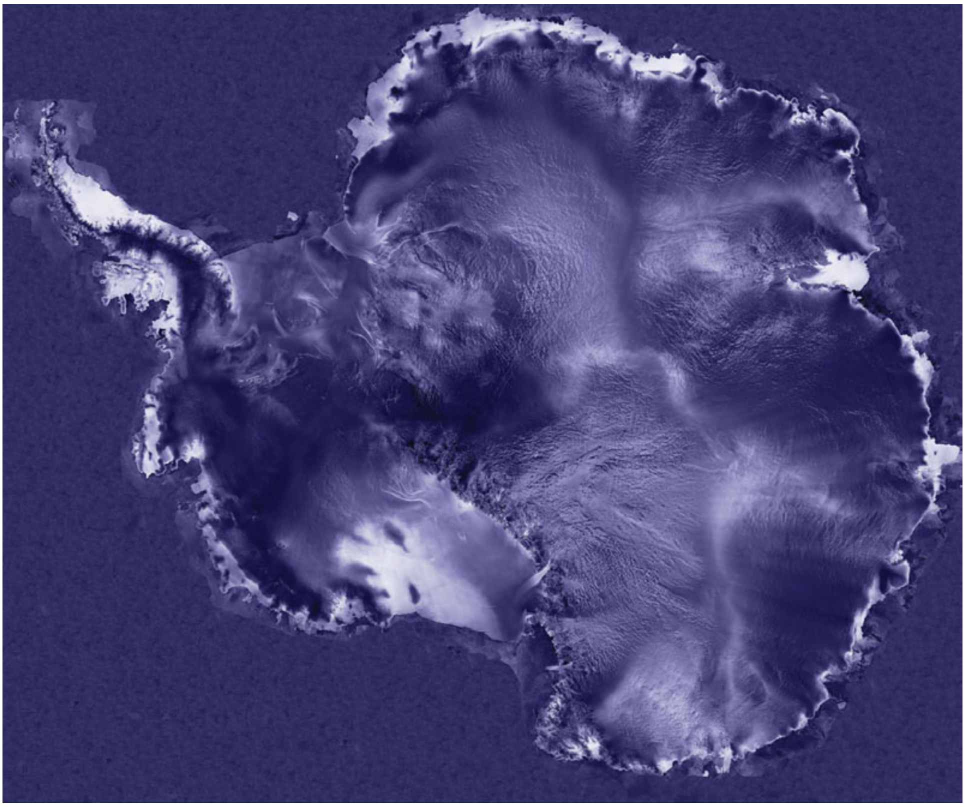

FIGURE 1 RADARSAT data of Antarctica from the Antarctic Mapping Mission. SOURCE: NASA/Goddard Space Flight Center Scientific Visualization Studio and Canadian Space Agency, RADARSAT International Inc.

BOX 1.1 CONTINUED

The Southern Ocean completely surrounds Antarctica and is bounded to the north by the waters of the South Pacific, South Atlantic, and Indian Ocean. It is very deep (in general, deeper than 4,000 m) and contains minimal shallow-water areas. The Southern Ocean also contains the Antarctic Circumpolar Current, which moves eastward around the continent and is the longest ocean current in the world. The Southern Ocean is an extremely important region of the globe for air-sea exchange of carbon dioxide, second only to the northern North Atlantic.

This is a place of extremes with many opportunities for learning and discovery (Figure 2). Antarctica presents scientists with a crucial platform for research to increase the understanding of Earth and the complicated processes that govern the climate and environment.

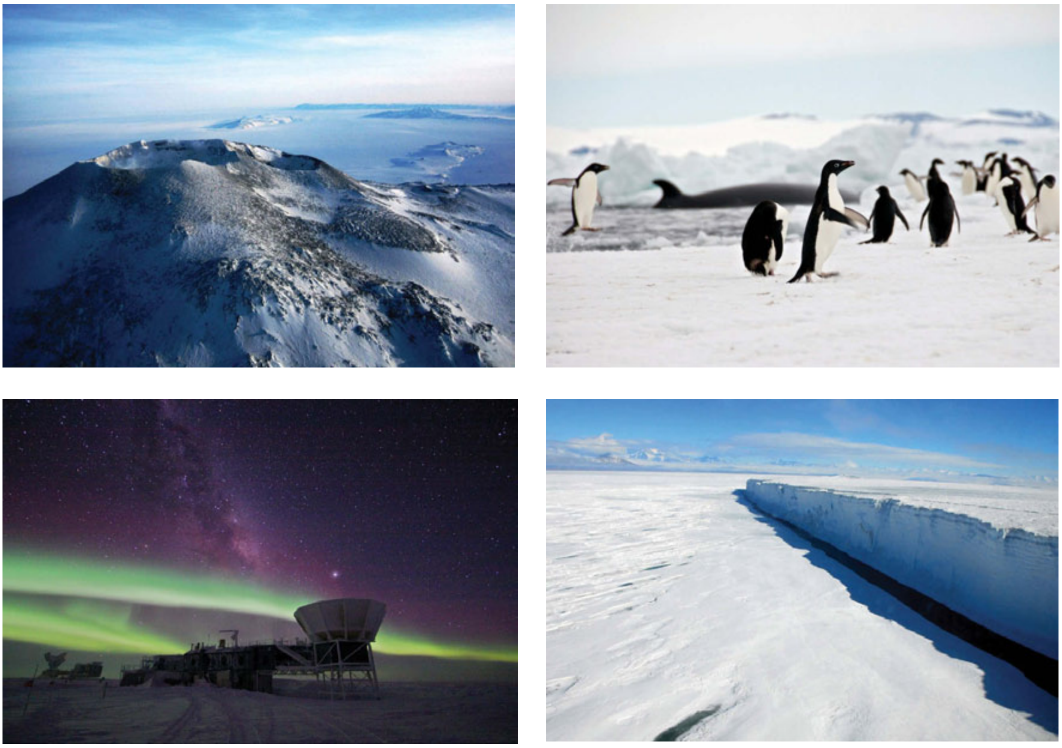

FIGURE 2 Examples of the unique nature and extremes of Antarctica. Clockwise from top left: aerial view of the Mt. Erebus crater, the southernmost active volcano; Adelie penguins and a Minke whale near McMurdo Station; a glacier extends into the sea ice in the Ross Sea; aurora display over the Dark Sector of Amundsen-Scott South Pole Station, where telescopes are studying the cosmic microwave background radiation to learn about the origin and evolution of the universe. SOURCES (clockwise from top left): Christopher Dean, NSF; Alex Isern, NSF; Robyn Waserman, NSF; and Keith Vanderlinde, NSF.

be used to leverage the efforts to address the logistical challenges that conducting scientific research in Antarctica and the Southern Ocean present—collaborations, technology, and education. Chapter 4 also outlines two areas that will require support to address the scientific questions identified here: an observation network with data integration and an enhanced scientific modeling effort. Finally, Chapter 5 provides a list of recommendations.

BOX 1.2 COMPILATION OF IMPORTANT REFERENCES

During this activity, the committee built upon the work of others and consulted a number of previous reports, papers, and articles on Antarctica and the Southern Ocean. The following is a selection of the references that were drawn upon by the committee during the report-writing process:

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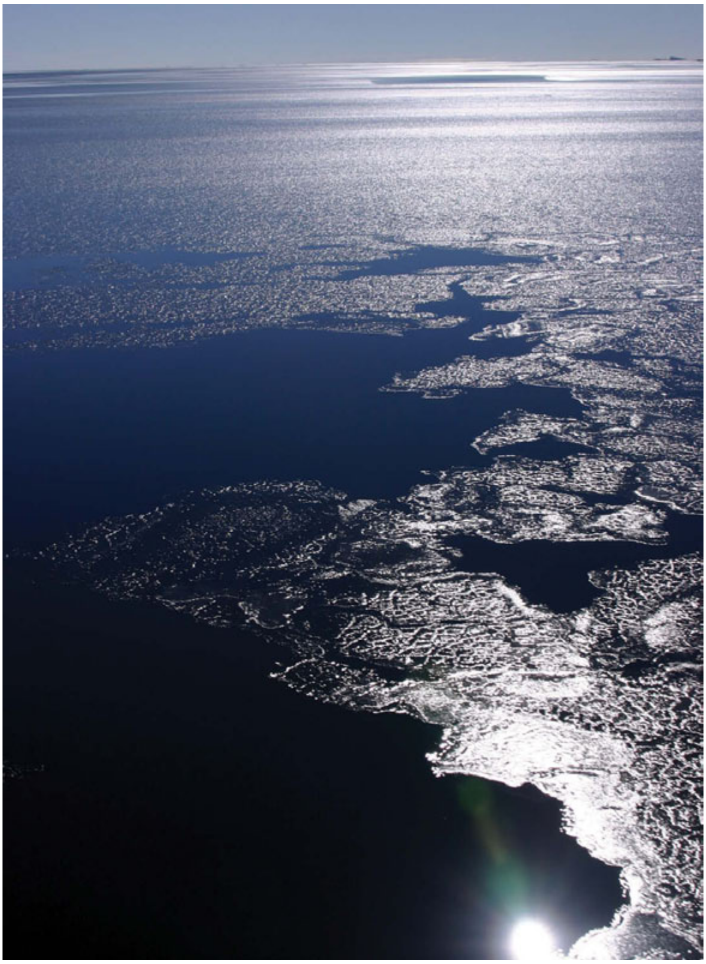
- Scientific Committee on Antarctic Research. 2011. *Antarctic Science and Policy Advice in a Changing World: Strategic Plan 2011-2016.* Cambridge, U.K.: Scientific Committee on Antarctic Research.



New ice forming on the Southern Ocean. SOURCE: Mike Usher/NSF.

CHAPTER TWO

Fundamental Questions of Global Change

The world is experiencing many changes. Global temperatures, on land and in the oceans, are increasing. Sea levels are rising, global weather patterns are shifting, and the chemistry and biology of the world's lands and oceans are changing. It is a unique time in history in that we now have great capacity to observe many of these changes and understand many of the reasons behind them.

Antarctica and the Southern Ocean are intimately involved in global processes that provide the key to understanding those changes. Formation of the deepest water in the global ocean circulation occurs in the Southern Ocean, as does upwelling to the sea surface of all the deep waters from other oceans. The Southern Ocean is an extremely important region of the globe for air-sea exchange of carbon dioxide, second only to the northern North Atlantic. The strong westerly winds that circle the Antarctic continent influence global atmospheric circulations. The Antarctic continental plate played a central role in the history of the formation of the continents and the resulting oceanic and atmospheric circulation patterns observed today. Understanding processes in Antarctica and the Southern Ocean is critically important to understanding processes in the global system.

Antarctica and the Southern Ocean comprise an unparalleled natural laboratory in which to study a multitude of constantly changing conditions. Short-term changes happen within lunar and annual cycles and within the context of longer-term oscillations of years to decades. In recent decades, changes to the global climate from human activities have been superimposed upon these natural variations, and the poles reflect these changes. Indeed, the Arctic has experienced large temperature changes already. The Southern Ocean has also experienced significant warming, with oceanic fronts being pushed 60 miles closer to the continent, but the situation in Antarctica is complicated by the influence of the Antarctic ozone hole, another human-induced change that has uniquely affected this region. These complex environmental forces need to be studied in order to understand how they affect global processes, and also to measure their impact on life, from bacteria to worms, microarthropods, fish, birds, and marine mammals. Antarctica and the Southern Ocean are critically important locations for observing physical, chemical, and biological changes that are happening on a global scale (National Research Council, 2010b).

This chapter explores important questions related to environmental change that will drive research in Antarctica and the Southern Ocean over the next 20 years. The questions here are not an exhaustive list, but rather highlight important research areas:

- How will Antarctica contribute to changes in global sea level?
- What is the role of Antarctica and the Southern Ocean in the global climate system?
- What is the response of Antarctic biota and ecosystems to change?
- What role has Antarctica played in changing Earth in the past?

The following sections generally include the following subsections for each of the issues discussed:

- Description of the global context for the issue;
- Current trends or understanding of the issue;
- Questions to better understand the issue in the future; and
- Required tools and actions to better understand the issue.

2.1 HOW WILL ANTARCTICA CONTRIBUTE TO CHANGES IN GLOBAL SEA LEVEL?

Global Context

Antarctica's ice sheets are maintained through a dynamic balance: snow and ice accumulate over the continent, flow to the margins, and are lost to the sea. Temperatures are rarely above freezing, even during summer (except in the Peninsula), and ice is primarily lost by calving or melting when it comes into contact with relatively warm ocean waters. Antarctica holds enough ice to raise global sea levels by more than 60 m (Huybrechts et al., 2000) (see Box 2.1). A big question persists: As the world warms, how much will ice loss accelerate, ice sheets shrink, and sea levels rise?

What Is Currently Known About Antarctica's Contribution to Sea level Rise?

Earth's geologic history provides some insight into Antarctica's relationship with global sea levels. During the Last Glacial Maximum, roughly 20,000 years ago, atmospheric carbon dioxide concentrations were 180 parts per million by volume, one-third lower than preindustrial values (Sigman and Boyle, 2000); Earth was colder on average by about 5°C; and larger ice sheets caused global sea level to be more than 130 m lower than today (Fairbanks, 1989). Through a combination of rising atmospheric carbon dioxide levels, changes in Earth's orientation and orbit around the Sun, and instabilities inherent in large ice sheets, a massive deglaciation occurred that caused

BOX 2.1 THE CONNECTION BETWEEN ICE AND SEA LEVEL RISE

Where land and ocean meet, the sea surface height changes regularly on short timescales as a result of tides and weather. On longer timescales sea level changes because of thermally controlled expansion or contraction of water in the ocean and because of changes in the amount of water stored on land in the form of groundwater and land ice. Also observed are changes in relative sea level due to the subsidence or lifting of the coast, but even larger sea level changes come from changes in the amount of water stored on land in the form of ice.

Paleoclimate records show how much variation in sea level has been experienced by Earth before. During the ice ages sea level varied by more than 130 m (400 ft) (Fairbanks, 1989); these variations were driven by variations in the amount of ice stored on land. At the Glacial Maximum the sea level was low enough to walk from Siberia to Alaska, while at other times sea level was 5-6 m (15-20 ft) higher than today. Evidence suggests that most of this sea level rise during the Glacial Minimum was from the melting of the West Antarctic Ice Sheet (WAIS). Such sea levels would put much of Washington, DC, and lower Manhattan under water, not to mention many low-lying coastal areas around the world. The WAIS may be unstable (Bamber et al., 2009; Katz and Worster, 2010) and could potentially cause a significant sea level rise. Robust models for predicting the behavior of the WAIS under various climate conditions are needed now (Joughin and Alley, 2011).

sea level to rise at an average rate of 10 mm per year for more than 10,000 years (Figure 2.1). Coral records indicate that the sea level increased at a rate in excess of 40 mm (about 1.6 in) per year during one interval around 15,000 years ago (Fairbanks, 1989). Antarctica and its ice sheets contributed about 20 m to the overall 130 m rise in sea level and they appear to have been at least partially responsible for the rapid rise noted 15,000 years ago (Clark et al., 2002).

Following the transition from the last glacial period, sea level was relatively stable for a period of approximately 7,000 years (Figure 2.1). However, increasing atmospheric carbon dioxide (CO_2) levels and warming since the advent of the Industrial Revolution raise concerns of significant sea level rise in the future. Presently, sea level is rising at approximately 3.5 mm per year as a combined result of thermal expansion of the oceans and melting of glaciers and polar ice sheets (note that sea ice disappearance does not contribute to sea level rise as it is already part of the ocean volume) (Beckley et al., 2007; National Research Council, 2010b). Sea level rise has been measured by a combination of tidal gauges and satellites, including altimetric data from the Jason satellites.[1] Since 2001, ice mass loss has also been measured from gravity field measurements from the GRACE[2] (Gravity Recovery and Climate Experiment) satellites

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[1] See *http://sealevel.jpl.nasa.gov/missions/*.

[2] See *http://earthobservatory.nasa.gov/Features/GRACE/*.

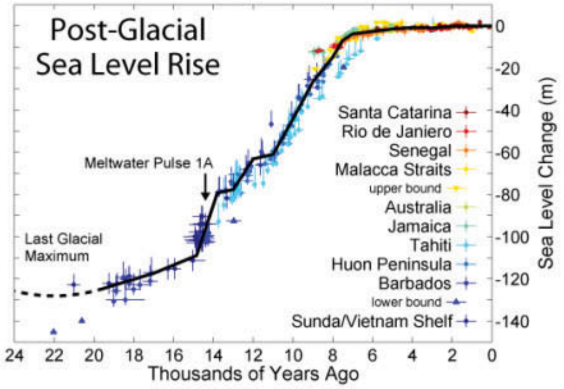


FIGURE 2.1 Changes in sea level since the last glacial period, showing a 130-m rise along with the relatively fast rates of rise beginning about 15,000 years ago. SOURCE: Image created by Robert A. Rohde/Global Warming Art. Based on data from Fleming, 2000; Fleming et al., 1998; and Milne et al., 2005.

(Ward, 2004). Starting from being nearly in balance during the early 1990s, Antarctica has been losing ice at an increasing rate and now contributes more than 0.5 mm to sea level rise each year (Rignot et al., 2011).

Antarctica's accelerating ice loss is, at least in part, attributable to disintegration of floating ice shelves. Although the loss of floating ice shelves does not contribute to sea level rise directly, the ice shelves provide a back pressure against the flow of ice, essentially buttressing the interior ice locked up on land and preventing it from flowing quickly. Once ice shelves are lost, continental ice flows more rapidly into the sea. As predicted more than 30 years ago (Mercer, 1978), ice shelves along the Antarctic Peninsula of Antarctica have been the first to significantly deteriorate (Morris and Vaughan, 2003), owing to the overall warmer conditions in this region. This ice shelf loss has been followed by an acceleration of ice flow into the sea (Scambos et al., 2004), similar to events that have been observed in Greenland (Thomas, 2004). The Antarctic Peninsula does not contain much ice because it is located in warmer latitudes and is narrow, so the immediate consequences for sea level are not large. However, the question remains whether the loss of floating ice shelves and consequent acceleration of continental ice observed in the Antarctic Peninsula is a harbinger of what is to come in West Antarctica or other parts of East Antarctica.

On the continental interior, summer temperatures atop Antarctica's ice shelves generally remain several degrees below freezing. A major question is whether future warming will lead to summer melting and jeopardize the stability of the ice shelves. Most of the Antarctic continent has not warmed as much as the global average in recent decades, but paleoclimate records from the last interglacial period and climate model predictions for the end of this century indicate, respectively, that Antarctic temperatures have changed and will change more than the global average over longer timescales (Clark and Huybers, 2009). In addition to surface warming from the atmosphere, ocean warming may also lead to thinning and possible destabilization of ice shelves. Indeed, the grounding line of the Pine Island Glacier has been observed to be migrating inward toward the continent, apparently because of increased subsurface melting of that ice shelf caused by warming ocean water (Thomas et al., 2004).

The geometry of Antarctica's ice also raises the concern that ice loss could substantially accelerate. Parts of the East Antarctic Ice Sheet and most of the West Antarctic Ice Sheet rest upon ground that is below sea level. The ice that extends above sea level literally weighs down upon the ice underneath, pressing it onto submerged ground. As the thickness of the ice sheet tapers toward its margins, it can lose contact with the ground to form floating ice shelves. In these regions, the ice sheet melts more rapidly because of the relatively warm ocean waters in which it bathes. When an ice sheet that is grounded below sea level loses ice, more of it will tend to float, which can lead to more rapid flow, more melting of ice, and even more rapid ice loss. Thus, loss of ice leads to more loss of ice, constituting a positive feedback that has the potential to accelerate sea level rise (Nicholls et al., 2007; Thomas and Bentley, 1978). For this reason, the West Antarctic Ice Sheet is sometimes referred to as the "weak underbelly" of Antarctica (Hughes, 1981).

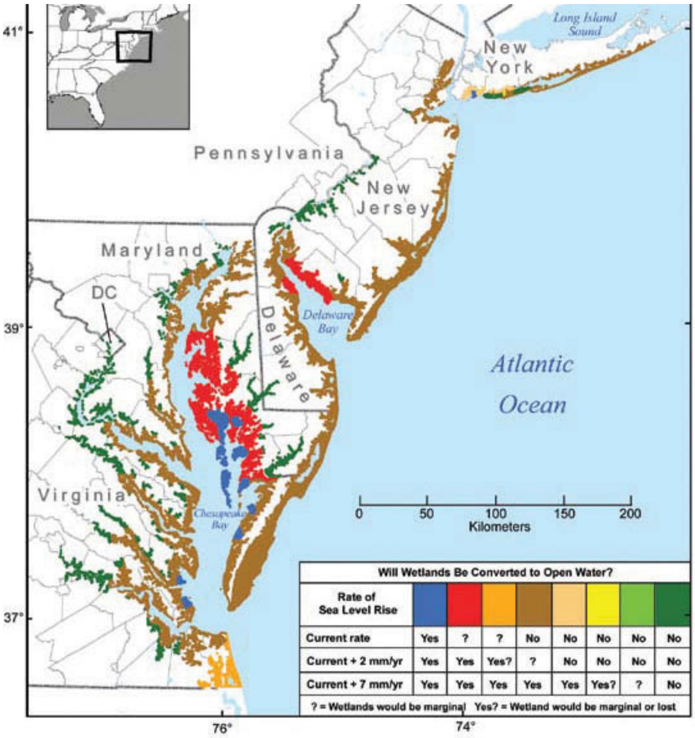
Importance to the United States

The estimated range of sea level rise expected to occur by 2100 is 0.4 to 2 m (National Research Council, 2011e; Pfeffer et al., 2008), but these are back-of-the-envelope calculations based on extrapolations from current trends. Indeed, the 2007 Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2007) almost entirely neglected to account for changes in the rate at which Antarctic ice is discharged into the ocean on the basis that not enough is known about how to model these processes. Antarctic contributions to sea level are therefore largely considered "a known unknown," wherein ignorance of likely outcomes hinders society's ability to understand what will happen and what consequences might follow.

Globally, rising sea level is expected to threaten the homes and livelihoods of hundreds of millions of people by the second half of this century (see Box 2.2). In an assessment of exposure to coastal flooding by 2070, Miami and New York City ranked

BOX 2.2 THE RISKS OF SEA LEVEL RISE

High rates of economic and demographic growth during the past century have multiplied populations and the infrastructure placed along coastlines worldwide. This leads to not only local communities and commercial centers being placed at great risk from rising sea levels, but also to nations being faced with extremely high economic, societal, and security challenges. Examples of problems already being faced in the United States from rising seas include shoreline retreat along most U.S. exposed shores and intrusion of seawater into freshwater aquifers in coastal areas, which threatens freshwater supplies (National Research Council, 2010a). More than one-third of U.S. residents live near a coast, and more than $1 trillion is contributed annually to the nation's economy from activities that occur on or along a coast (USGCRP, 2009). Future sea level rise poses risks to U.S. communities, coastlines, and infrastructure along much of the eastern and southern United States, the West Coast, and Alaska (see figure).



Will Wetlands Be Converted to Open Water?

Rate of Sea Level Rise	🟦	🟥	🟧	🟫	🟧	🟨	🟩	🟩
Current rate	Yes	?	?	No	No	No	No	No
Current + 2 mm/yr	Yes	Yes	Yes?	?	No	No	No	No
Current + 7 mm/yr	Yes	Yes	Yes	Yes	Yes	Yes?	?	No

? = Wetlands would be marginal Yes? = Wetland would be marginal or lost

Potential mid-Atlantic wetland survival. Areas where wetlands would be marginal or lost under three sea level rise scenarios (in mm per year). SOURCE: CCSP, 2009.

6th and 17th, respectively, in threatened impacts to the world's major cities (Nicholls et al., 2007). In particular, rising sea level threatens to cause more frequent flooding by increasing the height of storm surges and the peak level of tidal cycles. Overtopping coastal levees on even a single occasion can have dire consequences, as evidenced by the results of Hurricane Katrina in New Orleans in 2005. Higher sea level also threatens wetland habitats, as the U.S. Climate Change Science Program reported (Titus and Anderson, 2009), namely that most of the mid-Atlantic coastal wetlands will be lost in the next century if local sea level rises by as much as 1 m. The U.S. Navy has taken steps to examine the potential impacts of climate change, including those from sea level rise, on future naval operations and capabilities (National Research Council, 2011e).

Global average sea level is, of course, less relevant than how much sea level will rise in specific locations—primarily where the sea meets where people live and work—and here lies a poignant wrinkle. Loss of ice weakens the local gravitational attraction that the ice sheet exerts on the ocean, leading to a reduction in sea level at the margin of the ice sheet. Further afield from where the ice loss occurs, sea level rises by more than its global average, with the specific locations of maximal rise depending upon the rotation of Earth and the geometry of the ocean basins. Local variations in sea level also depend upon changes in ocean circulation and storm activity. As it happens, loss of ice from West Antarctica would cause about a 15 percent greater sea level rise along the eastern and western United States than the global average, with the largest increase centered approximately at Washington, DC, highlighting how the United States is uniquely exposed to the fate of West Antarctica and the Antarctic ice sheet (Mitrovica et al., 2009) (Figure 2.2).

Questions for the Future

Two critical questions arise: How much will Antarctica contribute to a rising future sea level and how quickly? Antarctica's ice sheets are strongly intercoupled with the fluid and solid portions of Earth, and developing an ability to predict their future behavior depends upon designing a comprehensive modeling and observing strategy. To give a sense of the system intercoupling, consider that determination of how much ice Antarctica has been losing in the past decade, based on satellite measurements of gravitational anomalies, requires knowledge of the rate at which the underlying bedrock is lifting. Determining bedrock uplift requires understanding the structural properties of the rock, as well as how much ice Antarctica has lost since the Last Glacial Maximum, some 20,000 years ago. As another example of linked system complexity, whether ice loss will accelerate depends, in part, upon the stability of the ice shelves

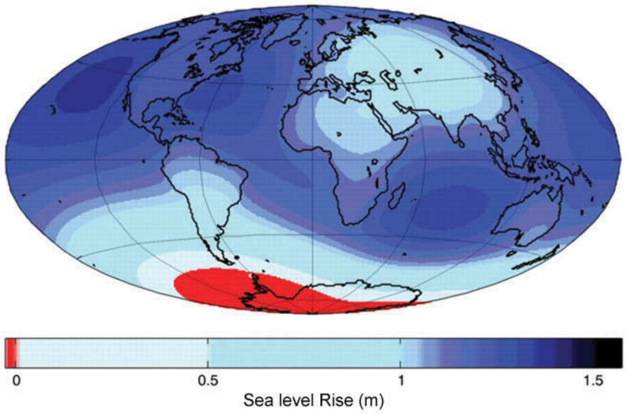


FIGURE 2.2 Sea level changes in response to a collapse of the West Antarctic Ice Sheet represented as an additional change relative to the global average of 5 m; this highlights the significant local deviations. Sea level rise is 15 percent higher than the global average along the U.S. coastline. Changes over land can be ignored. SOURCE: Mitrovica et al., 2009, reprinted with permission from the American Association for the Advancement of Science.

bordering Antarctica, which in turn depends on their temperature, and therefore the circulation and temperature of the oceans and atmosphere.

Required Tools and Actions

The committee recommends five actions that are needed to advance prediction of Antarctica's contribution to sea level in the future:

- *Develop greater predictive capacity for the flow of ice into the ocean.* Relative to the ocean and atmosphere, the dynamics of the cryosphere are poorly understood. This is partly because of difficulties inherent in observing and modeling ice flow: it is difficult to make physical measurements deep within and beneath ice sheets and ice shelves; many timescales of ice motion are longer than those afforded by instrumental records; and ice is a non-Newtonian fluid, whose motion depends sensitively upon its interactions with sediment or rock at its bed. As stated, the 2007 IPCC report neglected the possibility of change in the rate at which Antarctic ice is discharged into the ocean because not enough was known (IPCC, 2007), underscoring the need for further theoretical and observational work on ice sheets. Requisite work can be broken down according to ice interactions with the ocean, atmosphere, and solid Earth and are described in separate bullets below. Improved theoretical understanding and technical capacity is also needed, as detailed next.

- *Increase scientific and technical capacity to observe and model ice sheets.* The cadre of theoreticians and those making observations related to the Antarctic ice sheet is small relative to the scope of the problem. Teams of collaborators would need to include glaciologists, geologists, oceanographers, atmospheric scientists, and so on, and expansion of existing efforts across federal agencies and academia. Those components of ice sheets that can change relatively rapidly, especially those associated with ice streams and ice shelves, require particular attention.
- *Determine how the ocean transports heat to ice shelves and how this may change in the future.* Antarctica loses the vast majority of its ice via interactions with the ocean. The amount of melting beneath ice shelves depends upon transport of heat by the oceans, which is driven by a complex mix of wind stress and changes in water density brought about by heating, cooling, and fluxes of salt- or freshwater. Recent modeling studies (Pollard and DeConto, 2009) highlight how an increase in ocean heat flux could lead to rapid inward migrations of ice shelf grounding lines and loss of ice volume. Developing instrumentation and an observational program with which to monitor the conditions beneath ice shelves is a high priority (see Appendix C for enabling technologies). In conjunction with increasing observations, improved models capable of accurately representing the transfer of heat from the ocean to the cryosphere need to be developed and tested (also see Section 2.2).
- *Improve monitoring of surface temperature and ice accumulation.* It is not entirely certain whether the temperature of Antarctica is or is not increasing. A general warming trend was reported for surface atmospheric temperatures, based on surface and satellite observation (Steig et al., 2009). But a recent report, using similar data but different statistical methods, found little evidence of warming (O'Donnell et al., 2011). At the heart of this discrepancy is the sparsity of the international Antarctic observational network, which places heavy demand on statistical methods for estimating temperature variations in regions where direct observations are not being made. Nonetheless, there are both model analyses and paleoclimate observations that strongly suggest that Antarctica will eventually warm significantly more than the lower latitudes (Clark and Huybers, 2009). A warming of several degrees Celsius could lead to significant summer melting atop the ice shelves and cause their disintegration, as recently observed for the Larsen ice shelf (see Figure 2.3) (MacAyeal et al., 2003; Mercer, 1978). Similar to the limited and widely scattered Antarctic

temperature observations (often obtained at international bases around the continent), there are large gaps in monitoring snow accumulation over Antarctica, as well as a significant partial evaporation of snowfall. Because satellite observations of ice temperature and snow accumulation are not sufficiently reliable, a comprehensive surface observing network is needed to define these basic surface conditions.

- *Improve mapping of conditions and structures beneath the ice sheet and measuring uplift of underlying bedrock.* Subglacial topography and the composition of the underlying rock are important determinants of glacial flow. Determining which regions are below sea level is important for evaluating instabilities in the ice. However, the subglacial topography and geology of Antarctica is less well known than the topography of Mars (Gwinner et al., 2010). Comprehensive radar mapping of Antarctica is required. Determining the rate of uplift of the bedrock beneath Antarctica, which is still adjusting to the unloading associated with the last major deglaciation (between 18,000 and 7,000 years ago), is also critical for monitoring and assessing the changes of the mass of the ice sheet. In particular, correct interpretation of gravitational anomalies monitored

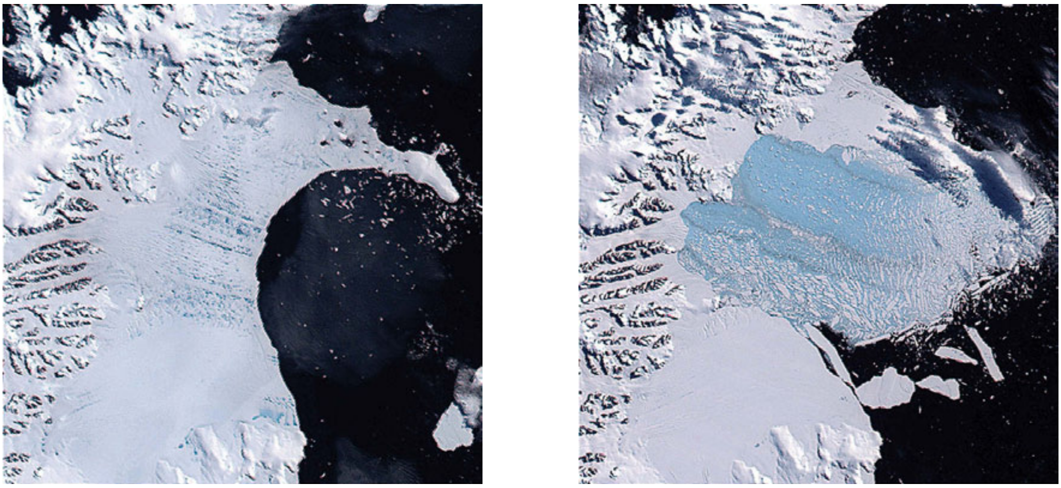


FIGURE 2.3 In 2002, the Larsen B ice shelf collapsed and delivered 3,250 km^2 of ice into the ocean. These images are derived from satellite data from the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument. SOURCE: Cavalieri et al., 2008, National Snow and Ice Data Center, University of Colorado, Boulder.

> from space requires measuring changes in the elevation of both the underlying bedrock and the overlying ice sheets. Bedrock uplift rates can be assessed both through Global Positioning System measurements as well as through models that incorporate the geologic history of changes in the size of Antarctic ice sheets. Lack of knowledge of the amount of bedrock uplift provides the largest source of uncertainty in determining the rate that Antarctica is losing its ice (Chen et al., 2009) (also see Section 2.4).

It is only through observations made in Antarctica that scientists were alerted to such phenomena as the ozone hole, rapid disintegration of the Larsen B ice shelf, acceleration of glaciers once the ice shelves were lost, and draining and filling of subglacial lakes. Given how limited direct observations of the Antarctic continent have been and how human actions are now prodding the climate system, many surprises seem possible in the future. In order to expect or learn from any surprises, there will need to be careful monitoring of Antarctica, including its ice, overlying atmosphere, and peripheral oceans. Observations made in Antarctica can be likened to an early warning network that, when adequately interpreted, analyzed, and placed into the context of a developed theoretical understanding, will alert society to acceleration of Antarctica's ongoing contribution to changing sea level or, possibly, uncover new mechanisms by which Antarctica can change sea level.

2.2 WHAT IS THE ROLE OF ANTARCTICA AND THE SOUTHERN OCEAN IN THE GLOBAL CLIMATE SYSTEM?

Although Antarctica and the Southern Ocean are physically distant from the Northern Hemisphere, they are directly connected to the entire global climate system. Some of the connectivity with lower latitudes is rapid, through the atmosphere, with adjustments on short timescales of the order of days to months. Some of the processes are more remotely connected and have longer timescales; these include the Southern Ocean's role in the global ocean overturning circulation and rate of carbon dioxide uptake. In stark contrast to the rapid warming of the Arctic, Antarctica and the Southern Ocean present a mixed picture of both climate change and climate variability.

Significant progress in understanding changes in the southern high-latitude coupled climate system over the next 20 years will require construction and operation of an observing system for the atmosphere, ocean, sea ice, and glacial ice. In parallel, successful predictive modeling will require greatly improved coupled modeling of all of the elements of the climate system and continuing improvement of the data-assimilation models, similar to those used for weather prediction, ocean state estimates, and retrospective climate analysis.

Climate in all regions of the globe is affected by greenhouse gases and aerosols from human emissions. The Antarctic region is far from immune, given the amplified climatic response of the polar regions. Climate in the Antarctic region is also affected by ozone depletion in the stratosphere due to anthropogenic chemicals. International protocols have reduced the release of many ozone-depleting chemicals, resulting in stabilization of the ozone depletion ("hole"), but it will take several more decades until the ozone's effects on climate will become insignificant (see Box 2.3).

The coupled climate system in the Antarctic region reaches from the stratosphere to the deep ocean and the continent, including the atmosphere, ocean, sea ice, and glacial ice. This section is organized by the various components of the climate system. Each subsection analyzes the global context, current knowledge, questions for the future, and required tools for that component.

BOX 2.3 THE OZONE HOLE AND GREENHOUSE GASES

The Antarctic ozone hole is generated by a blend of three factors operating in the stratosphere. First, chlorine gas mediates the destruction of ozone, and its 20th-century increase is due to the rise in atmospheric chlorofluorocarbon levels—long-lived chemicals produced by the chemical industry and used, for example, as coolants in refrigerators and air conditioners. This is why the ozone hole only began appearing around 1980; records prior to this period are quite limited. Second, cold temperatures are required to form stratospheric clouds from which the chlorine is released, which accounts for the occurrence of the ozone hole above frigid Antarctica. Third, sunlight is required to initiate chlorine formation and thus ozone destruction, which explains why the hole opens up in spring, as light returns to Antarctic latitudes. Ozone in the stratosphere absorbs ultraviolet radiation from the sun and heats up the stratosphere. Reduced ozone levels cause less absorption and therefore relative stratospheric cooling in the spring and summer above Antarctica, which also leads to cooler tropospheric temperatures (Solomon, 2004).

Greenhouse gases (for example, carbon dioxide and water vapor) absorb infrared radiation from the surface of Earth and trap the heat in the troposphere. If this absorption is very strong, the greenhouse gases retain most of the outgoing infrared radiation close to Earth's surface. This means that only a small amount of this outgoing infrared radiation reaches the carbon dioxide in the upper troposphere and the lower stratosphere. On the other hand, carbon dioxide emits heat radiation, which is lost from the stratosphere into space. In the stratosphere, this emission of heat becomes larger than the energy received from below by absorption and, as a result, there is net energy loss from the stratosphere and resulting cooling. To summarize, elevated carbon dioxide levels can warm the surface and lower atmosphere, but cools the stratosphere (Uherek, 2006).

The Atmosphere

Global Context

The higher latitudes of the Southern Hemisphere, including the icy and mountainous continent of Antarctica and the surrounding sea ice zone, are among the coldest regions on Earth. Their perpetual ice and snow cover contributes to a large temperature contrast between the tropics and the South Pole, which in turn generates the strongest westerly winds on the planet. The Southern Ocean westerly winds buffer the Antarctic continent from the warmer, wetter, and dustier lower latitude atmosphere. These westerly winds drive the Antarctic Circumpolar Current in the ocean (see Box 2.4), force much of the global overturning circulation, and, along with the seasonal cycle of incoming solar radiation, influence the growth of sea ice. Even so, the climate of these high-latitude regions is modulated by a number of tropical effects, most notably the El Niño-Southern Oscillation.

The westerly winds have clear natural "modes" of seasonal to centennial variability. These modes also affect air and ocean temperature, sea ice, and ocean currents. Moreover, anthropogenic forcing (byproducts of mankind including greenhouse gases, aerosols, and ozone-depleting chemicals; see Box 2.3) affect the state of these naturally occurring modes, much as beating on a drum produces sounds that depend on the naturally resonant modes of the drumhead. The leading natural mode, the Southern Annular Mode, exerts its influence throughout the year and exhibits decadal to centennial variability. The Southern Annular Mode has a simple geographic pattern (Figure 2.4) and exists in two phases. The positive phase of the Southern Annular Mode corresponds to stronger westerlies and plays a role in Antarctic continental temperature trends, shifts of the Antarctic Circumpolar Current and deep-ocean warming, among other phenomena. Other natural modes, such as the Pacific Southern American pattern, often produce more complicated spatial structures. These have important consequences, including implications described later in this section (see Southern Ocean Sea Ice).

What Changes Are Occurring in the Antarctic Atmosphere?

Surface temperature trends vary by location over the Antarctic continent (O'Donnell et al., 2011; Steig et al., 2009):

- The Peninsula: Since the 1940s, the western side of the Antarctic Peninsula has become one of the most rapidly warming places on Earth, primarily during the

BOX 2.4 SOUTHERN OCEAN CIRCULATION AND GLOBAL OCEAN OVERTURN

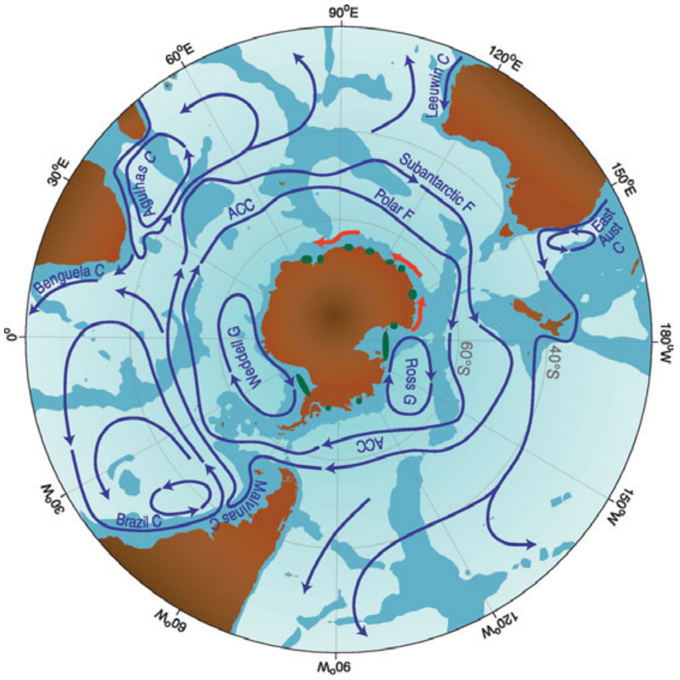
The Southern Ocean circulation is central to the global overturning circulation, as it not only affects the Southern Hemisphere but also, for instance, exerts controls on the remote North Atlantic overturning, which impacts European and North American climate (see figure). Because both the North Atlantic and Antarctic branches of the global overturning circulation are important for long-term climate adjustment, their strength and forcings should be closely monitored. Locally, circulation and upwelling in the Southern Ocean affect its sea ice and ice shelves.

The Southern Ocean circulation is dominated by the eastward flow of the Antarctic Circumpolar Current, which encircles Antarctica, driven by westerly winds. To the south, between the Antarctic Circumpolar Current and the continent, lie the extensive clockwise gyres of the Weddell and Ross Seas, as well as the westward flow along most of the Antarctic continental margin. Large-scale upwelling occurs throughout the Antarctic Circumpolar Current system, because the direct effect of the westerlies is to push surface water northward (because of the Coriolis effect). Deep waters formed in all of the oceans are upwelled to the sea's surface in the Antarctic Circumpolar Current system, different from all other upwelling systems that draw on waters only from the upper ocean.

The upwelled deep waters split and follow two very different paths, one through the upper ocean and one into the bottom and deep waters formed locally in the Antarctic (Figure 2.5). Along the upper ocean path, the upwelled water is warmed by the atmosphere and moves northward into the subtropical circulations in the Southern Hemisphere. It eventually finds its way to the far northern North Atlantic, where it sinks back to great depths as part of the North Atlantic branch of the global overturning circulation; these waters return to the Southern Ocean and are again upwelled. For the bottommost path, the upwelled water that is close to Antarctica is cooled to freezing, sinks to the bottom, and extends far into the Northern Hemisphere, moving slightly upward into the deep waters of each of the oceans and then returning back to the Southern Ocean. The key process that makes this water dense enough to sink to the bottom is the addition of salt rejected from the sea ice that is formed each winter. Sea ice production is largest in polynyas (pockets of exposed surface water, kept open by the winds) along the edges of the Antarctic continent and ice shelves. Very dense water is also created by brine rejection in the sub-ice cavity between the bottom of the ice shelves and the continental shelf, resulting in minimal air-sea gas exchange in these particular dense waters; ice melting in sub-ice cavities is an important process for ice shelf mass balance.

The upwelled deep waters are above the freezing point when they reach the upper ocean. Incursions of these relatively warmer waters beneath the sea ice and especially under the ice shelves are implicated in the changing melting rate of ice shelves (see Figure 2.6).

BOX 2.4 CONTINUED



Schematic depiction of the major currents in the Southern Ocean south of 20°S. Southern Ocean circulation is very important to global overturning circulation. (ACC, Antarctic Circumpolar Current; F, Front; C, Current; G, Gyre). Green areas indicate principal polynyas where dense water is formed. SOURCE: Adapted from Rintoul, 2011.

winter months. In contrast, the eastern side of the Peninsula is warming during summer because of strengthening of westerly winds that are primarily linked to stratospheric ozone depletion (Antarctic ozone hole) with a smaller contribution from increasing greenhouse gas concentrations.

- The Continent: The recent finding by Steig et al. suggests that all of West Antarctica is warming in winter and spring (1957-2006), while East Antarctica shows little change. Unfortunately, direct local temperature measurements are sparse over much of Antarctica, so these results remain controversial. Nevertheless, measurements obtained from the Siple Dome ice core in West Antarctica confirm that the climate there has warmed significantly since 1800 (SCAR, 2009).

Summer melting of the Antarctic ice sheet for 1979-2009 obtained from satellite observations appears strongly influenced by westerly wind variability associated with the Southern Annular Mode, as well as the El Niño-Southern Oscillation (Tedesco and Monaghan, 2009). Little overall trend is evident in the amount of ice sheet summer melting.

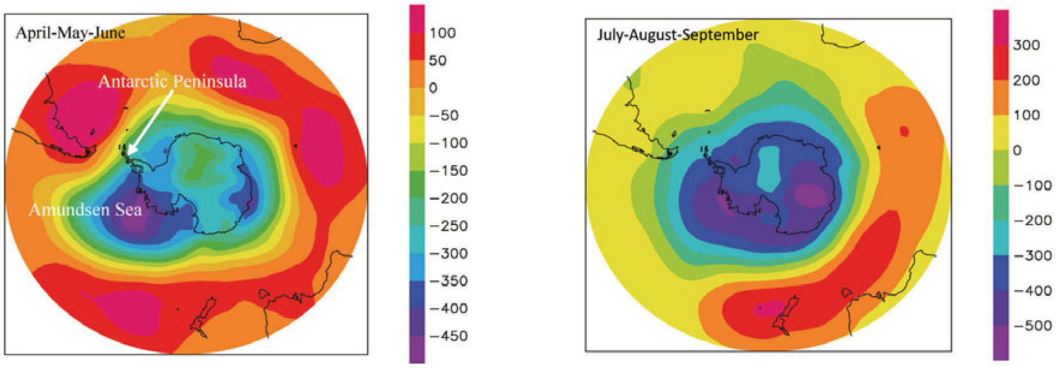


FIGURE 2.4 Spatial patterns of atmospheric surface pressure change associated with the Southern Annular Mode in Pascals for the average of (left) April, May, and June and (right) July, August, and September. The Southern Annular Mode describes variability of the surface atmospheric pressures or atmospheric flow that is not associated with the seasonal cycle. In the pressure field, the annular modes are characterized by north-south shifts in atmospheric mass between the polar regions and the middle latitudes; the figure shows the positive phase where pressures are lower over polar regions (cool colors) and higher in middle latitudes (warmer colors). In the wind field, the annular modes describe north-south vacillations in the extratropical zonal wind with centers of action located ~55-60°S and ~30-35°S latitude; the positive phase has stronger westerly winds along ~55-60°S latitude. SOURCE: Goosse et al., 2011, data from NCEP-NCAR reanalyses (Kalnay et al., 1996).

Questions for the Future

Human-induced drivers of change, or human "forcings," of the Antarctic atmosphere are mainly produced through stratospheric ozone depletion and greenhouse gas increases. These forcings may be contributing to the increasing Southern Annular Mode trend (strengthening westerlies) since the 1960s (Fogt et al., 2009) in the summer and fall. Greenhouse gas forcing cools the stratosphere even as it warms the surface. In opposite fashion, the forcing from ozone depletion causes the surface in East Antarctica to cool (see Box 2.3). The combination of these forcings cools the stratosphere, increases the equator-to-pole temperature gradient in the stratosphere, and hence strengthens the westerlies. Recent results have shown that ozone changes are the biggest contributor to the observed summertime intensification of the southern polar vortex during the second half of the 20th century, but that increases in greenhouse gases are also necessary to reproduce the observed trends (Arblaster and Meehl, 2006). At the surface of the ice, the effect of ozone forcing is presently comparable with the greenhouse gas forcing in Antarctica, so surface temperatures have not increased as much as they have in most regions of the planet. Because of treaty restrictions on chemical release, the ozone hole appears to have stabilized and is projected to recover over the next 50 years (Salby et al., 2011). As the cooling effect of the ozone hole disappears, the increased greenhouse gas forcing may quickly result in enhanced warming of the surface of East Antarctica while continuing to produce stratospheric cooling (Crow, 2011). This changing situation requires continuous monitoring.

The chemistry of the atmosphere at the continental ice surface sets the gases that are trapped in the ice, ultimately forming the record of the atmosphere that is included in ice cores (see Section 3.1). Antarctica is largely unexplored territory for atmospheric chemistry; what little has been done there in the way of observations has yielded surprises, including unexpected discovery of chemical radicals (Neff et al., 2008). Two field projects employing aircraft have extended observations to areas distant from the South Pole, but the data from these projects were insufficient to determine if the South Pole is representative of the entire continent (Eisele et al., 2008; Slusher et al., 2010). Overall, more observations are required to understand the chemistry of the atmosphere over Antarctica and will be necessary to more fully understand the connections of this region to global climate.

Existing observations of the winds, near-surface temperature, and snow accumulation in Antarctica are few and scattered about the continent in location and time because of the great difficulties of collecting such field data by humans. In many areas of Antarctica, observations are insufficient to describe either annual or seasonal variations. Other climatic elements such as surface pressure and cloud characteristics are even more uncertain. With such limited observations, it is difficult to determine if there have been or will be climate changes in response to anthropogenic greenhouse gas (GHG) forcing. It is clear that prior meteorological data sets obtained on land and in the atmosphere, as well as analyses of the atmospheric state, which are based on intensive computer modeling at the national climate and weather prediction centers using these inadequate data sets, are insufficient to provide answers to the following basic questions:

- Is the Antarctic climate being adequately monitored as the ozone hole recovers?
- Is rapid climate change due to anthropogenic (GHG) forcing about to cause large changes in Antarctica?
- Would rapid climate change be detected with current capabilities if it were happening?
- How does the Antarctic ice sheet respond to rapid temperature changes? Would surface melting rapidly increase and accelerate ice flow into the ocean? Would increases in snow accumulation compensate for mass loss to the ocean?

Required Tools and Actions

To document what is happening, the two key variables to measure are near-surface air temperature and snow precipitation and accumulation. An observing network for both of these variables would benefit greatly if it were designed using computer simulations of the observing system, and if robust observing platforms were widely deployed and maintained. Strategic ice coring and borehole thermometry building upon the successful achievements of the International Trans-Antarctic Scientific Expedition project can form the basis for establishing the changes of these variables during past centuries. Vigorous research is needed into the best methods to interpolate continent-wide estimates from sparse scattered observations and to estimate the uncertainty. Data recorded by the observing network over long periods would produce benchmarks to test the performance of Earth system models. The paucity of direct stratospheric and tropospheric measurements from weather balloons can be partially remedied by incorporating new observing technologies and platforms, including satellite radiances, observations from constant-level balloons equipped with dropsondes (Rabier et al., 2010), self-sustaining blimps, and drones (see Appendix C).

A second goal is to develop greatly improved Earth system models. Major efforts are necessary to develop Earth system models that are optimized for understanding climate change in the Antarctic. In order to usefully project future changes, these models will need to skillfully simulate present and recent past climate conditions. At present, limited efforts are put into optimizing the atmospheric components of models, such as for the ubiquitous stable boundary layer over the continent that produces the katabatic winds that blow largely downslope and dominate the near-surface climate of Antarctica, the surrounding ocean, and the atmosphere above the continent. Antarctic cloud models and precipitation predictions are based on midlatitude experiences and do not consider the near-pristine conditions of the high southern latitudes or the major biological contributions to cloud condensation and ice nuclei. At present, most climate models have crude representations of the stratosphere and specify only the effects of stratospheric ozone depletion. Implementation of realistic stratospheric simulations along with understanding and incorporating ozone and greenhouse gas chemistry into climate models is needed to produce accurate simulations of the future behavior of the Southern Annular Mode, the leading mode of variability in the high-latitude southern atmosphere. All of these improvements will help improve the fidelity of models, which improves the accuracy of projected future changes from those models.

Ocean Circulation

Global Context

The energetic eastward flow of the Antarctic Circumpolar Current connects all ocean basins through the wide band of open ocean between Antarctica and the continents to the north. Extending from the ocean surface to the sea floor, the Antarctic Circumpolar Current separates subtropical and polar waters and their associated marine ecosystems (see Box 2.4). The Antarctic Circumpolar Current has strong, narrow fronts, across which temperature changes are great. With satellite observations, it has been discovered that strong fronts in sea surface temperature in currents like the Gulf Stream can affect the winds and storms above them (Chelton et al., 2004). Recent work in the Antarctic Circumpolar Current is showing that similar ocean-to-wind feedbacks might operate there. Nutrient-rich surface waters in the Antarctic Circumpolar Current sink to middepths north of its Subantarctic Front, providing the source for a large fraction of the global ocean's primary productivity, and feeding the world's great fishing grounds along its continental margins. Within and south of the Antarctic Circumpolar Current, seawater upwells from great depth, bringing nutrients and carbon and slightly higher temperatures to the sea surface. The polar circulation moves these waters southward and westward along the margins of Antarctica, where cooling and

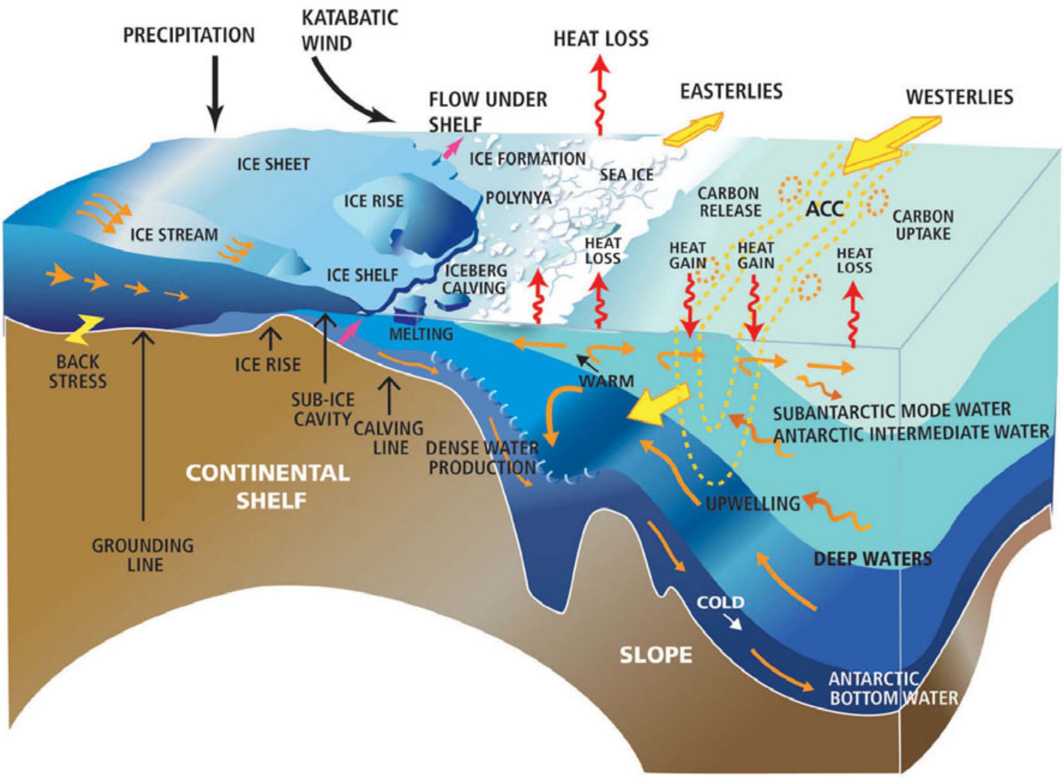


FIGURE 2.5 Cartoon of Southern Ocean circulation and glaciological processes occurring on the coast of Antarctica.

sea ice formation form the dense waters that contribute to filling the bottom layer of the world ocean (see Box 2.4 and Figure 2.5).

What Changes Are Occurring in the Southern Ocean?

Seawater at a depth of 700-900 m to the north of the Antarctic Circumpolar Current has been warming since the 1950s. Although some of the warming could be due to the warming atmosphere (Boning et al., 2008), the signal has been more closely linked to a southward shift in the current's position associated with southward shifting of the westerly winds (Gille, 2002, 2008; Sokolov and Rintoul, 2009). While the westerly winds intensified over the same period, the strength of the Antarctic Circumpolar Current did not change (Boning et al., 2008).

- Bottom seawater, below 3,000 m depth, has warmed throughout the Southern Ocean, at a greater rate than bottom water in the basins lying to the north of this region, implying warming of Antarctic Bottom Water (Purkey and Johnson, 2010).
- Newly formed bottom water in the Ross Sea, which is one of the major producers of Antarctic Bottom Water, has freshened since the 1950s (Jacobs et al., 2002), and the trend has continued based on a major survey in early 2011. The principal cause is likely due to an increased amount of meltwater discharged into the sea beneath the ice shelves of West Antarctica; the decline in the mass of these ice shelves has been greater than anywhere else in Antarctica (Figure 2.6).
- The upwelled deep water comes close to the sea surface near the Antarctic continent; in the Ross Sea, this layer has warmed by about 0.2°C and has shoaled (become shallower) by about 50 m since the 1950s; both are significant causes of melting the Ross Sea ice shelves from below (Jacobs and Giulivi, 2010). These temperature and depth changes could be related to intensification of the westerly winds, which may have accelerated the clockwise seawater circulation in the Ross Sea. The shoaling of warming water could be a cause of the increased melting rate of West Antarctic ice shelves.

Questions for the Future

Climate change in response to greenhouse gas forcing in the Southern Ocean will come about as the ocean and cryosphere warm in direct response to warming of the near-surface atmosphere. Indirectly, as the winds respond to climate change, the Southern Ocean circulation and water properties will change. The interplay of consequences due to warming and freshening versus those due to intensified westerly winds could be complex and is not easy to project based on current understanding and modeling. Without a comprehensive observational system in place, and advanced modeling of the Southern Ocean's circulation, sea ice, and ice shelves, it will not be possible to follow the near- and long-term responses to climate change.

There are several questions related to upwelling, stratification, and dense water production that will be important in the next 20 years:

- Will changes in the winds shift the location of the Antarctic Circumpolar Current, its fronts, and sea ice extent?
- Will changes in the westerly winds increase or relocate the upwelling of deep waters within the Southern Ocean?
- Will changes in upwelling of deep, warm waters and in ocean circulation south of the Antarctic Circumpolar Current increase melting of the (glacial) ice

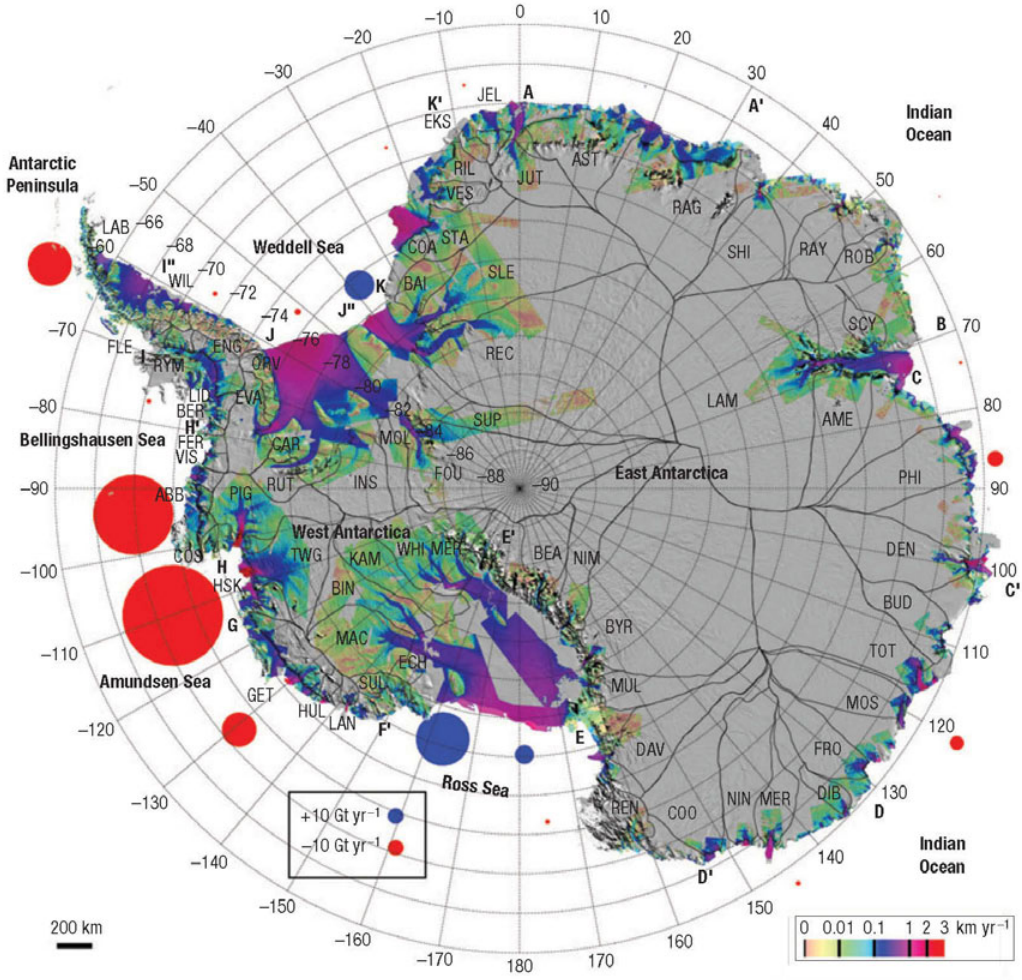


FIGURE 2.6 This image indicates the glacial surface velocities along the periphery of Antarctica and the mass loss (red circles) or gain (blue circles) of various Antarctic glaciers in gigatonnes per year. Data from satellite interferometric synthetic-aperture radar observations from 1992 to 2006 to estimate the total mass flux into the ocean, and mass fluxes from large drainage basin units with interior snow accumulation calculated from a regional atmospheric climate model for 1980 to 2004. The largest mass losses are from the glaciers from the West Antarctic Ice Sheet where it enters the Bellingshausen and Amundsen seas. SOURCE: Reprinted by permission from Macmillan Publishers Ltd: *Nature Geoscience* (Rignot et al., 2008), © 2008.

shelves? If so, will the additional freshwater at the Southern Ocean's sea surface, by increasing its stratification, reduce the effects of increased upwelling?
- Will formation of the bottom waters that fill the global ocean change (warming, freshening, weakening)?

There are also important questions related to connections of the Southern Ocean to the Northern Hemisphere:

- If the upper ocean waters that move northward out of the Southern Ocean are warmer and fresher, then will the stratification and upper ocean overturn in the midlatitude Southern Hemisphere increase?
- Will the North Atlantic's deep overturning, far from the Southern Ocean, be affected by changes in Southern Ocean winds, overturning, and stratification?

Required Tools and Actions

The climate-interacting portions of the Southern Ocean's circulation extend from the top to the bottom of the water column, and from the grounding lines of the ice shelves on the continental shelves for thousands of kilometers to the north, past the northernmost extent of sea ice to several hundred kilometers north of the Antarctic Circumpolar Current. Observations throughout this large area are particularly challenging because of stormy conditions with extremely large wave heights, seasonal sea ice cover, the long polar night, and the extraordinary challenge of observing within sub-ice cavities deep beneath the floating portion of ice shelves. Key parameters to measure throughout the water column are horizontal velocity, temperature, salinity, and oxygen. Biological productivity and carbon uptake also need to be studied (see next section), with measurements of nutrients and two or more of the carbon system parameters (pH, alkalinity, partial pressure of CO_2 (PCO_2), and dissolved inorganic carbon). Ocean modeling that assimilates data (with frequent reanalyses) and predictive ocean modeling are also essential.

The air-sea momentum (wind forcing), heat, and freshwater fluxes that govern the dynamics of the Southern Ocean occur in a very complex environment that includes a 1,500-km extension of the sea ice edge northward in winter and the retreat of sea ice back to the continent each summer (around much of Antarctica). Fluxes through the pack ice are difficult to quantify, providing one of the major challenges to be met by any successful future observational campaign over the next several decades. The largest heat losses from the ocean occur within regions less than 100 km from the Antarctic coast and ice shelf margins. Observations of air-sea fluxes of heat, freshwater, and CO_2 present major instrumental challenges (Bourassa et al., In press). Enormous improvements in measurements of present day air-sea flux components would be essential; these are now provided only by estimates from atmospheric reanalyses that are based on satellite observations and exceptionally sparse local observations (e.g., National Centers for Environmental Prediction, European Centre for Medium-Range Weather Forecasts).

A comprehensive proposal for an international Southern Ocean Observing System (SOOS) has been published (Rintoul et al., 2011). This planned system would become a part of the Global Ocean Observing System,[3] which is organized under the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization. SOOS will be comprised of a large suite of observational instruments to analyze the water column, including profiling floats, moored time series stations, routine gliders, and miniaturized sensors for biology and biogeochemistry, with a broad additional range of satellite and in situ instrumentation. If implemented, SOOS would make a significant contribution to answering many of the important questions above.

Southern Ocean Carbon Uptake and Ocean Acidification

Global Context

The Southern Ocean is an extremely important region of the globe for air-sea exchange of carbon dioxide (CO_2), second only to the northern North Atlantic (see Figure 2.7). The Southern Ocean hosts a large and diverse ecosystem, from the microorganisms in the seawater to the largest marine mammals. Rising temperatures due to higher levels of greenhouse gases will affect many aspects of the Southern Ocean and Antarctica's climate. As CO_2 levels rise in Earth's atmosphere, there will be (1) changes in CO_2 exchange with the sea which will alter atmospheric CO_2 levels, and (2) effects from increased dissolved CO_2 to increase ocean acidity that reduce the availability of calcium carbonate for shell and bone formation in many marine organisms.

On balance, the whole of the Southern Ocean is a net sink for excess anthropogenic atmospheric CO_2, but there are large, counterbalancing elements, and the relative importance of these elements can shift. The balance is currently dominated by CO_2 uptake in the deep mixed layers just north of the Antarctic Circumpolar Current. However, CO_2 release occurs both within and south of that current, where deep waters upwell to the sea surface. These deep waters come from the Atlantic, Indian, and

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[3] See *http://www.ioc-goos.org/.*

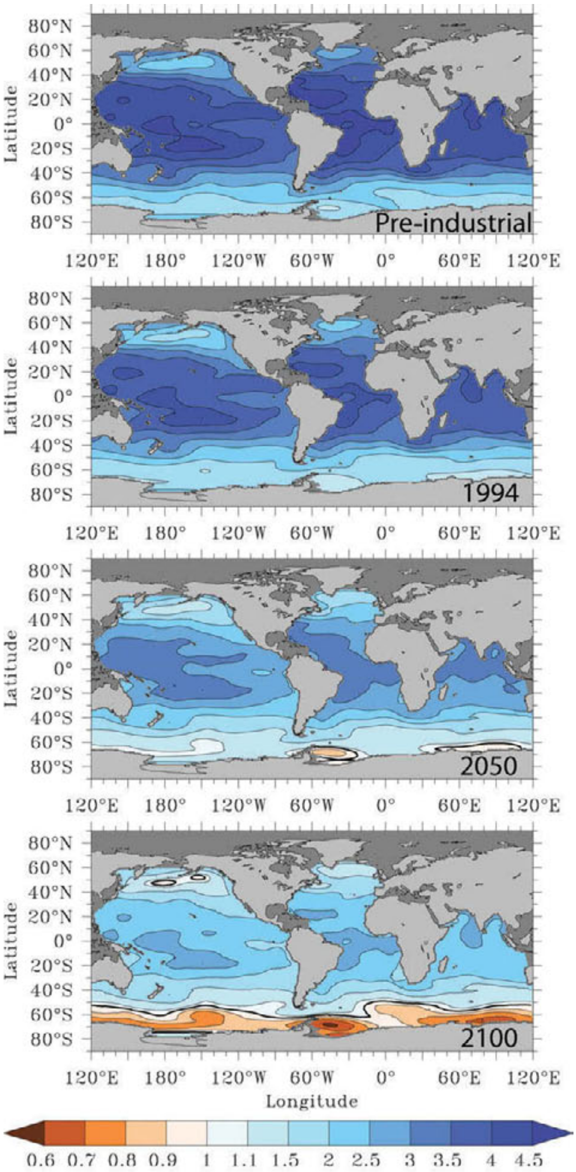


FIGURE 2.7 The effects of ocean acidification at the sea surface are illustrated with maps of the surface water aragonite saturation state showing where calcium-carbonate-based structures (like shells) would be dissolved: values <1 are undersaturation of seawater with respect to aragonite, indicating that there would be dissolution. These maps highlight the sensitivity of the Southern Ocean under greenhouse gas forcing scenarios. Maps for "pre-industrial" (1765) and 1994 are based on observations and extrapolation from observations; maps for 2050 and 2100 are the average of 13 ocean general circulation models under an IPCC "business-as-usual" scenario (Orr et al., 2005). SOURCE: Fabry et al., 2008, by permission of Oxford University Press.

Pacific oceans; because they have been far below the sea surface for up to hundreds of years, they have accumulated excess carbon. The westerly winds are expected to increase in strength in response to increased greenhouse gases (see earlier section, The Atmosphere), which will both increase the deep water upwelling rate (and carbon release) and possibly also enhance deep mixed-layer formation (carbon uptake). Increasing seawater temperatures will also lower carbon dioxide solubility in seawater and change the overall chemical equilibrium in seawater.

What Changes Are Occurring in the Southern Ocean?

Ocean acidification is the "other CO_2 problem" (Doney et al., 2009; National Research Council, 2010d) (see Box 2.5). The lowering of pH is a response of the carbonate buffer system in seawater to anthropogenic CO_2 uptake into the ocean. The problem is greatest in cold polar waters because the low temperature increases CO_2 solubility and decreases the saturation level; the result is that the polar oceans could experience decreases in carbonate saturation to harmful levels by midcentury. Much of the anthropogenic CO_2 that has been absorbed by the ocean is in the North Atlantic, but the Southern Ocean north of the polar front zone also shows a large CO_2 increase over the past decade. The mean Southern Ocean surface pH has already declined measurably (by 0.1 unit) (National Research Council, 2011b).

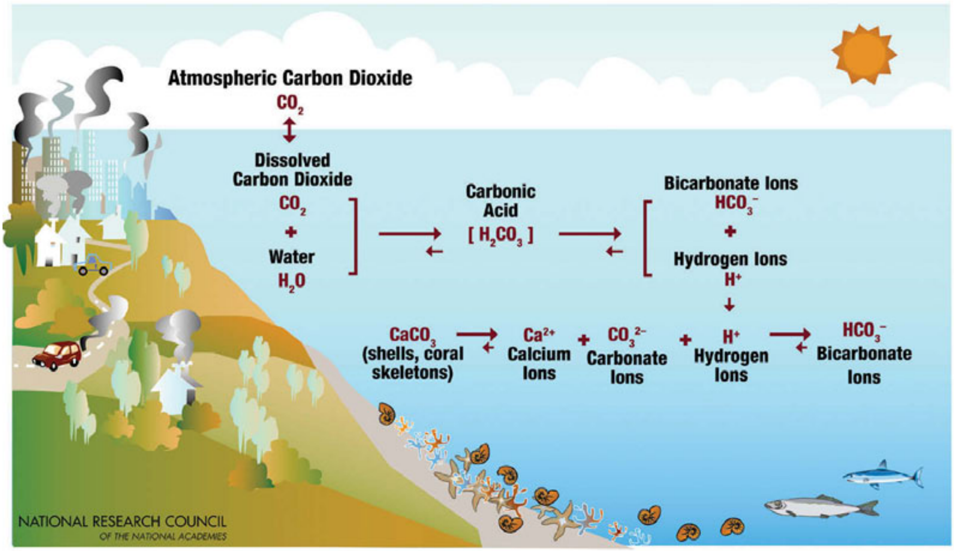
The principal concern of acidification is not the direct effect of reducing pH but the associated decrease in carbonate saturation, which makes it more difficult for marine organisms to build and maintain their calcium carbonate shells and other body parts. Some direct effects of acidification on calcification and growth of particular organisms such as coccolithophorids, crustaceans, and corals are beginning to be described, but higher-level effects on ecosystems are very poorly understood. For example, how will Antarctic food chains change if organisms such as krill and pteropods (small winged mollusks) are vulnerable to acidification? The implications for predators consuming krill, such as seabirds, seals, and whales, are unclear, as are the impacts on fish and fisheries.

Acidification will interact with other processes of change, such as ocean warming, in complex and hard-to-predict ways. For example, recent warming of deep waters along the Antarctic Peninsula appears to allow the invasion of predatory crabs. Crab physiology is sensitive to cold temperatures, so they have been absent from Antarctic seas since the Eocene, approximately 56 to 34 million years ago, and benthic mollusks have not experienced recent evolutionary contact with shell-crushing predators. The shells of these calcified organisms may be weakened by future acidification, rendering them

BOX 2.5 OCEAN ACIDIFICATION MECHANISMS

As the concentration of carbon dioxide (CO_2) increases in the atmosphere, more CO_2 dissolves in the world's oceans. The solution of more CO_2 in the ocean leads to the formation of more carbonic acid (H_2CO_3) and more hydrogen ions (H^+). Acidity is defined by the concentration of hydrogen ions, so, as CO_2 increases, the oceans become more acidic.

Calcium carbonate ($CaCO_3$), composing the shells of many organisms, is often thought of as insoluble "chalk" with two crystalline forms, calcite and aragonite. $CaCO_3$ is, however, in equilibrium with calcium (Ca^{2+}), carbonate (CO_3^{2-}), and hydrogen ions in the surrounding ocean. Increases in hydrogen ion concentrations result in a depletion of carbonate (CO_3^{2-}), causing desaturation of the ocean levels of calcium carbonate and subsequently the dissolution of calcite or aragonite in the skeletons of marine organisms (see figure). In addition because freshwater is 10 times more acidic (pH 7) than normal ocean water (pH 8), significant input of freshwater (from melting ice) will also reduce carbonate levels and cause dissolution of the calcium carbonate skeletons of ocean organisms. This is why calcium carbonate saturation levels depend on ocean salinity. There is also a depth or pressure dependence of carbonate levels.



Cartoon depicting chemical mechanisms involved in ocean acidification. SOURCE: National Research Council, 2010d.[a]

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[a] See *http://oceanacidification.nas.edu/?page_id=29*.

even more vulnerable to invading predatory crab populations in Antarctica (Thatje et al., 2005). There is also additional concern that altered pH will cause physiological challenges that induce a metabolic cost to organisms, thereby changing the performance of even noncalcifying organisms.

Questions for the Future

A major question is how the rate of CO_2 uptake, and the resulting acidification of the Southern Ocean, will change as the overall climate system changes (warming, wind stress, position of frontal systems in the Antarctic Circumpolar Current, rates of ocean upwelling). The upwelled deep waters of the Southern Ocean carry excess CO_2 as compared to surface water, which means they are slightly more acidic and will impede future CO_2 uptake from the atmosphere. Warming will increase the flow of freshwater from melting glaciers into the sea. This freshwater input has less capacity to absorb excess CO_2 from the atmosphere and is thus more prone to acidification. The question then is, Will there be increased ocean acidification associated with increased glacial melt? A major question in global change biology is whether organisms will have the genetic ability to adapt or the physiological plasticity to remain in place and tolerate these new conditions. There is also the impact on biogeographic range that might be an issue for polar organisms, that is, where to migrate to find colder temperatures.

Another major concern is the proposed global-scale sequestration of liquefied CO_2 within the deep ocean (National Research Council, 2011b) as a means to partially mitigate the buildup of anthropogenic CO_2 in the atmosphere. CO_2 capture and direct injection into the deep sea bypasses the surface layer and avoids many of the expected consequences of acidification. However, the effects of enriched CO_2 levels on deep sea food webs are unknown, as is the ultimate stability and fate of deep sequestered CO_2.

Required Tools and Actions

Over the next 20 years, the committee anticipates the deployment of a comprehensive observation system to monitor the changing state of the Southern Ocean carbon system, including pH sensing packages to follow acidification at the scale of individual organisms. Accompanying the new data streams from the observational infrastructure would be new information management capabilities, new models, and sophisticated physiological studies to understand the responses of biota to chemical and physical changes in the ocean environment.

Intensive study of the components of the Southern Ocean carbon system will require sustained, year-round observations from moorings, floats, gliders, and autonomous underwater vehicles (see Appendix C) that can sample under sea ice as well as in open water. These observations will need to include chemical (e.g., pH, alkalinity, dissolved inorganic CO_2, PCO_2) and biological measurements, as well as physical measurements (velocity, temperature, salinity). Some of these measurements will require novel and robust sensors. The response of the carbon system to changes in the strength of westerly winds, increasing temperature, and freshwater influx needs to be documented as the climate changes. Targeted experiments for key polar species should document their response to calcium carbonate undersaturation associated with ocean acidification. Changes in interactions between species, food webs, and ecosystems need to be documented. Climate change will bring changes in seasonal sea-ice cover, warming, and southward expansion of the range of lower-latitude species, which should be documented. The SOOS implementation plan (Rintoul et al., 2011) presents a detailed proposal for observing the chemical, biological, and physical components of these interacting systems.

Southern Ocean Sea Ice

Global Context

Sea ice covers most of the Southern Ocean in winter and extends as far north as 55°S in places, almost 1500 km from the continent of Antarctica. In summer the ice melts almost all the way back to the continental and ice shelf margins, cycling between coverage of 15-16 million km^2 in winter to 2 million km^2 in summer (NSIDC, 2010) (Figure 2.8).

Southern Ocean sea ice is a critically important agent in the Antarctic and global climate system. Sea ice anomalies (deviations from the average amount of sea ice) can persist for several months and have the potential to strongly affect the variability of both the atmospheric and oceanic circulation. Sea ice reflects a large percentage of incident solar radiation, which changes the rate of solar heating of the ocean and atmosphere. Locally, sea ice controls the rate of heat exchange between the ocean and atmosphere. Globally, it helps to maintain the equator-pole temperature gradient, thereby exerting control over global atmospheric and hence oceanic circulation. Sea ice influences the Southern Ocean circulation by reducing sea surface temperatures, redirecting surface currents, and creating dense waters when salt is rejected as the ice forms. Sea ice affects the underlying marine ecosystems. Sea ice also greatly complicates the deployment of sensors and instruments for continuous observations within

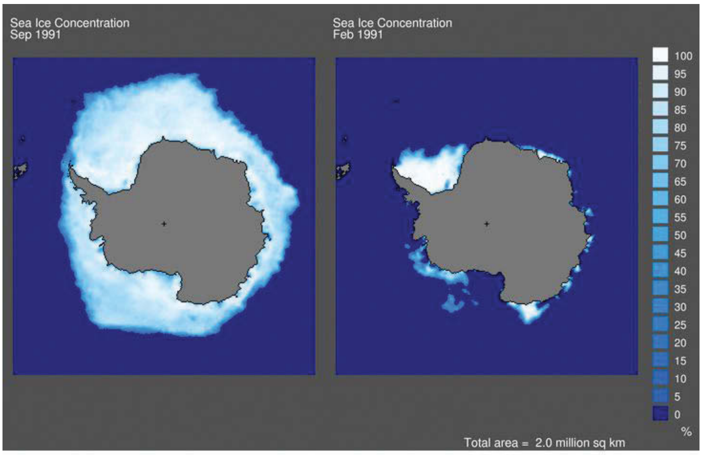


FIGURE 2.8 Sea ice coverage cycles between winter and summer. Winter (September, left) and summer (February, right) sea ice cover in 1991. SOURCE: National Snow and Ice Data Center, University of Colorado, Boulder.

the water column and measurements of air-sea fluxes, as well as measurements of surface conditions from satellites.

What Changes Are Occurring to Antarctic Sea Ice?

In the Arctic, the decrease of sea ice cover for at least the past 30 years is attributed to global warming. In contrast, there has been a very small increase in Antarctic sea winter ice cover over the same 30 years (Figure 2.9). Unlike the Arctic, where the reduction in sea ice extent has been spatially coherent, in Antarctica sea ice trends have a strong regional variability. While sea ice extent has decreased markedly in the Bellingshausen/Amundsen and western Weddell seas, it has increased in the Ross Sea. These opposing regional trends, arguably as large as the Arctic sea ice trends, have resulted in a positive trend of about 1 percent per decade (Cavalieri and Parkinson, 2008).

In the long term, with continuing anthropogenic release of greenhouse gases, the atmosphere will continue to warm and winter Antarctic sea ice extent is expected to be much reduced (in summer it retreats to the continental edge around much of the continent as part of the normal annual cycle), as projected for the next century by IPCC models. This simulated decrease is likely to accelerate as the surface cooling associated with ozone forcing declines. The volume of winter sea ice that is formed is

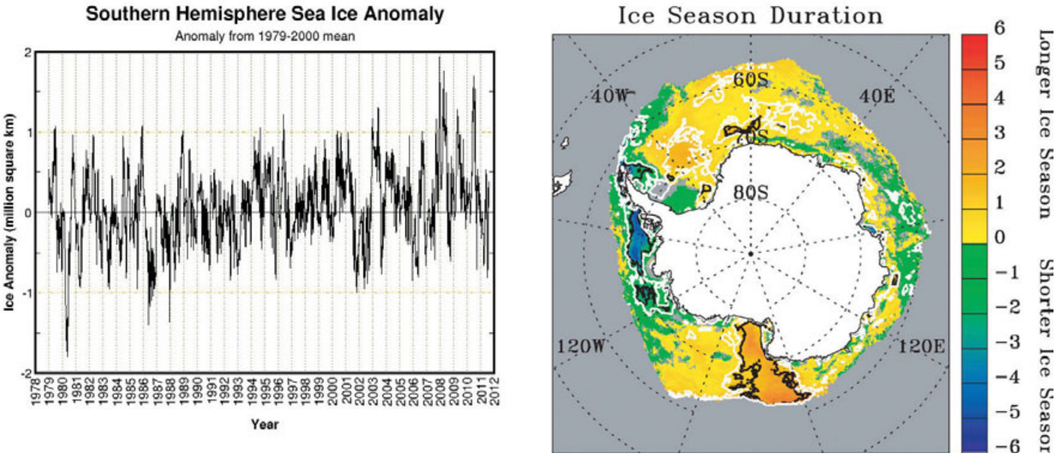


FIGURE 2.9 Unlike in the Arctic, sea ice trends in Antarctica have strong regional variability and winter sea ice cover has slightly increased over the past 30 years: (top) Antarctic sea ice cover anomalies (difference from the 1979-2000 mean) and (bottom) trend in ice season duration (days/year) for 1979-2004. SOURCES: (top) Cryosphere Today, University of Illinois at Urbana-Champaign, (bottom) Stammerjohn et al., 2008, Copyright 2008 American Geophysical Union, reproduced by permission of American Geophysical Union.

also expected to shrink, leading to thinning of the ice, in the same way as observed in the Arctic. Sea ice loss is expected at all longitudes and especially in the West Antarctic vicinity. Such reduction in the seasonal cycle of sea ice concentration and volume would lead to a reduction of brine rejection at the margins of Antarctica. This will influence the future formation of Antarctic Bottom Water (Sen Gupta et al., 2009) and could thereby weaken the strength of the deepest cell of the global overturning circulation (see Figure 2.10).

Questions for the Future

Much of what is known about Antarctic sea ice surface area and thickness, variability, and change is limited to what satellites have observed since the satellite observation record began in 1979. Some of this information is supported by very sparse direct surface observations. One recent project, Sea Ice Mass Balance in the Antarctic, uses a variety of remote sensing measurements including altimetry data and passive and active radar to create a baseline data set for future observations. Using this baseline, scientists can more accurately monitor changes in the sea ice balance. The data can be used in model validation and in validation of the satellite observations and can

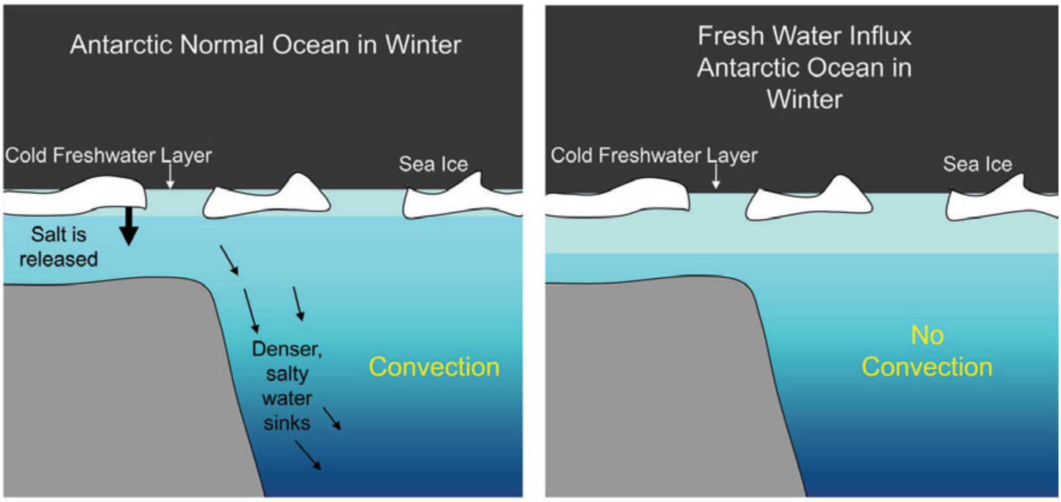


FIGURE 2.10 Schematic depiction of the potential disruption of normal ocean convection by an influx of meltwater that dilutes the Antarctic surface water leading to loss of convection. This could have implications for global overturning circulation. SOURCE: T. Budinger.

facilitate better future predictions of sea ice cover. This can potentially help scientists understand why current climate models predict a decline in Antarctic sea ice over the 20th century while observations show a small increase.

Overall, the explanations of the satellite-observed spatial variation have primarily relied on those offered by atmospheric circulation mechanisms, rather than by complete explanations that include the entire climate system. Although much has been learned, large knowledge gaps remain, in particular the following:

- Atmospheric circulation mechanisms explain only a portion of sea ice trends; what accounts for the remainder?
- The ocean certainly plays a role in sea ice variability, but to what extent?
- What are all of the potential feedback mechanisms between the loss of Antarctic sea ice and the global climate?
- As they become more sophisticated, can climate models faithfully reproduce sea ice variability and extent in their simulations?
- Given that sea ice is a critical component of the global climate system, research in the Antarctic region should include efforts to understand these gaps in the observations and understanding.

Required Tools and Actions

Answers to the foregoing questions require better understanding of the sea ice–climate system interaction, especially the factors controlling sea ice formation, transport, and decay. Achieving realistic sea ice projections hinges on simultaneous (or concurrent) improvement in sea ice observations and climate models, in particular the sea ice component of models. Improving the sea ice component models will require two types of observations: process-scale observations to develop, refine, and constrain the model parameterizations, and large-scale observations to validate the large-scale simulated patterns. To facilitate this, sustained small-scale (i.e., surface) observations of sea ice cover (i.e., concentration), thickness, and extent are needed, as well as simultaneous observations of the oceanic and atmospheric variables that contribute to the presence of sea ice. These include ocean-ice-atmosphere heat flux as well as observations within the water column. At the large scale, data sets with good spatial and temporal coverage of mean sea ice thickness would reduce current model errors in sea ice concentration and extent. If this information were available, along with continued satellite coverage of ice concentration and extent, it should immediately improve simulations. Therefore, to reduce the uncertainties, a combined program of sustained observation of sea ice parameters and advanced climate model development, with sea ice information fed into the climate models, is needed.

Within the next 20 years the committee believes that a better understanding of the sea ice–climate system interaction, especially the factors controlling sea ice formation and decay, is possible. From this improved understanding the goal of simulating realistic projections of past, current, and future Antarctic sea ice conditions is realizable.

The Southern Ocean's Interaction with Glacial Ice

Global Context

The edges of the continental ice sheet extend into the ocean in massive ice shelves that cover about half of the circumference of Antarctica (Figure 2.6). They typically extend about 100 km offshore of their grounding line. The ice shelves in the semienclosed Weddell Sea (Filchner and Ronne ice shelves), Ross Sea (Ross Ice Shelf), and Prydz Bay (Amery Ice Shelf) are even more extensive. The ice shelves are typically 200-700 m thick. Climate change has already led to warming of the global atmosphere that, in turn, has caused melting in and near the Antarctic Peninsula. Massive breakups of ice shelves observed during the past several decades along the Antarctic Peninsula have triggered faster loss of ice from the land-fast glaciers behind them (Scambos et al., 2004). The impact of increased glacial ice loss on sea level rise was discussed previously (Section 2.1).

A crucial component of the climate system in the Antarctic region is interaction of the ocean with glacial ice. Beneath the ice shelves there is interaction between the ice, seawater, and glacial meltwater that drains out from under the continental glaciers (Figure 2.5). The seawater that flows through the sub-ice cavities under the ice shelves is cooled to freezing and becomes part of the very dense bottom waters forming around the continental edge. The plumes of this ice shelf water typically contain up to a few per mil of pure glacial meltwater that freshens the salty shelf waters or is incorporated into the plumes of newly formed Antarctic Bottom Water. The addition of this glacial freshwater can influence Antarctic Bottom Water formation (see earlier section, Ocean Circulation) and enhance Southern Ocean acidification (see earlier section, Southern Ocean Carbon Uptake and Ocean Acidification). Understanding the rate of change of glacial ice melting due to the influence of the ocean is critical to understanding the climate system in Antarctica and the Southern Ocean.

What Changes Are Occurring to Antarctic Glacial Ice?

The seawater in sub-ice cavities melts the ice shelves from below, a primary factor in the mass balance of the shelves. The rate of melting depends on initial seawater temperature, temperature of the glacial ice, and the pathways of shelf waters flowing underneath the floating ice shelves. A few estimates of glacial ice melt rates underneath floating ice shelves have been obtained by measuring the chemistry and temperature of waters flowing into and out of the sub-ice cavities (Loose et al., 2009; Schlosser et al., 1990). Such estimates have large uncertainties.

Upwelled deep waters, which are well above freezing, can reach the Antarctic shelves, enter the shelf water region, and enhance the melting of glacial ice from below. Recent observations suggest enhanced interaction between the upwelled deep waters and the ice shelves and sea ice (Jacobs et al., 2002). Increasing winds are projected to increase upwelling rates, which would enhance subglacial melting. Waters in front of West Antarctica's Pine Island glacier have shown enhanced meltwater fractions (Figure 2.6) and a loss of mass detected by satellite observations. According to satellite observations, several other ice shelves are losing mass. It is believed that a good fraction of this mass loss is due to melting from below (Rignot and Jacobs, 2002). Major questions arising from these observations include the nature of the processes by which ocean-glacial ice interactions contribute to the thinning of floating ice sheets and how this contribution might change in the future.

Questions for the Future

There is an urgent need to better understand the dynamics of the ocean-glacial ice interaction beneath floating ice shelves, to improve the estimates of their melting rates, to establish the rate at which the ocean-glacial ice interaction adds freshwater to the global ocean, and to determine changes in the preconditioning of the shelf waters that flow underneath the ice shelves. This improved understanding will contribute to better projections of future sea level rise caused by melting of glacial ice in Antarctica. Over the coming decades, scientists should acquire both the data and modeling capacity to be able to quantify the amount of freshwater released from melting glacial ice into the ocean, as well as produce better projections of future melting rates.

Required Tools and Actions

There are several methods that will need to be applied in combination to answer the questions posed above. They include the following:

- Long-term measurements of the properties and circulation patterns of the continental shelf waters adjacent to floating ice shelves, including their variability and change (hydrographic sections, moorings).
- Observations of the seawater and the glacial outflows beneath floating ice shelves and their variability and change (autonomous underwater vehicles [AUVs], under-ice drifters, and instruments deployed via holes drilled through the ice shelves), including advanced technologies for launching and recovering autonomous vehicles that can provide continuous monitoring of salinity and temperature profiles in the cavities under ice shelves and under sea ice during the Austral winter.
- Studies of the connectivity between shelf waters and the Antarctic Circumpolar Current with its "relatively warm" Circumpolar Deep Water to estimate the heat flux onto the ice shelves and the transport of ice shelf water off the shelves (hydrographic sections, AUVs, drifters or gliders, and moorings).
- Satellite measurements of the elevation changes of Antarctic floating ice shelves.
- Improved modeling of the ocean-glacial ice interaction at the front of the ice sheet and beneath floating ice shelves.

The Climate System

Overall, a systems approach to the future of climate–glacial ice–sea ice–ocean science in Antarctica is needed. Perhaps even more intimately than in the Arctic, these systems are inextricably linked in Antarctica. Comprehensive understanding of the global system requires understanding of the Antarctic and Southern Ocean region. Earth system modeling facilitates this approach and will allow scientists to understand past and current events as well as predict the future.

To apply an efficient systems approach in Antarctic studies scientists have to continue to improve the understanding of subsystems that frequently suffer from poor observational records, especially concerning seasonal cycles, and poor characterization of their dynamic features. Simultaneous efforts to increase the density and scope of observations and quantitative description of the subsystems using conceptual, analytical, and numerical models should provide researchers with the information needed to design observing systems and models that can capture the main features and resonance points of Antarctic and the Southern Ocean as a whole. In a final step, such Antarctic and Southern Ocean observing systems and models have to be integrated into comprehensive Earth system models. These activities are not seen as occurring sequentially, but rather they should take place simultaneously to take advantage of synergies that can be gained by exchange between the communities working primarily on regional and global scales, respectively.

Ultimately, models require observations to improve process understanding and to validate predictions. The foremost need to improve the understanding of the role of Antarctica and the Southern Ocean in the global climate system is significantly increased observational capacity in Antarctica and the Southern Ocean.

2.3 WHAT IS THE RESPONSE OF ANTARCTIC BIOTA AND ECOSYSTEMS TO CHANGE?

Global Context

Although Antarctica is well known for its penguins, seals, and whales, recent research has revealed an abundance of other life forms, including active food webs in freshwater lakes and soils that extend beyond 80°S. The previous concept of terrestrial, freshwater, ice, and marine systems in Antarctica having only short food chains of low diversity has evolved as more species are discovered and a greater diversity is recorded in habitats once considered lifeless. Nevertheless, the magnitude of the impacts of global change on the structure and functioning of terrestrial and freshwater systems are readily detectable compared to nonpolar systems containing many more species.

The Southern Ocean is characterized by extreme gradients in biological productivity. The deep waters are rich in nutrients that have accumulated from the continuous rain of organic debris from the sunlit euphotic zone in the surface layer throughout the world ocean. These nutrient-rich waters upwell and effectively fertilize the surface layer (Figure 2.11). In much of the Southern Ocean, plant production is limited by the availability of iron. The most productive regions are the continental shelves and other regions, where the strong currents of the Antarctic Circumpolar Current scour the continental shelves, harvesting iron from the sediments, resulting in much higher produc-

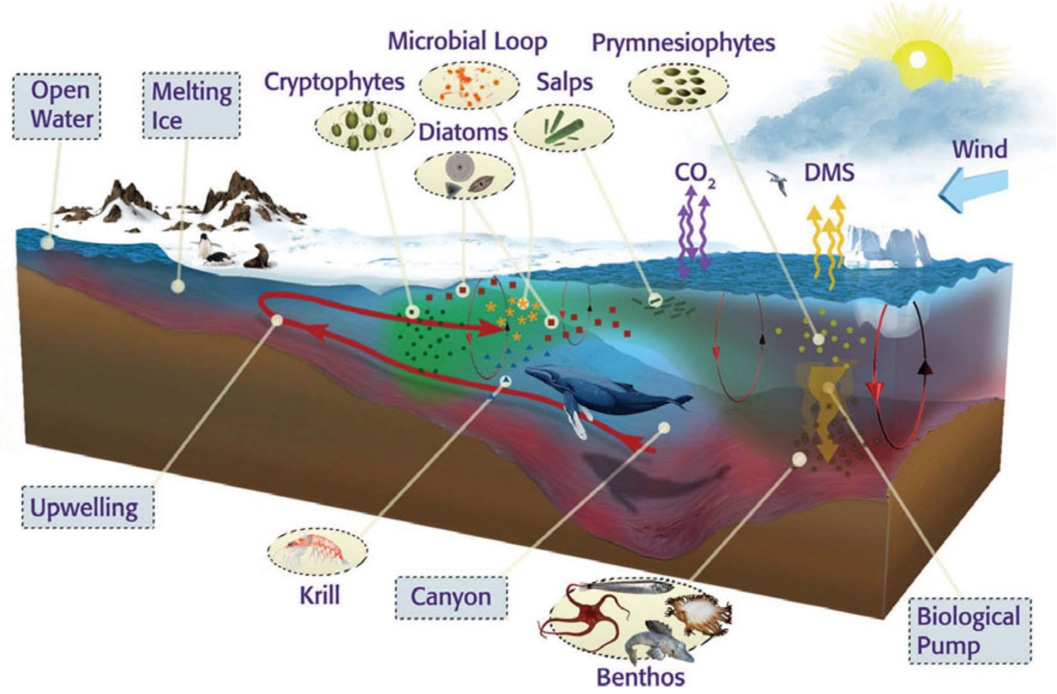


FIGURE 2.11 Cartoon view of the marine ecosystem of the west Antarctic Peninsula. The system is currently characterized by large predators such as penguins, seals, and whales, sustained by upwelling that supports high productivity and large krill populations. But these typical Antarctic food chains might be in a process of transformation into a new system dominated by gelatinous salps and microbes—dead ends in the food chain. SOURCE: Coastal Ocean Observation Lab, Rutgers University.

tivity downstream. Further offshore, where the availability of iron is limited, the open Southern Ocean is a marine desert of low productivity (Moore et al., 2001).

Similar gradients exist on land as well. The Antarctic Peninsula is becoming slightly greener as temperatures warm and glaciers recede. Other Antarctic terrestrial ecosystems are among the simplest and most oligotrophic on the planet, nurtured as much by stores of "legacy" nutrients and organic matter accumulated over millennia as by contemporary production.

These variations make Antarctica and the Southern Ocean a unique, living laboratory for the study of ecosystem change. Ecosystems in Antarctica are simple enough that they can be studied for rules on how they respond to change, yet they are sufficiently complex that they are analogous to ecosystems in the rest of the globe.

What Environmental Changes Are Occurring?

The Antarctic region, once considered pristine, is no longer as isolated from or immune to changes that are occurring globally. The marine and terrestrial ecosystems of Antarctica have evolved largely in isolation from the rest of the planet since the opening of the Drake Passage approximately 30-40 million years ago and the establishment of the Antarctic Circumpolar Current, but remote forcings such as climate change, global transport of pollutants, invasive species, and increased ultraviolet radiation are altering biotic communities across the Antarctic continent. Other environmental changes include the local effects of increasing human presence due to tourism and scientific research, where visits to the continent from both activities have grown dramatically since the 1950s (National Research Council, 1993). The ecological system may still be recovering from the harvesting of whales, seals, and penguins that was prevalent in the first part of the 20th century. With increasing human presence come accompanying concerns about habitat destruction, overfishing, pollution, and other toxic effects on the environment. Contamination from oil spills and the disposal of waste remains a serious concern. In addition, the introduction of alien species and diseases into these areas can be harmful to indigenous wildlife populations and ecosystems (Frenot et al., 2005). The effects from the combination of these factors on Antarctic ecosystems are generally not known.

Of the various human influences, the impacts from human-induced climate change may prove to be the largest. Climate variability and change alter temperature and precipitation; some regions experience long-term increases, and some have decade-scale periods of cooling interrupted by brief warming events (see Box 2.6). Less than 0.5 percent of the continental land surface is exposed, including nunataks, cliffs, and seasonal

BOX 2.6 ANTARCTIC ECOSYSTEM RESPONSES TO CLIMATE VARIABILITY REVEALED BY LONG-TERM OBSERVATIONS

The Palmer and McMurdo Dry Valleys Long Term Ecological Research (LTER) projects have maintained observations of environmental variability and ecosystem responses since the early 1990s. Today research findings from these projects are among the best examples documenting the responses of marine and terrestrial ecosystems to climate forcing. Comparison of the responses of these diverse ecosystems is helping scientists to construct a general theory of ecosystem response to climate change and devise better models to predict how Earth's ecosystems will change in the future under specific climate change scenarios (National Research Council, 2011d).

The climates of the western Antarctic Peninsula marine ecosystem studied by Palmer LTER and the polar desert of the Dry Valleys studied by the McMurdo LTER are both poised near the freezing point and are thus potentially vulnerable to large alterations in ecosystem behavior as temperatures warm or cool, and change the balance between freezing and melting of ice. Polar marine ecosystems are very strongly influenced by the dates of advance and retreat of sea ice as well as the annual duration of sea ice cover and its areal extent. Organisms from the base to the top of marine food chains have life cycles adapted to the annual rhythm of sea ice advance and retreat. Similarly, the organisms in Dry Valley soils depend on the flow of liquid water from melting glaciers and permafrost in summer. Coordinated meteorological and ecological observations show the common denominators of how populations of organisms have responded to environmental variability in these two contrasting ecosystems.

In the Palmer Station region of the Antarctic Peninsula, the mean winter (June-July-August) air temperature has risen by 6°C since 1950, and, in consequence, the duration of sea ice cover has declined by more than 80 days since 1978 (Figure 1) (Stammerjohn et al., 2008). The Dry Valleys have experienced a period of cooling since at least 1986, with attendant changes in lake levels (Figure 2) (Doran et al., 2002). Both systems experienced bottom-up changes at the base of their food webs and also top-down effects on apex predator populations. In the marine ecosystem, phytoplankton stocks declined in the north and increased in the south in response to changes in sea ice, winds, and ocean mixing (Montes-Hugo et al., 2009). At the same time, the Adélie penguin population declined by 80 percent in response to both direct warming effects and food reduction moving up from the base of the food web (Figure 1) (Schofield et al., 2010). In the Dry Valley lakes, the rate of photosynthesis (primary production) declined as ice thickened, reducing light penetration into the water. The nematode top predators in the soil declined by 50 percent as soils dried in response to colder temperatures (Figure 2).

In addition to nonlinear, and possibly long-lasting, changes due to steady climate forcings, ecosystems can also experience long-lasting effects due to sudden pulses or events such as unusual weather over the course of a single season. A hemisphere-wide atmospheric circulation anomaly in spring-summer 2001-2002 caused unusually warm temperatures across the continent (Massom et al., 2006). On the Peninsula, catastrophic late-season snowfalls and later flooding caused the largest single-season decline in Adélie penguin breeding success in 30 years (Figure 1). The effects of this loss of an entire breeding cohort are still evident 10 years later. In the

continued

BOX 2.6 CONTINUED

Dry Valleys, record high temperatures and glacier runoff returned lake levels to pre-1986 highs, erasing the effects of 15 years of cooling in just a few weeks (Doran et al., 2008). The extreme increase in soil moisture levels caused a reorganization in soil nematode species composition that was still evident in 2008 (Barrett et al., 2008).

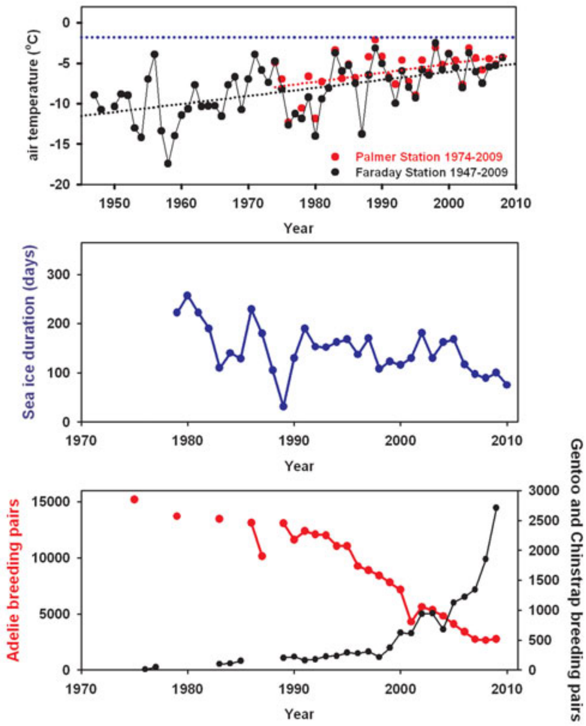


FIGURE 1 Climate variability and ecosystem response on the western Antarctic Peninsula; as temperatures have warmed and sea ice duration has decreased, Adélie breeding pairs have decreased while those for Gentoo and Chinstrap penguins near Palms have increased. Top: surface air temperature at Faraday Station (now Vernadsky Station), 1947-2009 (black) and Palmer Station, 1974-2009 (red). The blue dotted line is the freezing point of seawater (–1.8°C). Middle: duration of sea ice cover at Palmer Station, 1978-2010. Bottom: population trends for Adélie, Gentoo, and Chinstrap penguins near Palmer Station, 1975-2010. SOURCES: See Ducklow et al. (2007) for details and sources. The Faraday/Vernadsky data are available from the BAS READER project at *http://www.antarctica.ac.uk/met/READER/data.html*. The bottom two plots were constructed using data from the Palmer Long Term Ecological Research project (*http://oceaninformatics.ucsd.edu/datazoo/data/pallter/datasets*). Photo: Adélie penguins in meltwater pool covering nesting site following late season snowfall. Note submerged eggs. Courtesy W. R. Fraser.

BOX 2.6 CONTINUED

These observations are important for several reasons. First, they illustrate the complexity of the climate-biosphere system with nonlinear responses over a range of timescales. Second, they show that Antarctica is not a mosaic of disconnected, independently performing ecosystems. Rather, systems as far apart and different as the two LTER sites responded in similar ways to the 2001-2002 warming event. Third, they underscore the critical need for a sustained, spatially extensive, multiparameter observing system. Finally, these coordinated geophysical-ecological-biogeochemical observations contribute to a wider theoretical understanding of ecosystem functioning.

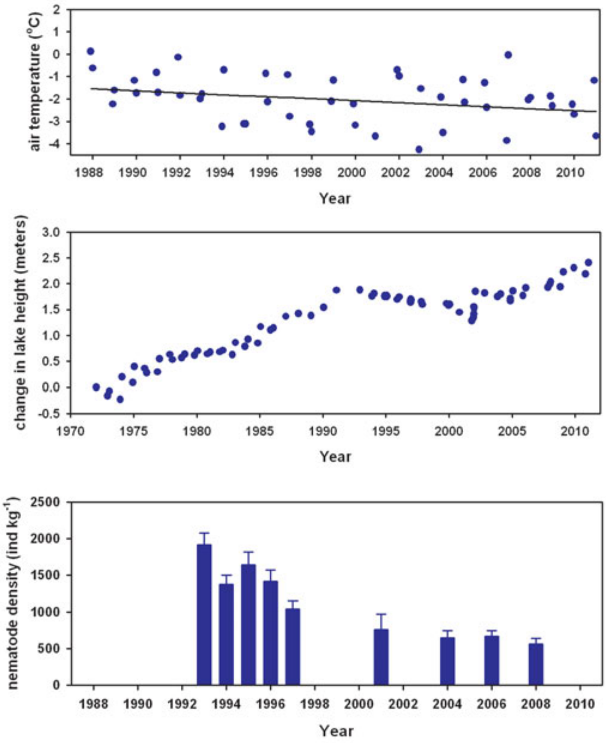


FIGURE 2 Climate variability and ecosystem response in the McMurdo Dry Valleys. Top: midsummer (December-January) surface air temperature, 1988-2011. Middle: change in height of Lake Bonney surface, relative to 1972. Bottom: changes in density of soil nematodes at Lake Hoare, 1993-2008. SOURCES: See Doran et al. (2002) for details and sources. Plots constructed using data from McMurdo Dry Valleys Long Term Ecological Research project (*http://www.mcmlter.org/data_home.htm*). Photo: High flow of glacier runoff during summer melting event. Courtesy A. G. Fountain.

snow and ice-free areas. These areas range from biologically more complex terrestrial ecosystems on the Antarctic Peninsula and "oases" near the East Antarctic coast to the less complex ecosystems in the McMurdo Dry Valleys (Fox et al., 1994). On both land and sea, warming and ice melt will increase the area of exposed surfaces, provide new habitats for colonization by organisms, and cause changes in ecosystem functioning. As sea ice disappears, new areas of ocean surface will be exposed to increased solar radiance, and biological productivity may increase. Natural colonization rates will increase and species ranges will expand. Rapid expansion of the biogeographical ranges of native plant species has been noted in maritime Antarctica, as have increases in biological production in continental lakes.

These changes in range expansion and growth rates of native species due to warming could lead to fundamentally different organization of Antarctica's ecosystems, including more complex ecosystem structures, and an increase in the biotic factors (predation, competition, pathogens) that control rates of biogeochemical processes rather than the current dominance by physical factors (National Research Council, 2010b). Understanding current distributions of native species is central to detecting and predicting the effects of climate change. Fortunately, there has been significant progress in identifying some species and the factors that determine their ranges, which can be used to predict future range expansions, new community assembly, and altered ecosystem function.

Questions for the Future

The mechanisms of ecosystem response to global change remain controversial (Trivelpiece et al., 2011), but there is a growing consensus that climate change generally affects ecosystems by destroying existing habitats or enabling new ones (see above) and by disrupting the trophic and other phenological connections among prey and predator populations. Evidence for the effects of climate change on the structure and function of marine, freshwater, and terrestrial systems is still based on a few observational ecological studies and even fewer laboratory and field manipulation experiments (National Research Council, 2011d). Advances in knowledge of the structure and function of Antarctic ecosystems have been substantial, yet researchers are still unsure of the spatial and temporal variability of ecosystem responses to climate change and other global changes. Major questions related to environmental change include the following:

- How vulnerable or resilient are marine, freshwater, and terrestrial food webs to changes such as warming, enhanced water availability, habitat disturbance, ocean acidification, pollutant accumulation, and loss of sea ice?

- What are the functions of Antarctica's diverse ecosystems in biogeochemical cycling and how will they change?
- Are the marine and terrestrial ecosystems of Antarctica organized differently than ecosystems elsewhere on the globe? And does this temper their responses to change?
- Could Antarctic ecosystems switch to an unknown, alternative state with different structure and functioning?
- Is the Peninsula a harbinger of larger-scale changes to come? Will ecosystems of the continental interior follow the lead of the Peninsula?

Required Tools and Actions

Scientists do not yet know if environmental changes proceed from north to south or from the continental margin to its interior. Lack of geographically extensive, long-term observation records and the paucity of observations south of the Peninsula and McMurdo regions impede rigorous testing of these questions. The fortuitous location of a planetary climate change hotspot in a region with advanced scientific facilities at the many research stations along the Peninsula provides an unparalleled opportunity to understand and predict the future course and consequences of climate change. Meteorological and biotic data needed for model projections also come from long-term observations in lakes, streams, soils, permafrost, and glaciers of the McMurdo Dry Valleys. But there is a dearth of observations at other terrestrial, coastal, and interior sites to indicate the future effects of climate change. To place these local changes in a continent-wide context, and predict the future course of change across Antarctica, a comprehensive coordinated observing and prediction system encompassing all the major elements of the Antarctic environment is needed, including the terrestrial ecosystems, permafrost, surrounding ocean, sea ice, ice shelves, ice sheets, and subglacial habitats. The variables to be captured by a comprehensive Antarctic Observing Network are described later in this report, including geophysical climate observations and coordinated measurements of diagnostic ecosystem structure and biogeochemical function (see Section 4.4).

Antarctica is an international laboratory for studies of global change and ecosystem responses to environmental variability. In the coming decades Antarctica will continue to undergo significant changes due to human activities. Climate change has already altered the ecosystems of the peninsula, and its impacts may well reach across the continent in the coming century. Increased tourism, overfishing, and other human activities will impose new burdens on the management of Antarctica. Moving forward in the coming two decades, it will be increasingly necessary to come to terms with these possible realities. Yet because of the unity of purpose imposed by the Antarctic Treaty, Antarctica provides the world with the only example of an entire continent reserved primarily for scientific research. A continental-scale, interdisciplinary, observation-prediction-management system will be needed to provide timely data to support decision making, adaptive management, and governance of the continent as the press of human intervention on its climate, natural resources, ecosystems, and biogeochemical cycles becomes ever more intense.

The committee's vision for science in Antarctica in the next two decades is an integrated observing, information, and modeling effort enhanced by powerful new genomic tools, geochemical tracers, and increased modeling efforts to build a predictive understanding of ecosystem response to rapid climate change.

2.4 WHAT ROLE HAS ANTARCTICA PLAYED IN CHANGING THE PLANET IN THE PAST?

Global Context

The interaction between solid Earth tectonics and the changing planet is complex, multifaceted, and tightly connected. On a very long timescale, the movements of tectonic plates (where plates may consist of entire continents and ocean basins), their fragmentation, or the collision of several plates have dramatic consequences. Consequences range from earthquakes and volcanoes to the construction of new mountain ranges, the opening of gateways between vast oceans, and the triggering of global climate shifts. New mountain ranges provide the high topography where glaciers first grow—glaciers that can become the nucleation point for major ice sheets.

In Antarctica these tectonic processes have driven the uplifting of vast reaches of Earth's surface, producing spectacular mountain ranges such as the Transantarctic Mountains that cut across the continent and the Gamburtsev Mountains that are hidden completely beneath the thick cover of the East Antarctic Ice Sheet (Figures 2.12 and 2.13). The tectonic and glacial histories of Antarctica are tightly linked. Without its high topography, the history of the Antarctic ice sheet would have been quite different. Without the continental glaciation the mountains of Antarctica would have been quite different. Understanding the mechanisms and timing of the formation of these mountains is linked to the understanding of the changing climate of Antarctica and of the planet in the past.

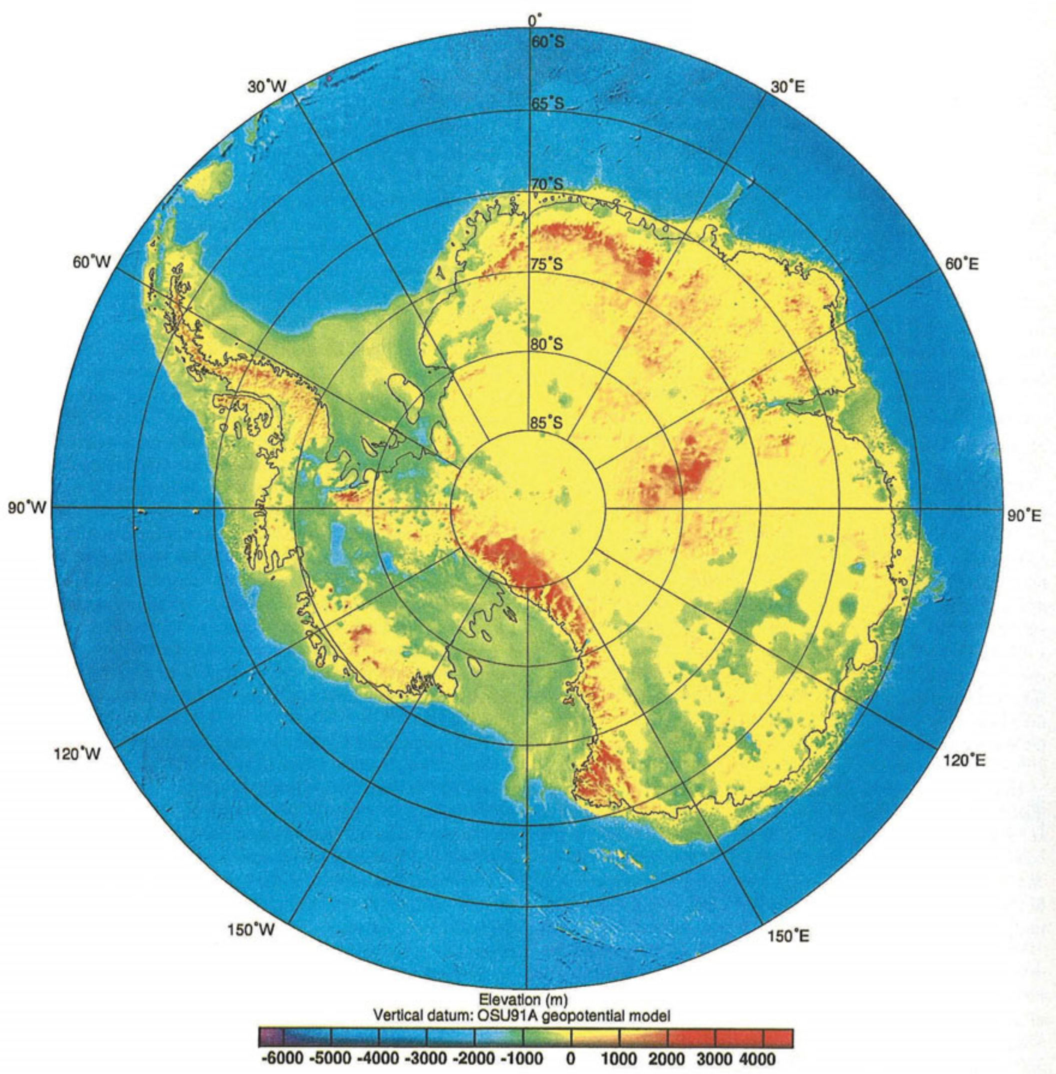


FIGURE 2.12 The tectonic processes that lead to the formation of mountain ranges seen here are linked to the glacial histories of Antarctica. SOURCE: Bedrock elevations relative to sea level from Lythe et al., 2001.

What Is Currently Known About Antarctica's Geologic History?

The tectonic opening of key oceanic passageways has controlled global climate and shifted global circulation patterns within the atmosphere and the deep oceans. Over 200 million years ago, Antarctica was the centerpiece of the Gondwana, a massive

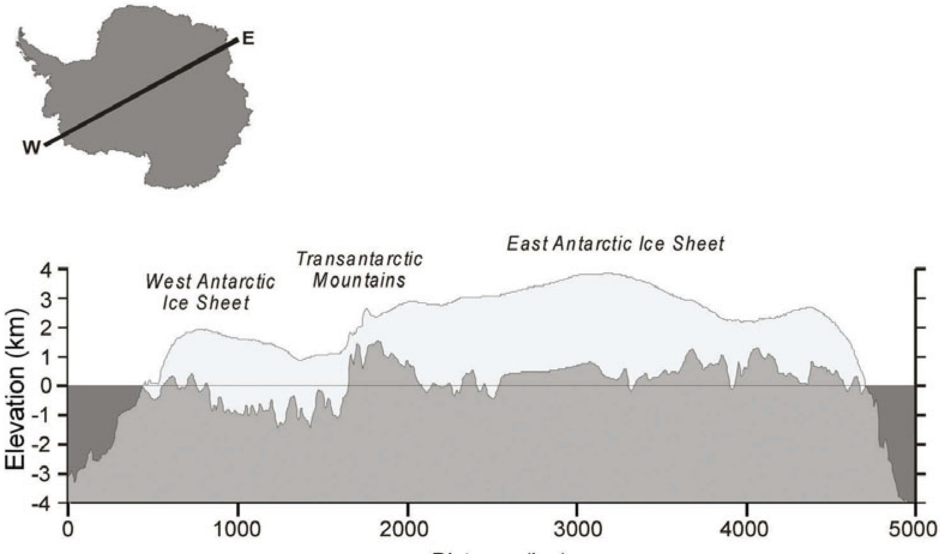


FIGURE 2.13 Cross-sectional profile of the Antarctic ice sheet based on BEDMAP bed topography (Lythe et al., 2001) and surface topography (Liu et al., 1999). The inset indicates the location of profile end points. SOURCE: G. Clarke; NRC, 2007a.

supercontinent consisting of what later became Antarctica, India, Australia, South America, and Africa. Around 180 million years ago, this supercontinent began to break apart, and Antarctica commenced moving into its present polar position. The climate of the planet was significantly different when Antarctica arrived at the South Pole (roughly 100 million years ago). Because of thick ice, there is no knowledge of the geology of most of East Antarctica, but outcrops at the Transantarctic Mountains and along the Antarctic Peninsula, for example, show that at that time lush forests grew there and were inhabited by dinosaurs and mammals (Francis et al., 2008). With the final separation of the supercontinent and the 10-fold drop in global atmospheric carbon dioxide (CO_2) levels from 3,000 parts per million (ppm) in the Cretaceous, to around 500 ppm approximately 34 million years ago, both Antarctica and the globe cooled (Arthur et al., 1988; Jenkyns et al., 1994; Kuhnt et al., 1986). As a seaway formed between South America and Antarctica between 34 and 24 million years ago, the isolation of the southern continent began (see Figure 2.14). The Antarctic Circumpolar Current (see Box 2.4) began circulating and likely reduced the amount of heat that the ocean previously brought from the midlatitudes to the edges of Antarctica. Thus, tectonic fragmentation and falling CO_2 levels shifted Antarctica from a green continent to a white continent encased in ice. Understanding the opening of the Southern Ocean

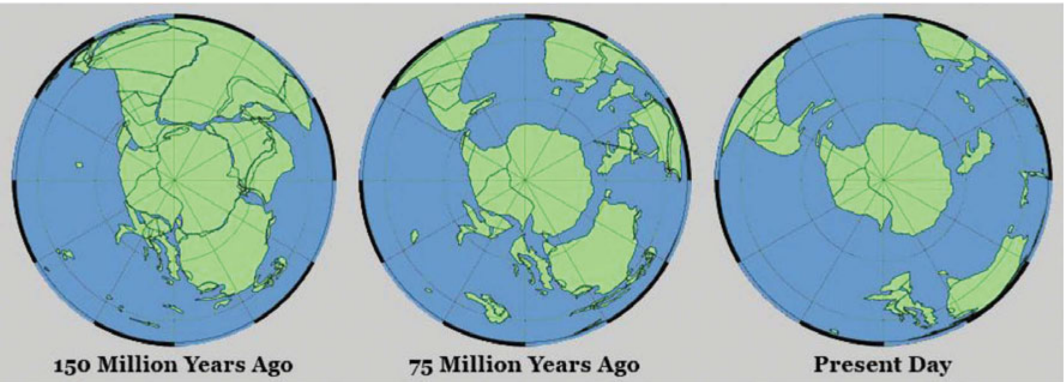


FIGURE 2.14 This figure illustrates (left) the Gondwana supercontinent, (middle) the transition and opening of the oceanic passageway around Antarctica, and (right) present-day geography and bathymetry. SOURCE: ODSN-Geomar.

as Gondwana fragmented is critical to understanding how Antarctica became glaciated and why the global climate became much colder. Researchers have learned much about the processes of past climate change from Antarctic sediment and ice cores. The Antarctic ice cores provide key insights into past changes in the global atmosphere while sediment cores reveal how the ice sheets have waxed and waned in the past (see Section 3.1). This information is crucial to constraining global climate models of the past and of the future.

While ice sheets mantle the entire Antarctic continent and the most dramatic environmental change is being observed along the edges, the crucial location for understanding the mechanisms of how these thick, slow-moving, enormous pieces of ice will change is the interface between the ice and the underlying rock. The presence of water or water-saturated sediments acts as a lubricant to the ice sheet, enabling ice to slide from the center of the continent to the ocean. Subglacial lakes (National Research Council, 2007a) usually formed in rifted basins and are linked to the onset of fast ice flow (National Research Council, 2007a). Tectonically driven heat flow variations are key controllers of basal melting rates and the distribution of subglacial water. Knowledge of the basal conditions—what is happening beneath the ice where ice meets water or solid rock and sediment—is key to understanding ice sheet dynamics and how the ice sheets will move.

Questions for the Future

Projections of future Antarctic ice sheet dynamics depend heavily on acquiring knowledge of what lies below that ice, including the physical properties of the ice column and the properties of ice-rock and ice-sediment interfaces. Constructing useful models of ice sheet and shelf movements to estimate their potential for destabilization will depend on obtaining major expansions of core sampling, annual ice budget measurements, and ice sheet velocity mapping. Without carefully defining basal conditions, especially with respect to how slippery the beds are and how much melt is present at the base of each ice sheet, ice sheet models will not be able to produce reliable estimates of how the ice sheets will change in the future. Contemporary estimates of continental ice movements are shown in Figure 2.15.

Required Tools and Actions

Understanding the role Antarctica has played in global systems over time will require a holistic study of both the thick ice sheets and the underlying Earth crust. Major gaps remain in the fundamental knowledge of the structure of the Antarctic continent. Determining how the continent was formed is one key to understanding the role Antarctica has and will play in the global system. Studies of the base of the ice sheet will require sampling through the thick ice and should include accurate measurements of heat flow. Projections of future changes suggest that warm ocean waters will eventually reach the margins of East Antarctica, an ice sheet that presently appears relatively stable. Key approaches include systematic surface and airborne geophysical observations in both East and West Antarctica along with sampling of the rock beneath the thick mantle of ice. Both studies of the fundamental architecture of the Antarctic continent and essential ice sheet dynamic studies will require airborne radar and laser observations from long-range aircraft complimented by coincident gravity and magnetic field measurements. Sampling the base of the ice sheet and the underlying bedrock requires development of a new generation of rapid drilling systems for access to the bed with minimal contamination of the environment. While much emphasis has been placed on the apparent instability of portions of the West Antarctic Ice Sheet, much of East Antarctica remains absolutely unknown yet is critical to the understanding of the continent and the ice sheets. Regions to be sampled include the enigmatic Gamburtsev Mountains, subglacial lakes, and other major subglacial provinces. Marine drilling targets range from the Weddell Sea coast to new sites in the Ross Sea. Dynamic drilling programs including the Integrated Ocean Drilling Program and Antarctic Geological Drilling have been very effective at determining the climate history of Antarc-

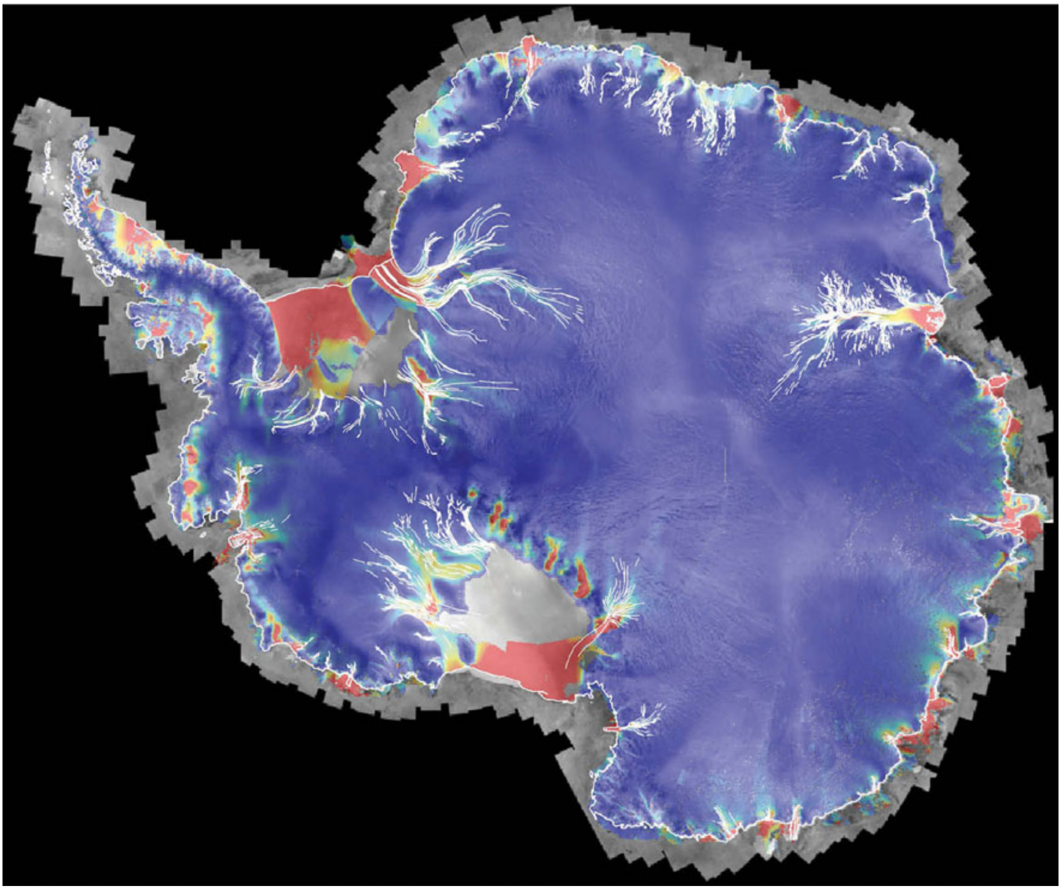


FIGURE 2.15 Composite surface speed of ice from RADARSAT-1. Speed is represented by a color log 10 scale (0 in deep blue to 1,000 m/yr in red). This type of information is crucial to develop reliable ice sheet models. SOURCE: Jezek, 2008.

tica. Ongoing marine geophysical studies of the surrounding oceans including high-resolution marine bathymetry, and marine seismic measurements will be important to examine the mechanisms and timing of prior major tectonic events.

Initiatives to expand knowledge of the geology and glaciology of Antarctica through collaborative international efforts have already begun (Bell, 2008). However, the large scale of the necessary observations and the observing network remains daunting considering the difficult task of diagnosing and monitoring the motions and melting of an ice and land mass that is approximately 1.4 times the area of the United States (British

Antarctic Survey, 2005). In parallel with major advances and expansions in sampling networks, advanced mathematical modeling with understanding of the basic fluid mechanics of the continental ice sheet is needed. Validation activities based upon actual sampling of the ice sheet's properties would improve these models.

In 20 years, the committee envisions that there will be an improved understanding of the tectonic evolution of Antarctica, including the formation of the major mountain ranges, the distribution of key geologic terrains beneath the ice sheets, and the opening of major ocean basins surrounding the continent. Understanding tectonic evolution will inform the understanding of the basal geologic framework and the conditions necessary for developing accurate ice sheet models.

Red lights help maintenance workers doing routine repairs on the South Pole Telescope. SOURCE: Daniel Luong-Van/NSF.

CHAPTER THREE

Fundamental Questions of Scientific Discovery

The voyages to Antarctica by Cook, Scott, Amundsen, and others starting in the late 18th century were fundamentally about discovery. Early explorers wanted to discover whether *Terra Australis,* predicted as early as the second century, existed. In the late 19th century and early 20th centuries, explorers pressed inward on the Antarctic continent to set foot on the magnetic and geographic South Poles and discover more about the nature of this strange and forbidding place. What was under the ice? How did seals and birds live in such extreme climate and weather? And perhaps most important, was Antarctica a place with a future for humans? The hope for treasure, a major impetus for exploration in the Age of Empire, was dashed early: there was no easy way to explore for, and much less to exploit, mineral and other resources Antarctica might hold.

In the middle of the 20th century, it became clear that the strongest reason to continue to explore Antarctica and the Southern Ocean was the acquisition of scientific knowledge. The trigger was a burst of discovery called the International Geophysical Year (IGY) that ran from July 1957 through December of 1958. The headlines of the IGY may not have been as large as those for the first artificial satellites, Sputnik and Explorer I, launched in October of 1957 and January of 1958, respectively. But Operation Deep Freeze, led by U.S. Navy Admiral George Dufek, effectively reopened Antarctica for scientific exploration just prior to the IGY, creating a U.S. scientific presence that eventually evolved into the U.S. Antarctic Program. The IGY proved that international scientific collaboration was possible, and the full manifestation of that vision was the Antarctic Treaty in 1959. With this treaty Antarctica became a continent free from territorial disputes and reserved for scientific research.

Scientific discoveries have followed ever since. A record of the history of the planet's atmosphere has been found trapped in tiny air bubbles inside the ice. New life forms in the ocean and on land have been described. New lakes were discovered underneath miles of ice on the Antarctic continent, including Lake Vostok, with as large an area as Lake Ontario. New information about the Antarctic ice sheet and the sea ice surrounding it has been obtained from satellite-based observations. New insights into the nature of the solar system and the universe have been gleaned from looking out into space from Antarctica.

This chapter highlights several areas of science that will be important in discovery-driven scientific research in Antarctica and the Southern Ocean in the next two decades. As in the previous chapter, this is not an exhaustive list, and each area is represented by an overarching question:

- What can records preserved in Antarctica and the Southern Ocean reveal about past and future climates?
- How has life adapted to stress and changes occurring in Antarctica and Southern Ocean environments?
- What can the Antarctic platform reveal about the interactions between the Earth and the space environment?
- How did the universe begin, what is it made of, and what determines its evolution?

3.1 WHAT CAN ANTARCTICA AND THE SOUTHERN OCEAN REVEAL ABOUT PAST CLIMATES?

Global Context

The rocks, sediments, and ice of Antarctica and the Southern Ocean host a trove of information about the past history of Earth. These records have yielded important discoveries about how Earth's climate has changed in the past. These discoveries have permitted a reconstruction of past climatic conditions and an exploration of their stability and variation across a wide range of temporal and spatial scales. If people are to understand present climate and predict future climate change, then they need to understand how and why climate varied in the past.

These records come from drilling into the rocks, sediments, and ice, as well as from examining the geological features, in Antarctica and the surrounding Southern Ocean. These records reach back to differing points in Earth's history and contain varying types of information. The fossil records in rocks and sediments show the geographic and historical extent of various organisms. Physical and chemical analyses of sediments, rocks, and organisms retrieved from ocean drilling cores provide additional important records of past climate conditions including ocean temperatures, salinity, circulation, and biological productivity. These cores have been drilled beneath the West and East Antarctic ice sheets, beneath floating ice shelves, and across the continental shelf beneath the Southern Ocean. Ocean sediments are an excellent source of high-resolution, long-duration, spatially distributed paleoclimate information (IODP, 2011).

Many of the most important records of Earth's past climate come from ice cores. Studying the composition of the ice and the impurities and gases locked up in the large ice sheets of Antarctica (as well as Greenland) has yielded numerous discoveries about Earth's past climate. Over time, each year's snowfall gets buried and compressed, turning into ice at depth. This ice provides a unique high-temporal-resolution archive of past climate conditions locally, as well as regionally and globally. Chemical and physical measurements are made on samples from the ice cores extracted from the ice sheets, as well as from the gas trapped in tiny bubbles within and between the ice crystals (see Figures 3.1 and 3.2). Typical measurements include past concentrations

FIGURE 3.1 A 1-m-long section of ice core from the West Antarctic Ice Sheet Divide Ice Core; section contains a dark ash layer. SOURCE: Photo by Heidi Roop.

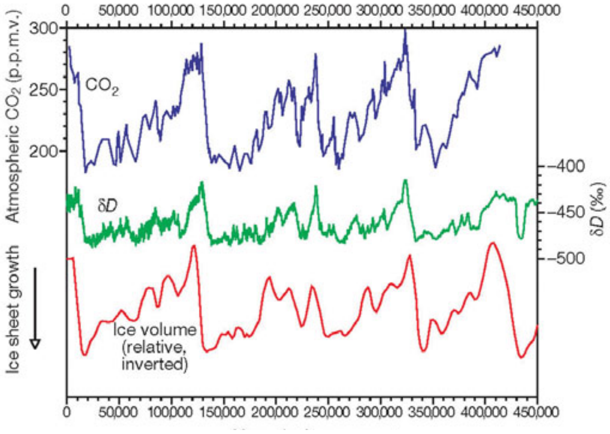


FIGURE 3.2 The history of atmospheric CO_2 back to 420 kyr ago as recorded by the gas content in the Vostok ice core from Antarctica. The ratio of deuterium to hydrogen in ice (expressed as the term δD) provides a record of air temperature over Antarctica. SOURCE: Sigman and Boyle, 2000. Reprinted by permission from Macmillan Publishers Ltd.

of greenhouse gases (such as carbon dioxide [CO_2] and methane [CH_4]), past temperatures (reconstructed from variations in the isotopic composition of water molecules and from englacial temperatures measured in boreholes), and dustiness.

Studying terrestrial glacial geologic features that define glacier boundaries has led to discoveries of the extent of past ice sheets, including limits on ice thickness and the location of the ice sheet margins. These geologic features include trimlines (sharp boundaries on the side of a valley or mountain formed at the upper limit of glacier thickness) and moraines (accumulations of soil and rock formed by glaciers). This research is aided by surface exposure age dating of boulders and exposed rock outcrops. Other terrestrial features such as channels and outwash deposits found in the Dry Valleys provide paleohydrology information. Marine glacial geologic features such as scour and drag marks across the continental shelf indicate the presence of grounded glacial ice and also provide a history of retreat during deglaciation. This information is critical for reconstructing past ice extent and volumes.

What Is Currently Known About Earth's Past Climate?

The longest ice-core record back in time thus far was collected from Dome C in East Antarctica, where a ~3-km ice core was used to reconstruct the paleoclimate for the past 800,000 years. Through this and other long East Antarctic records, scientists have discovered synchronous changes between the Northern and Southern hemispheres over glacial-interglacial cycles and have developed theories on how the climate responds to changes in Earth's orbit, as well as the role of greenhouse gases in driving these changes. Deep ice cores (~1-3 km) collected from West Antarctica, where accumulation rates are considerably higher than in East Antarctica, are also important. These cores provide high-temporal-resolution records (albeit of shorter duration) from a region strongly connected to the tropical Pacific, where ocean-atmosphere dynamic processes such as the Southern Oscillation Index/El Niño cycles dominate. Shallow ice cores, collected along internationally supported traverse routes (such as the International Trans-Antarctic Scientific Expedition) provide century- to millenial-length records at much higher spatial scale and thus provide some of the best insight into the physical mechanisms responsible for past climate variation. Overall, these ice-core records are critically important to understanding the past history of the climate all over the globe.

Spatially, reconstructions of past temperatures primarily reflect past local surface conditions, but records of well-mixed gases extracted from tiny bubbles within the ice provide researchers with one of very few measures of past global atmospheric composition. Given the spatially variable nature of Earth's climate and this mixture of local and global influences on historical records, it is becoming increasingly clear that a single ice core is insufficient to answer outstanding global climate questions. Shallow ice-coring projects have allowed for a much more spatially representative view of natural climate variability during the recent past, as well as reducing the noise inherent in any single record. These records are critical to understanding atmosphere-ocean-ice interaction and predicting future climate. Additionally, multiple boreholes surrounding any new deep ice cores provide greater spatial context, without the need for retrieving multiple deep ice cores at any one location.

Overall, arrays of ice, rock, and sediment cores are needed to reduce the noise inherent in any single core's record and to investigate the spatial nature of past climate variability. Ocean sediment cores in the Southern Ocean have been few in number, such that there is still much to be discovered from further ocean drilling near Antarctica.

Questions for the Future

Significant paleoclimate questions remain to be answered, and many of these questions concerning past climate conditions also have important bearing on understanding and predicting future change. The questions include the following:

1. How warm was Antarctica in the past, and what was the role of greenhouse gases in initiating and/or amplifying this warming? Are such conditions expected to recur in the future?
2. What caused East and later West Antarctica to glaciate? Is there evidence for their (potentially rapid) collapse in the past, and under what climate conditions did it occur? How stable are the Antarctic ice sheets, particularly the marine-based portions of the East and West Antarctic ice sheets? Past sea level reconstructions from corals and paleoshorelines suggest that extremely rapid rises and falls of sea level have occurred over very short periods of time, indicating dynamic ice changes.
3. How quickly has Antarctic ice melted in the past? Does this provide any insight into how quickly Antarctica will respond to present and future climate perturbations? Growing scientific evidence points toward a much higher sea level during the previous interglacial period (the Eemian) with recent estimates in the range of 5-6 m above the present sea level. However, the source of this water is unknown. Since 5-6 m is more than the entire amount of ice presently stored in Greenland and in mountain glaciers around the world, this large a quantity suggests a significant component had to have come from melting

somewhere in Antarctica. Sea level was even higher prior to 2.6 million years ago, during the Pliocene, implying an even smaller Antarctic ice sheet at that time. What climate conditions caused the ice sheet to be smaller? Will similar conditions be approached in the future, and should major Antarctic melting be expected in the future? And if so, when?

4. About 800,000 years ago, the mode of climate variations changed from a regularly cycling climate (a glacial and interglacial climate every 40,000 years) to a climate in which larger ice sheets grew and then quite rapidly collapsed over intervals of about 100,000 years. From analysis of Antarctic ice cores, atmospheric CO_2 levels are known to closely track the global temperature and ice volume during the past 800,000 years; but why did glaciation vary with a different period earlier? And did atmospheric CO_2 levels follow suit? To answer these questions, longer records of atmospheric CO_2 are required. This information may be obtainable from older Antarctic ice, if it can be found and measured. Estimates of the oldest ice in Antarctica range from ~100,000 years in much of West Antarctica, to ~1.5 million years deep in the East Antarctic interior, to possibly older ice buried in isolated locations in the Antarctic Dry Valleys and elsewhere.

Required Tools and Actions

Answering these basic questions (and others yet to be posed) will require an ambitious program of ice-sheet and sediment drilling, as well as near-continent sediment sampling by scientists over the next 20 years. For ocean sediments, expanding paleoclimate knowledge will require both shallow and deep coring. For ice cores, a combination of deeper ice cores, multiple arrays of shallow cores, and borehole geophysical logging will be required. This will require a substantial scientific and technical effort supported by complex logistical efforts, including the design and construction of new equipment for both drilling and boring into ice. The isolated position and harsh climate of Antarctica provide compelling reasons for trying to make the novel drill designs lighter, faster, more efficient, and more robust than systems used in the past. Not surprisingly, many other countries are also investing significant time and resources into ice coring with similar goals and constraints. The United States would benefit by evaluating other models of supporting ice-coring activities, as well as supporting more international collaboration in the design and implementation of this new technology moving forward. Site selection for deep ice coring could be improved by first drilling an access borehole in a reconnaissance mode to test expected age-depth profiles and determine whether the base of the ice is wet or frozen. Multiple coring and borehole projects supported simultaneously have the opportunity to make more substantial scientific progress over the next two decades than the current field research model of supporting a single deep drilling site once every 10-15 years. Gathering more paleoclimate information from ice and sediment cores is crucial for understanding Earth's past climatic shifts, which is one of the best ways to understand how future shifts could occur.

3.2 HOW HAS LIFE ADAPTED TO ANTARCTICA AND THE SOUTHERN OCEAN ENVIRONMENTS?

Global Context

The Antarctic Ocean and continent pose extreme challenges for organisms to survive there, from bacteria and fungi to plants and vertebrates. In mammals and birds, low air temperatures and high wind speeds make maintaining body temperature challenging. Low seawater temperatures and prey availability at great depths require mammalian and avian species to develop the ability to dive deeply and simultaneously tolerate long-breath-hold dives without getting the bends. Only a small number of mammalian and bird species have been able to adapt and prosper in this harsh environment. The evolutionary adaptations of body shape, composition, cardiovascular adaptations, and metabolism of these vertebrate species have been vital for their survival and are just beginning to be understood. They also hold the keys to the genetic basis for successful biochemical and physiological strategies that allow them to tolerate hypoxia (low oxygen levels), survive hypothermia (low body temperature), and avoid a host of other important pathological problems that plague humans—such as premature and blue babies who are hypoxic, adults with heart attacks and strokes, or drowning victims. How life tolerates these extremes in Antarctica can have important implications for human well-being including treating and preventing human diseases, engineering frost-resistant plants (e.g., making agricultural commodities thermostable and cold tolerant), and developing thermostable products (everything from ice cream to vaccines and organ transplants). See Box 3.1.

In addition to learning about birds and mammals to gain understanding of humans, knowledge of the lifestyles of some seals and penguins that travel long distances and dive to great depths can be used to gather data on ocean variables. For example, Southern Elephant seals, when instrumented with miniaturized sensors, can obtain environmental data at places and depths (>900 m) where ships or submarines have difficulty traveling (see Appendix C). Adélie penguins make daily foraging trips into submarine canyons that are climate-sensitive hotspots of biological activity. By taking advantage of these marine mammals and birds, measurements of salinity, tempera-

BOX 3.1 FISH ANTIFREEZE AND ICE CREAM

An example of adaptation to extreme environments is the Antarctic ice fish, *Macropteris maculates*, that uses an antifreeze protein in its blood to live in freezing waters. The presence of the protein influences nearby water molecules and prevents potentially harmful ice crystals from growing. By lowering the freezing point of the body fluids and tissues of the fish, the protein enables the fish to survive despite temperatures that would otherwise freeze the blood. Some manufacturers have taken advantage of this unique property and synthesized the protein for use in low-fat ice cream production. The protein is used to enhance the taste and texture of the ice cream while minimizing the fat content. It helps to maintain the structure of the ice cream and inhibits partial thawing by preventing ice crystallization. This process has led to the improvement of taste-test ratings as well as a dramatic increase in sales of light ice cream.

ture, and other variables of oceanographic interest can be recorded and transmitted to polar orbiting satellites when the seal or penguin surfaces. Data from these animals are especially important because they frequent the areas of greatest food productivity. The Antarctic research fleet is inadequate to access regions deep in the winter sea ice and investigate one of Earth's largest and least-studied ecosystems. These are examples of the potential knowledge to be gained from the many organisms living in this extreme environment.

On the Antarctic continent, there are the many reminders that Antarctica is a polar desert, including the freeze-dried, mummified remains of seals in the Dry Valleys that have been preserved for decades. The fast rates of sublimation, low relative humidity, and high winds make Antarctica the driest desert on earth. Similar to any desert, organisms in Antarctica use many types of survival strategies to conserve water and metabolic activity. A few plant species and a variety of organisms (bryophytes, algae, lichens, microarthropods, nematodes, rotifers, tardigrades, fungi, protozoa, and particularly bacteria and Archaea) experience cold temperatures, long periods of darkness, and additional environmental stresses (climate change, habitat change, etc.) in addition to desiccation. How do they survive in this harsh environment and how will they adapt to new stresses? Analyzing the structural, physiological, biochemical, and genetic aspects of multiple stress tolerance provides a basis for comparative studies and a means to examine the complexity and evolution of ecological communities.

What Is Known About How Living Things Adapt to Life in Antarctica and the Southern Ocean?

Beyond the fundamental biology, physiology, genomics, and evolution of a few remarkable individual organisms, scientists remain surprisingly ignorant about community composition, population interactions, trophic exchanges, and functioning of the many organisms inhabiting sea ice, glaciers, and inland terrestrial and aquatic ecosystems. Antarctica, with relatively simplified species assemblages and ecosystems near the physiological tolerance limits for life, provides an unparalleled opportunity to probe the laws of community assembly, species interactions, and ecosystem responses to climate variability. Exploring the diverse array of ecosystems, ranging from the ultraoligotrophic (extremely deficient in nutrients) subglacial lakes and dry nunatak soils near the Beardmore Glacier to the luxuriant phytoplankton blooms at the sea-ice margins, provides the opportunity for a new understanding of ecosystem ecology and biogeochemistry. For example, bacteria that are actively metabolizing were detected under an inland Antarctic glacier in a permanently cold, dark, oxygen-starved, and sulfate-rich ancient marine brine. These bacteria convert iron compounds, thereby creating energy and food (Mikucki et al., 2009).

Microbes exist in a wide range of environments in both the soil and the water. A systems biology approach, involving the study of systems of biological components such as nucleic acids, proteins, cells, organisms, or entire species, will promote a fully integrated understanding of polar organisms. A systems biology approach is warranted because the behavior of dynamic and complex living systems may be hard to predict from the properties of individual parts. Combining the results of metagenomics, metatranscriptomics, metaproteomics, and metabolomic studies in mathematical and computational models will allow scientists to describe and predict dynamic behavior in polar microbial communities, leading to a fully integrated understanding of polar microbial biology.

What Can Antarctica Reveal About Life in Other Environments on Earth and Beyond?

Not only can the survival mechanisms of life in Antarctica teach us about the world and provide insights for improving the human condition, but also studies of Antarctic life can provide a window from which to search for life elsewhere in the universe, especially the solar system. The McMurdo Dry Valleys have long been considered the best terrestrial analogue for Mars (Doran et al., 2010). The recent Decadal Survey for Planetary Science (National Research Council, 2011f) notes that the Dry Valleys "have many features that make them plausible analogs of a younger, warmer, wetter Mars" and calls for continued support for such research by the Office of Polar Programs. Continued research in Antarctica will provide important information that could help in the selection of a sampling site on Mars, as well as insight with respect to analysis of Mars samples to identify signatures of life.

Similarly, the discovery that many of the moons of the outer planets have oceans under a shell of ice has raised the possibility that life may exist in those oceans (National Research Council, 2011f). An example is Europa, one of the moons of Jupiter. The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) are planning a joint mission, the Europa Jupiter System Mission, with a tentative launch date of 2025 to explore the system. Saturn's moon Enceladus has sufficient internal heat to drive geysers that have been observed by Cassini (Porco et al., 2006), and the recently released Planetary Science Decadal Survey (National Research Council, 2011f) listed an Enceladus Orbiter as a high-priority mission. Although there is no current plan to land on Europa and sample the subsurface ocean directly, a future mission to do so has been discussed by the scientific community and popular press. Subglacial Antarctic lakes (National Research Council, 2007a), including the 14-million-year-old liquid Lake Vostok that lies beneath about 12,300 ft of ice and may soon be accessible to scientists, represent important analogs and testbeds for a future Europa mission. More to the point, however, sampling subglacial lakes will provide access to early life forms frozen in time. For research and discovery, these remote and unique ecosystems are free from human contact and provide a testbed for determining feasibility, strategy, and instrumentation not only for the Mars mission, but also for knowledge of the life history of planet Earth.

Questions for the Future

Recent advances in nucleic acid sequencing technologies have enabled researchers to embark on the systematic prospecting of genomes for features that helped shape evolutionary divergence and that will advance biomedical and biological science. Taking advantage of these new technologies for Antarctic exploration and for advancing knowledge of the past and future world was detailed in a series of recommendations in the report *Frontiers in Polar Biology in the Genomic Era* (National Research Council, 2003). The opportunity to discover new knowledge of the biology and ecology of Antarctica at the genomic level over the next two decades is immense. Since the initial sequencing of the human genome a decade ago, the speed of advance in DNA sequencing has increased dramatically, resulting in significant decreases in cost. These advances could eventually permit genomic analysis of all life forms living in Antarctica, especially the microbes. DNA sequencing will provide a foundation from which to launch studies of proteins and metabolic systems and determine if life in Antarctica requires shared common survival strategies. Is there a unique coding of the genomes of Antarctic-adapted life forms?

In one example, the genome of the Weddell seal, a deep-diving Antarctic seal, is now being sequenced. Information on adaptation strategies can also have implications for humans. For example, how does the Weddell seal genetically code for its enormous blubber layer, to provide insulation from the Antarctic cold? Will this provide clues to the basis of human obesity? How does it stop the production of facial sinuses (the Weddell seal has no sinuses, thereby allowing tolerance to great seawater pressures)? How does the Weddell genetic code allow it to tolerate the prolonged periods of ischemia (restriction of blood flow) and hypoxia in its prolonged dives?

Proteomics, the large-scale study of the structure and function of proteins, will provide vital information about how bacteria, protists, animals (vertebrates and invertebrates), and plants adapt to and function in the extreme climates of Antarctica. Proteomic studies involve mRNA transcript analyses, protein turnover measurements, protein structure determinations, and posttranslational modification catalogs. Understanding how organisms have adapted to the extreme conditions of Antarctica requires defining the structures of their proteins and identifying metabolic specificities. This will require next-generation infrastructure for sequencing, computational analyses, and bioinformatics to decipher similarities and differences in Antarctic species occupying extreme habitats. These investigations will be central to understanding the physiology of metabolic pathways of cells under extreme environmental conditions of Antarctica.

Genomic, proteomic, and metabolomic studies allow scientists to address how changes in temperature and seawater chemistry, associated with rising atmospheric CO_2, affect a host of biological processes in individual organisms and communities of protozoans and metazoans. The results of these studies may assist in predicting the effects of rising CO_2 levels and temperatures on polar biology and the capacity of polar ecosystems to adapt to future environmental conditions that are driven by climate change (Hofmann and Todgham, 2010). Several mechanisms have been identified in humans that prompt genomic instability, thereby allowing the occurrence of more frequent mutations and genomic plasticity. These mechanisms include the presence of trinucleotide repeats and transposons. Relatively recent data suggest that similar mechanisms are also present in polar organisms. For example, both repetitive elements (NOTO-1) (Parker and Detrich, 1998) and transposon-like elements (LINEs) (Kazazian and Goodier, 2002) were discovered in Antarctic notothenoid fish. Also microbial populations, characterized by large population sizes and short generation times, may respond to CO_2 enrichment through genetic change. Whether Arctic- or

Antarctic-adapted organisms have enough genomic plasticity to adapt to future conditions remains to be determined. It is anticipated that the continued effort to apply genome sciences in polar biology will expand knowledge of the genomic plasticity of both Arctic and Antarctic organisms.

Required Tools and Actions

To advance understanding of the fundamental biology of organisms from bacteria to mammals, and how they function in the Antarctic ecosystem, new tools and infrastructure for exploration and discovery will be essential to identify the diversity of life and its functioning in the extreme environment of Antarctic glaciers and oceans. Examples include the following:

- Ice coring and ultraclean sampling technologies for subglacial lakes and other under-ice environments;
- Sensor networks for environmental monitoring and recording animal behavior and migration;
- Remote sensing to monitor vegetation and land expansion;
- Genome surveys and sequencing technology—A Census of Antarctic Life that builds on the Census of Antarctic Marine Life to include life in sea ice, glaciers, permafrost, terrestrial, and aquatic ecosystems; an initial focus on metagenomics would be most fruitful;
- Extensive upgrades of lab facilities to accommodate the newest technologies and advanced analytical facilities for genomics, metagenomics, proteomics, and metabolomics; the volume of sample processing and analysis will demand on-site analyses; on-site analysis becomes necessary to avoid the dissipation of metabolic function or other problems that can occur if samples are frozen and then analyzed weeks after collection;
- Increased communications capability—larger bandwidths for data transfer from sensor networks in real time (for example, for sensors placed temporarily on Antarctic vertebrates transmitting to polar orbiting satellites, and for environmental data and genetic information from instruments in the field);
- Infrastructure to conduct manipulative experiments in the field (see Box 3.2).

The genomic era has only just begun for Antarctic biology. The advent of new tools for exploration into Antarctic ecosystems is both exciting and challenging. Over the next 20 years, many species in Antarctica will have their DNA decoded, which will allow comparison of temperate species with Antarctic species. The genetic information for Antarctic species adaptations can then be analyzed for physiological adaptations to

BOX 3.2 CONTROLLED ECOSYSTEM EXPERIMENTS

A hallmark of modern ecology has been manipulative experiments conducted at the ecosystem scale to identify, in a controlled experimental way, the principal factors causing ecosystem change and to determine impacts of climate and biodiversity change on ecosystem performance and ecosystem services. Famous examples include soil warming experiments at the Harvard and Duke Experimental Forests, biodiversity manipulations in several other research reserves, and iron enrichments at various ocean sites (Melillo et al., 2002; Peterjohn et al., 1993). Because of severe logistic obstacles and prohibitions imposed by the Antarctic Treaty, such approaches at this scale have seldom been performed in Antarctica. In order to gain mechanistic understanding of how global changes will affect Antarctic ecosystems, infrastructure is needed to carry out hypothesis-driven experiments at the scale of a landscape or ecosystem in strategically selected locations such as the Dry Valleys or penguin rookeries. Scientific rationales and potential impacts will have to be carefully described to gain permission under treaty provisions for such large-scale studies. Antarctic Specially Managed Areas such as those near Palmer Station are ideal for such frontier scientific research.

Diana Wall discusses research in the Dry Valleys. SOURCE: C. Elfring.

hypoxia, hypothermia, and tolerance of the physical effects of deep diving. It will be useful to learn if humans have evolved similar genetic strategies.

Survival strategies that have evolved in Antarctic life forms provide information useful for understanding species diversity and functioning in other ecosystems (deserts, freshwater, oceans, and cold climates), dispersal and distribution of microorganisms when soils erode and ocean circulation changes, and new mechanisms for preservation of perishable food, human organs and tissues for transplantation, and other cryogenic applications. Molecular aspects of desiccation and freezing tolerance have just begun to unfold, and very little genomic data are available on extremophiles. Third-generation sequencing technologies will quickly fulfill the potential to detect in situ changes in the genetic response (functional genes and gene product expression) of biota (short and long term, and across multiple spatial scales) in Antarctica. Over the next 20 years, metagenomics will allow comparison of functional genes and exploration of habitats where life had not been expected to exist.

3.3 WHAT CAN THE ANTARCTIC PLATFORM REVEAL ABOUT THE INTERACTION BETWEEN THE EARTH AND THE SPACE ENVIRONMENT?

Global Context

Space weather refers to changes in the space environment and how those changes impact an increasingly technologically dependent civilization. The level of radiation, both electromagnetic (such as x-rays) or particulate (such as energetic protons), can change dramatically on short timescales, and those elevated radiation levels can damage spacecraft systems, pose hazards to astronauts, or even produce changes in the ionosphere that impact radio communications. Earth's magnetic field can be disturbed by its interaction with the varying solar wind, which is driven in turn by varying solar activity. These magnetic disturbances are known as magnetic storms and can impact critical systems both in space and on Earth (see Figures 3.3 and 3.4).

As society becomes more dependent on space-based technologies, we become more vulnerable to severe space weather events, which now have the possibility of disrupting large parts of society's infrastructure. A 2008 National Research Council report, *Severe Space Weather Events: Understanding Societal and Economic Impacts* (National Research Council, 2008), detailed how an event similar to the "Carrington event" of 1859, which caused visible auroras all over the globe, could result in trillions of dollars in damages if it were to happen now. Such an event would damage not only satellites

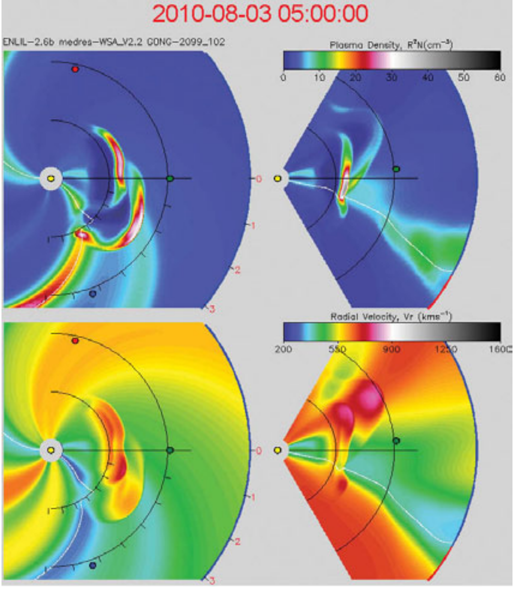
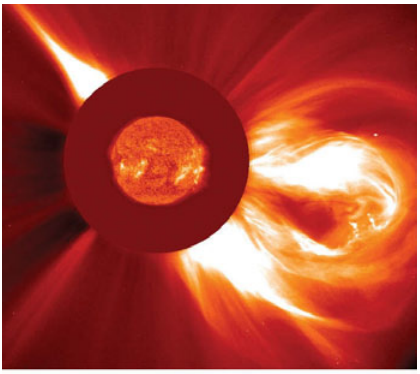


FIGURE 3.3 The solar system display for the solar wind plasma model developed by the Center for Integrated Space Weather Modeling and now in operation at the Space Weather Prediction Center. The figure shows the prediction of coronal mass ejections on their way from the Sun to Earth. The Sun is the yellow dot and Earth is the green one. The left-hand panels show the view looking down on Earth's orbit; the right-hand panels show the view from behind Earth as it moves away from the observer in its orbit. SOURCE: National Oceanic and Atmospheric Administration (NOAA).

FIGURE 3.4 A composite image from the Solar & Heliospheric Observatory satellite (a joint NASA/ESA mission) showing a coronal mass ejection blasting out into space. Such events produce environmental changes that are termed "space weather." SOURCE: NASA.



but also power grids on the surface, possibly leaving many areas of the United States without electric power for months.

In order to predict space weather it must first be understood. Significant progress has been made in the decades since the discovery of the Van Allen radiation belts in the 1950s, fields of high-energy particles (mainly protons and electrons) held in place by the magnetic influence of Earth, but much work needs to be done to be able to create predictive models that produce the information users need, such as being able to predict when Global Positioning System (GPS) information (see Box 3.3) could be lost. The vision of the space science community is that in 20 years science will have developed the knowledge needed to protect our space-dependent civilization from harm.

Antarctica can play a critical role in realizing that vision, both in scientific research and the application of that research to operational systems for space weather monitoring and prediction. Antarctica provides a unique platform for space weather research and monitoring because, unlike the oceanic Arctic, year-round ground-based observations from areas across the Antarctic continent are possible. From Antarctic vantage points one can sample the footpoints of magnetic field lines that reach out in the solar wind, throughout near-Earth space where satellites fly, and into the distant magnetotail where solar wind energy is episodically stored and released through processes still

BOX 3.3 SPACE WEATHER AND THE GLOBAL POSITIONING SYSTEM

The Global Positioning System, or GPS as it is popularly known, has emerged as a major piece of technological infrastructure that is critical to national security, industry, and commerce. The use of GPS-guided munitions has revolutionized warfare, allowing for much more precise delivery of those munitions to their targets. GPS has also had an enormous impact on a wide variety of industries, from agriculture (tractor guidance, cropduster targeting, tracking livestock, etc.) to oil drilling (precise guidance of drills). GPS is also widely used by ordinary people for navigation, as almost all smart phones have GPS capabilities.

GPS works by using simultaneous radio signals from several near-Earth-orbiting spacecraft to pinpoint the position of the receiver. Each spacecraft broadcasts its position and the time at which the signal is sent. Based on the difference between the time lags to several spacecraft (a minimum of four is needed), the receiver is able to triangulate its position. Because of the large value of the speed of light, small time errors can lead to large spatial errors. As a consequence, GPS requires corrections from general relativity and from the varying speed of light as electromagnetic waves pass through the ionosphere. The ionospheric corrections are calculated based on typical ionospheric conditions. But space weather can produce significant departures from those conditions, leading to significant GPS errors. The ability to predict natural variations in the ionosphere that would lead to significant errors in GPS information is a major objective for the Space Weather Prediction Center.[a] Reaching this objective will require data assimilative modeling. Antarctic observations will be important both in the basic research needed to create the models, as well as (eventually) providing operational, real-time, ionospheric diagnostic data that the models will require.

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[a] See *http://www.swpc.noaa.gov*.

not completely understood. Moreover, Antarctica provides a platform for polar satellite communications hardware that will be necessary for real-time operational data delivery.

Questions for the Future

In looking to the next two decades, the two top priorities for space weather prediction are determining the distribution and intensity of geomagnetically induced current that can damage the electrical power grid and predicting the loss of GPS information due to ionospheric disturbances. Antarctica can play an important role in this work by providing the measurement platforms (radar, ionosonde, riometer, magnetometer, all-sky camera) for data collection, which can then be used in model validation and data assimilation modeling. Another space weather objective is to further the understanding of the acceleration processes that create the radiation belts. Characterizing the near-Earth radiation environment is likely to take on increased importance in the next 20 years. NASA's Radiation Belt Storm Probes (RBSP) will study this problem, and it will have an Antarctic component in the Balloon Array for RBSP Relativistic Electron Losses (BARREL) mission. Looking further ahead, understanding the solar cycle and long-term solar variations is a critical question for a space-based civilization.

Required Tools and Actions

Space weather modeling, following the lead of tropospheric weather prediction, is beginning to incorporate techniques such as ensemble and probabilistic forecasting, and data assimilation.[1] The latter requires a high density of observations (such as full coverage of the Antarctic ionosphere from incoherent scatter radars) that expanded instrumentation of Antarctica would provide. Antarctic data would provide a crucial component of a more capable National Weather Service capacity for space weather monitoring and prediction. Incoherent scatter radars can provide a global diagnosis of the southern polar ionosphere, and comparisons between northern and southern polar cap dynamics can provide crucial information for validating simulations. The high polar plateau of Antarctica is the only site where studies of the magnetosphere have the potential to learn how to protect the stability of electronic devices and technology (e.g., GPS and satellite communication) upon which society so heavily now depends.

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[1] See NOAA's Space Weather Prediction Center (*http://www.swpc.noaa.gov/*) and the National Science Foundation's (NSF's) Center for Integrated Space Weather Modeling (*http://www.bu.edu/cism/*).

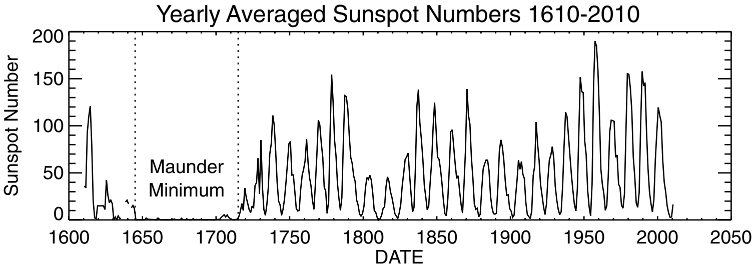


FIGURE 3.5 This figure illustrates the yearly averaged sunspot numbers from 1610 to 2010. The Maunder Minimum is a period of low sunspot activity in the late 17th century. SOURCE: D. Hathaway, NASA Marshall Space Flight Center.

Finally, there is much that is not understood about the role of solar variability in producing climate variability. The Maunder Minimum (Eddy, 1976) (Figure 3.5) and its role in the Little Ice Age is still a subject of considerable debate. The bulk of the 17th century was a period of very suppressed solar magnetic activity that was coincident with a period of cool temperatures in Europe and elevated cosmic rays; this was due to the weak solar magnetic field that shields the heliosphere from the galactic cosmic ray flux. Long-term cosmic ray and atmospheric observations made in Antarctica can provide important data to study whether there is in fact a link between cosmic ray flux and climate. This will be particularly important in the coming decades given the very weak solar cycle (solar cycle 24) that may signal the end of the Modern Maximum and the beginning of a minimum in sunspot activity. Coupled with an increased understanding of solar behavior and the evolution of the solar cycle, the committee believes that in 20 years this question can be definitively answered.

3.4 HOW DID THE UNIVERSE BEGIN, WHAT IS IT MADE OF, AND WHAT DETERMINES ITS EVOLUTION?

Global Context

Scientists working at the Amundsen-Scott South Pole Station are pursuing answers to the most fundamental questions of our origins—questions that have been asked since the dawn of civilization. How did the universe begin? What is it made of? What determines its evolution and what is its ultimate fate?

Scientists are also pursuing answers to the questions at the frontier of physics and particle astrophysics: How do cosmic accelerators work, and what are they accelerating? What is the dark matter that holds the galaxies together? New instruments have opened up an entirely new window on the universe in the form of neutrino astronomy.

Antarctica plays a unique and pivotal role in the pursuit of these questions by providing exceptional atmospheric conditions—high, cold, dry, and stable—for viewing the fossil light from the Big Bang and the cosmic microwave background radiation, and by providing the large volumes of exceptionally transparent and stable ice for detecting high-energy neutrinos from space (see Box 3.4).

What Is Known Now?

There are many important research directions in astrophysics, but two of the most exciting fields in which Antarctica offers unique opportunities to advance over the next two decades are the understanding of the origin and evolution of the universe through measurements of the cosmic microwave background and the exploration of the high-energy universe through neutrino astronomy. These fields are also highlighted in the recent Astronomy and Astrophysics decadal report (National Research Council, 2010c).

The Cosmic Microwave Background

The cosmic microwave background (CMB) radiation provides a pristine view of the early universe as it was nearly 14 billion years ago, roughly 380,000 years after the Big Bang. The physical processes that shaped the universe, from its first instants to the present day, are imprinted on the intensity and polarization distribution of the background radiation.

The discovery of the CMB in 1965 (Penzias and Wilson, 1965) provided overwhelming evidence that the universe evolved from a hot dense state, the Big Bang. This has had an enormous impact on the understanding of the universe. The importance of the discovery was recognized with the awarding of the physics Nobel Prize in 1978. Remarkably, the intensity of the background is so uniform across the heavens, that it took almost three decades before maps of sufficient sensitivity to detect any spatial variations were obtained. Results from the Cosmic Background Explorer (COBE) satellite in 1992 showed the structure in the background is at a level of only 1 part in 100,000 and its spectrum is that of a thermal blackbody at a temperature of 2.725 ± 0.001 K (Fixsen and Mather, 2002). (The COBE team leaders John Mather and George Smoot received the physics Nobel Prize in 2006.)

BOX 3.4 WHY MAKE ASTRONOMICAL OBSERVATIONS FROM ANTARCTICA?

The high Antarctic plateaus provide exceptional atmospheric conditions—high, cold, dry, and stable—for viewing the cosmos from infrared to millimeter wavelengths (see excellent review of Antarctic atmospheric site testing by Burton, 2010). At these wavelengths the dominant contribution to atmospheric opacity is water vapor. As water vapor is not well mixed in the atmosphere, astrophysical measurements suffer further from the spatial and temporal fluctuations of atmospheric noise. This is referred to as "sky noise" and is often the dominant source of noise in large-scale astrophysical maps made at these wavelengths. Because of the extreme cold and high altitude of the Antarctic plateaus, even if the atmospheric water vapor is saturated the net amount of water, that is, the precipitable water vapor (PWV), is extremely low, leading to consistently good atmospheric transmission (see figure). Furthermore, the extreme cold, the low wind velocities, and the lack of diurnal solar heating lead to extraordinary stable atmospheric conditions that should result in very low sky noise at millimeter wavelengths. In fact the sky noise at the South Pole has been shown to be at least an order of magnitude better than at other established terrestrial sites (Bussmann et al., 2005; Sayers et al., 2010), and it is expected to be better still above the higher domes (e.g., Dome A).

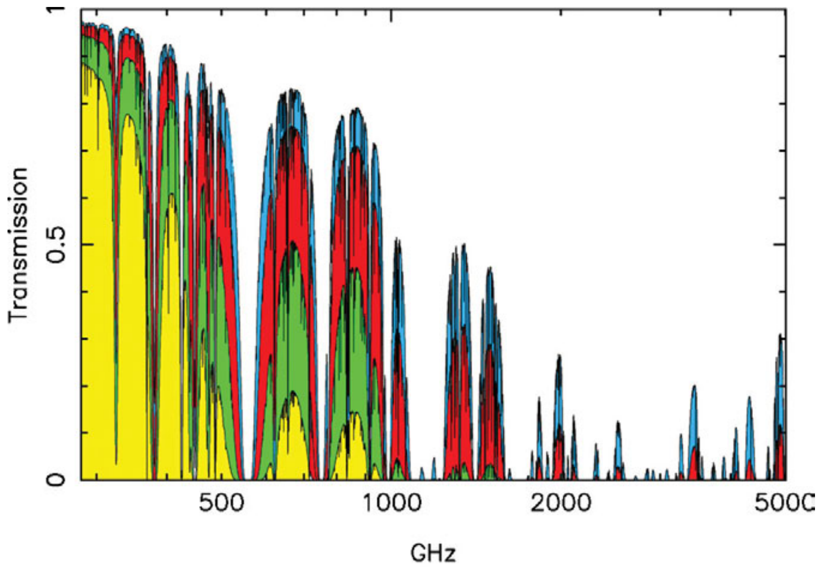
At optical and near-infrared wavelengths, spatial and temporal atmospheric temperature fluctuations lead to degraded resolution or "seeing" due to the distortions to the wave front of the light as it passes through the turbulent air (e.g., the twinkling of stars). Unlike the midlatitude sites with high, fast-moving jet streams overhead, the dominant source of atmospheric turbulence above the Antarctic plateau is near the ground, caused by the katabatic winds and the ground-level inversion layer driven by the radiative cooling of the surface. Above this low layer (only tens of meters at the highest sites; Swain and Gallee, 2006), exceptional "seeing" conditions prevail (Agabi et al., 2006). Furthermore, since the turbulent layer is so close to the telescope, simple tip-tilt adaptive optics systems are able to provide corrections over a large field of view. The extreme cold also leads to an order-of-magnitude reduction in the atmospheric brightness at near-infrared wavelengths compared to good midlatitude sites (Phillips et al., 1999).

Last, the geographical location also leads to unique observing capabilities. For example, astronomical objects viewed from the South Pole never rise or set but remain at the same elevation, allowing exceptionally long, deep, and uniform observations.

Over the past two decades the push has been to obtain increasingly sensitive measurements of the intensity and polarization of the cosmic microwave background. Observations from the Amundsen-Scott South Pole Station (see Figure 3.6) and from the long-duration high-altitude balloons launched from McMurdo Station have been at the forefront.

From measurements of the cosmic background and measurements made at other wavelengths, scientists now have a cosmological model that accounts for the properties of background radiation measurements, as well the vast range of structure

BOX 3.4 CONTINUED



Atmospheric transmission plot from 300 to 5,000 GHz, or 1,000 to 60 µm, for medium winter conditions on Mauna Kea: 270 K, 620 mbar, and 1.5 mm PWV (lowest curve, in yellow); the Atacama plain: 260 K, 525 mbar, and 0.6 mm PWV (green); Dome A: 200 K, 550 mbar, and 0.14 mm PWV (red), and the best 10th percentile conditions at Dome A: 0.07 mm PWV (top curve, in blue). Transmission in Antarctica is significantly better than in other locations. SOURCE: Yang et al., 2010.

observed in the universe. This cosmological model for the origin and evolution of the universe is beautifully simple and has profound implications for new physics and our place in the universe. A pictorial overview of the model is shown in Figure 3.7.

In this model, the first instants (~10^{-35} seconds) of the universe began from a sub-atomic region of space-time at extraordinarily high energy. This space exponentially expanded faster than the speed of light to produce a universe much larger than can be observed currently. This explanation accounts for the isotropy of the background radiation, that is, the fact that background radiation reaches Earth uniformly from all

FIGURE 3.6 A C-130 aircraft taking off near the telescopes at the NSF Amundsen-Scott South Pole Station. These telescopes exploit the extraordinary transparent and stable atmosphere at millimeter wavelengths to map the intensity and polarization of the cosmic microwave background radiation to investigate the origin and evolution of the universe. SOURCE: Photo by Steffen Richter.

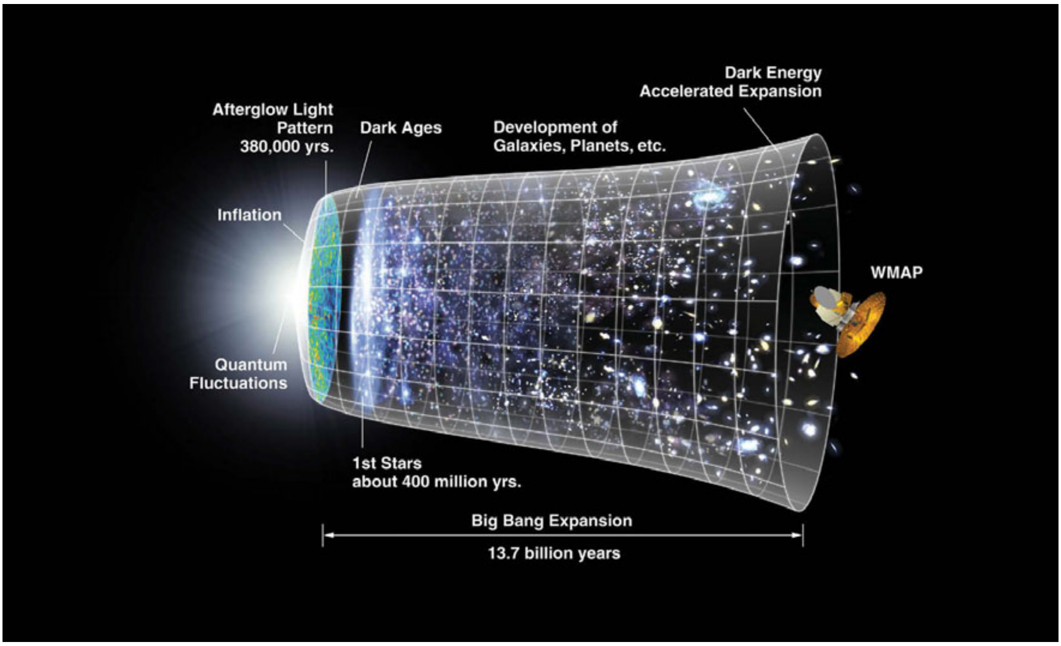


FIGURE 3.7 Pictorial representation and timeline of the standard cosmological model for the origin and evolution of the universe. The horizontal axis represents time and the vertical width represents the change in the rate of the expansion of the universe. After a period of exponential expansion, the epoch of inflation in the first instants of the universe, there is a long period of slowing expansion during which the galaxies and large-scale structures formed through the force of gravity, followed by recent acceleration of the expansion due to dark energy. The figure is from the science team of NASA's Wilkinson Microwave Anisotropy Probe (WMAP) satellite, which is shown to the right viewing the universe. SOURCE: NASA.

directions. Overall, this model is based on limited amounts of data and needs much more evidence to prove its validity. Astrophysicists hope to test this theory, known as Inflation, by searching in the polarization of the CMB radiation for the tell-tale signature of gravitational waves generated in the inflationary epoch.

The model also includes the makeup of the universe, as determined from analysis of the cosmic microwave background radiation (see Box 3.5). Ordinary matter—all the material that is described in science textbooks—is found to make up only a small fraction, ~4.5 percent, of the universe. The "dark matter," the presence of which has been inferred by astronomers to account for the gravity holding galaxies and clusters of galaxies together, makes up 23 percent of the density of the present universe (NASA/WMAP Science Team, 2010). It is not composed of ordinary matter in some nonluminous form. It is a new, as-yet-unidentified type of matter.

A surprising recent discovery in cosmology, and indeed in physics, is that the majority of the mass-energy density of the present universe is attributed to dark energy. Measurements of distant Type 1a supernovae revealed that the expansion of the universe was not slowing down as expected, but rather that the rate of expansion was accelerating (Perlmutter et al., 1999; Riess et al., 1998). Measurements of the background radiation confirmed the presence of dark energy and are now being used to help understand its nature (e.g., see Sehgal et al., 2011; Vanderlinde et al., 2010).

Neutrino Astronomy: Opening a New Window on the Universe

Light is customarily used to study the cosmos, where photons, the particles of light, act as cosmic messengers. For example, the cosmic microwave background discussed above is studied using light at millimeter wavelengths (low-energy photons with energy ~10^{-3} eV), while optical astronomy uses light at wavelengths of order 1 μm (~1 eV). High-energy astrophysics is pursued with much shorter wavelength photons, with energies of several 10^3 eV (x-rays) and at much higher energies extending to 10^{13} eV (gamma rays). Other elementary particles, such as astronomical cosmic rays made up of energetic protons and other charged nuclei, have been studied for nearly 100 years as cosmic messengers.

A mystery in astrophysics is the mechanism that accelerates cosmic rays to extremely high energies. Cosmic rays have been observed to strike Earth's atmosphere with energies up to 10^{21} eV, an energy many orders of magnitude higher than can be produced in man-made accelerators. Because the cosmic rays are charged particles, their trajectories are scrambled by the magnetic field of the galaxy. Therefore, the direction from which they arrive does not point back to their origins. At energies above a few 10^{13} eV, even the propagation of gamma rays through space is limited by their interaction with

BOX 3.5 COSMIC MICROWAVE BACKGROUND RADIATION

Maps of the cosmic microwave background such as the one shown here (Figure 1) are analyzed by constructing angular power spectra to compare with theoretical predictions of their statistical properties. The most recent angular power spectrum is shown in Figure 2. The figure combines data from the WMAP satellite on large angular scales (Larson et al., 2011) with that from the 10-m South Pole Telescope on small angular scales (Keisler et al., 2011). It shows a stunning harmonic series of features, much like the overtones of a musical instrument. These data aid in the determination of the makeup of the universe.

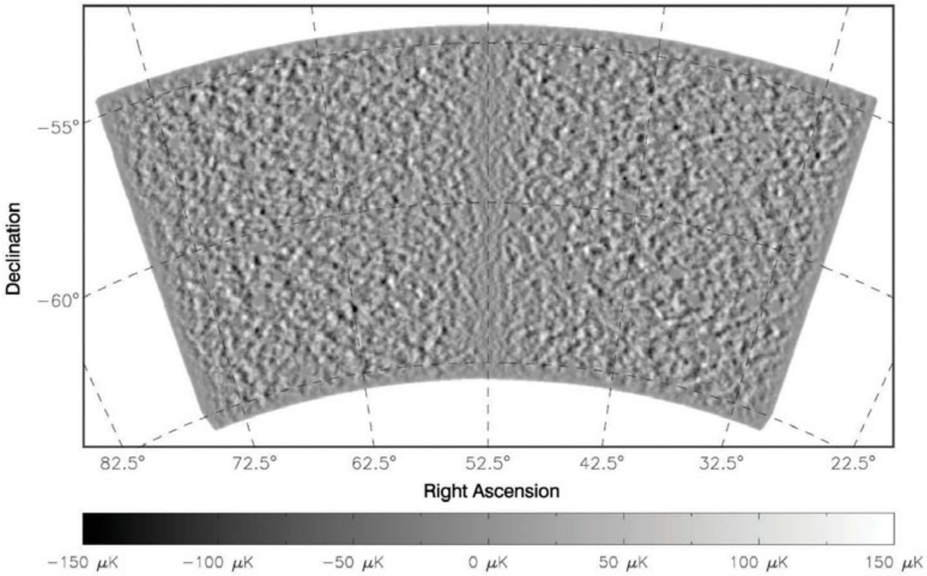


FIGURE 1 Map of 250 square degrees of the sky obtained with the 10-m South Pole Telescope at 2 mm wavelength and a resolution of 1 arc minute, from a survey covering 2,500 square degrees. The map is dominated by features in the cosmic microwave background radiation, the 14 billion-year-old fossil light from the Big Bang. The features are detected at high signal to noise throughout the map (the noise level is ~18 mK). Bright compact features in the map are due to external galaxies (in emission) and the Sunyaev-Zel'dovich effect from clusters of galaxies (in absorption). SOURCE: Keisler et al., 2011.

BOX 3.5 CONTINUED

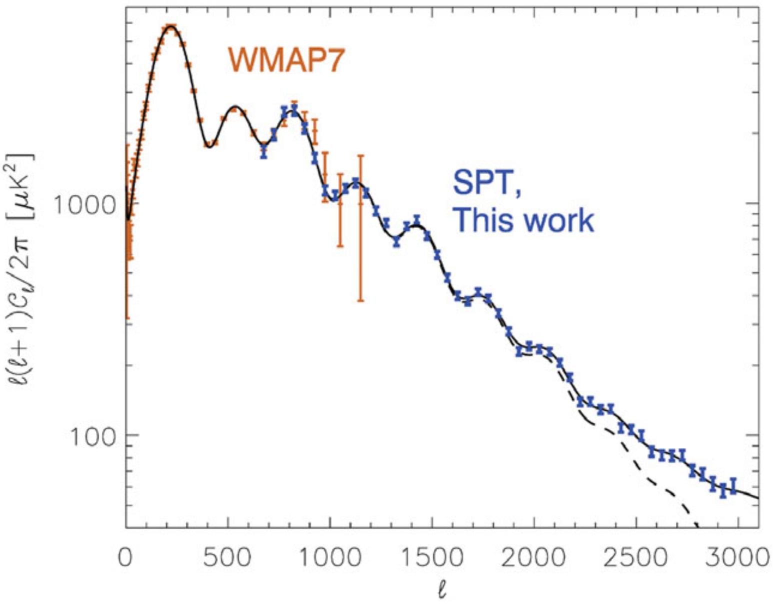


FIGURE 2 The angular power spectrum of the structure from maps of the cosmic microwave background radiation. Much like a graphic equalizer display illustrates the makeup of music as a function of wavelength, i.e., with the bass at long wavelengths (low frequencies) and the treble at short wavelengths (high frequencies), the spectrum above shows the components of the sound waves in the early universe as a function of their wavelength projected across the sky. The index "l" for multipole number is a measure of wavelength with higher multipole numbers corresponding to shorter wavelengths (high frequency). Analysis of the beautiful harmonic series of peaks in the spectrum reveals the makeup of the universe. SOURCE: Keisler et al., 2011.

the cosmic background photons, producing electron-positron pairs. To answer the question "How do cosmic accelerators work and what are they accelerating?" requires a multipronged approach including cosmic ray observatories, space- and ground-based gamma-ray observatories, and importantly—but only recently possible—high-energy neutrino observatories.

Neutrinos are nearly massless particles that carry no charge, and because they interact only via the weak interaction, that is, not via electromagnetic interactions, they travel from their source unaffected by magnetic fields or interactions with the cosmic microwave background. Neutrinos have a mean free path that exceeds the radius of the observable universe. Although this makes them extremely hard to detect, it also makes them, in principle, incredibly powerful messengers for probing the universe because their paths will point directly back to their origins, whether it is deep within the Sun, a supernova or gamma-ray burst across the observable universe, or the accretion disk or jet associated with a supermassive black hole. Furthermore, neutrinos are a byproduct of proton interactions, making any source of protons also a source of neutrinos. They are therefore perfect messengers for addressing the long-standing mystery of the origin of the ultra-high-energy cosmic rays (Chen and Hoffman, 2009).

A detector with an enormous mass is required to increase the chance of an interaction with an astronomical neutrino. The IceCube experiment was designed to meet this challenge. It exploits the clear Antarctic ice as detector and Earth itself as a telescope. The IceCube neutrino observatory was just completed and is poised to open neutrino astronomy at energies of 10^{12} to 10^{15} eV as a new window on the universe (see Box 3.6). IceCube seeks to answer fundamental questions as to the physical conditions in gamma-ray bursts and the workings of nature's accelerators that produce the remarkably high-energy photons and cosmic rays. As a particle physics detector capable of detecting neutrinos with energies far above those produced in laboratories, IceCube will use the cosmos to complement man-made particle physics accelerator experiments to search for clues of the unification of the fundamental forces at high energies.

Questions for the Future and Required Tools

Did the Universe Start with a Period of Inflation? If So, Then What Are the Physics Underlying Inflation? What Are the Masses of the Neutrinos?

The greatest science opportunity for future Antarctic cosmic microwave observations is to test whether Inflation is the correct model for the origin of the universe. At the extremely high energy state believed to prevail during the inflationary epoch, space-time would be highly distorted, creating gravitational waves that would lead to unique signals in the polarization of the background radiation that could, in principle, be observable today if the inflationary energy was sufficiently high. An unambiguous detection of this gravitational wave signal would be an astonishing discovery with enormous impact for the understanding of the universe and our place within it. It would provide the "smoking gun" proof that Inflation is the correct theory for the origin of the universe as well as determine the energy scale of inflation.

The observed distribution on the sky of the intensity and polarization of the cosmic microwave background is also affected by gravitational lensing from the structures in the universe encountered by the background photons in their journey through the universe. These distortions, on somewhat smaller angular scales than those caused by inflationary gravitational waves, are a sensitive probe of growth of structure in the universe, which in itself is sensitive to the fraction of the universal mass budget contributed by neutrinos. Future polarization measurements of the cosmic microwave background can therefore be used to constrain the sum of the masses of the neutrinos, an important constraint for developing a full understanding of the physics of the universe.

The current generation of cosmic background experiments and those planned to start in the next few years may find evidence for the long-sought inflationary polarization signal. However, the definitive polarization measurements required to provide a clear unambiguous detection, or to set the most stringent limit possible on the energy scale of inflation, will require a major increase in sensitivity. A goal is to produce polarization maps of the 3 K cosmic background with noise levels of order 10 nK. These maps will also include the contaminating polarized emissions from astronomical sources from the galaxy and external galaxies.

The noise of the superconducting bolometric detectors used for the polarization measurements are already background limited (i.e., the measurement noise is dominated by the variation in the arrival of incident photons and not the noise of the detector itself). Therefore, the only way to improve sensitivity is to develop wide-field telescopes and larger cameras. To separate the desired cosmic background signal from the contaminating sources of polarized emission, the sky will need to be mapped in several wavelength bands and at an angular resolution of a few arc minutes or better, so the unique spectral and spatial signatures of the signal can be observed.

The astrophysics community has begun planning ahead for possible future developments using long-duration Antarctic balloons and enhancements to the observing program at the South Pole to produce these maps. To provide the increased sensitivity and frequency coverage, one possible solution is to deploy an array of several

BOX 3.6 ICECUBE

The IceCube neutrino observatory completed in December 2010 is poised to open high-energy neutrino astronomy as a new window on the universe. The IceCube detectors consist of photodetectors embedded in a cubic kilometer of the clear ice deep below the South Pole Station (see Figure 1). The detector searches for the flash of blue Cherenkov light emitted from the

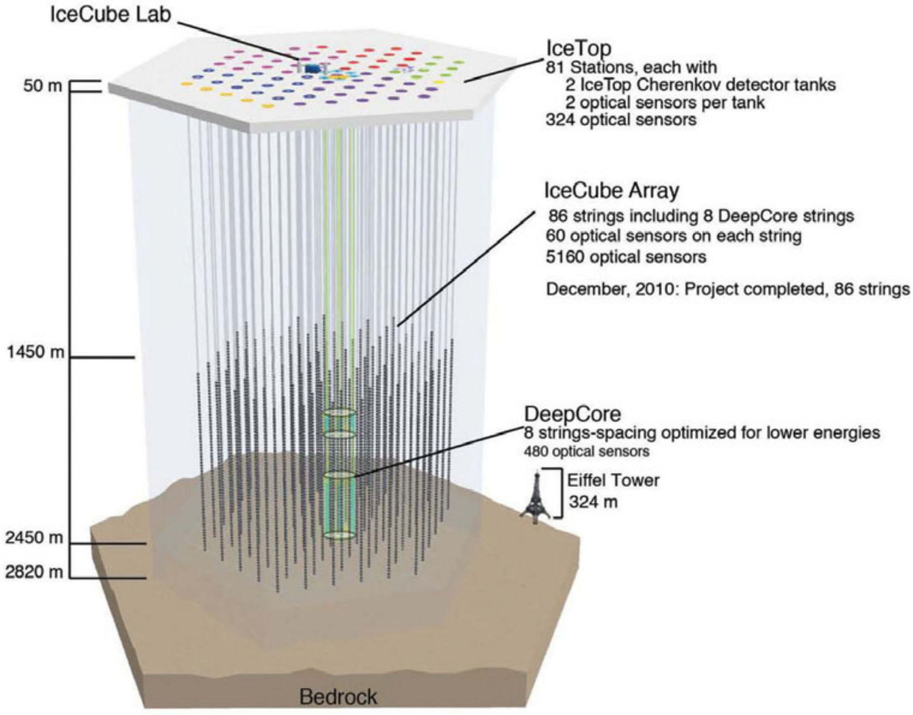


FIGURE 1 Schematic view of the IceCube neutrino observatory at the South Pole. After 7 years of South Pole drilling operations, 86 strings and 162 IceTop tanks were installed and connected to the central data acquisition system to complete IceCube. A total of 5,484 optical sensors were deployed and commissioned. Now more than 250 scientists in 36 institutions worldwide are mining the data for a variety of science goals, such as the search for highest-energy cosmic neutrinos, dark matter, or neutrinos from supernova explosions. SOURCE: IceCube Collaboration.

BOX 3.6 CONTINUED

secondary particles created in the rare interaction of a high-energy neutrino with a nucleon in the ice (see Figure 2). To discriminate against interactions from other particles, the IceCube team searches for particles coming from the north, as only neutrinos are able to pass through the core of Earth. In this way Earth itself serves as the telescope and the Antarctic ice cap as the detector.

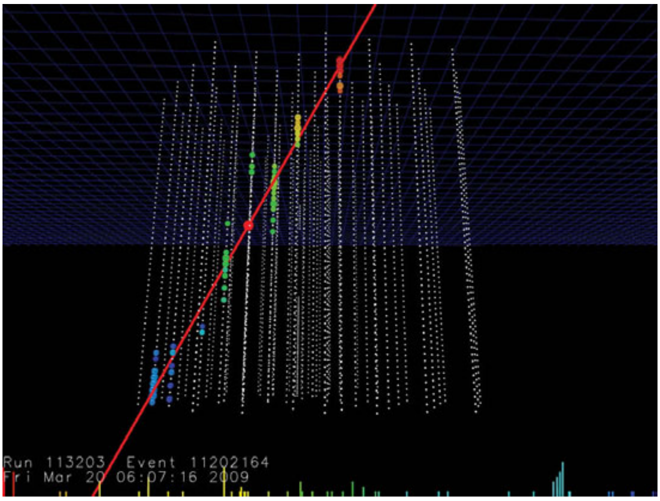


FIGURE 2 Display of a typical muon neutrino event in IceCube. SOURCE: IceCube Collaboration.

dedicated cosmic background telescopes, each equipped with cameras containing of order 2,000 background-limited dual-polarization pixels. Such a project places demands on the infrastructure of the South Pole Station; a new laboratory building would be required, as well as additional power to cool the detector arrays, and for the data to be transferred to the United States for inspection and analysis, the daily data transmission would have to be increased by an order of magnitude over the current 100 GB/day. This would require a great deal of further planning.

What Is the Origin of the Highest-Energy Cosmic Rays? What Are the Properties of the Neutrinos? What Is the Dark Matter Particle?

The recently completed IceCube instrument will be the leading neutrino observatory for many years into the future. It is poised to make the first discoveries of extragalactic neutrinos from TeV (10^{12} eV) to PeV (10^{15} eV) energies. As has been demonstrated over and over again, the opening of each new astronomical window has led to unexpected discoveries. IceCube may well lead to transformational advances in the understanding of the physics of the universe. Now that IceCube is fully operational, its science value and future potential should be clear in roughly 5 years. Future opportunities in Antarctic neutrino astronomy and particle astrophysics will emerge naturally as enhancements to IceCube, either by extending its reach in energy or by using IceCube to monitor particle interactions as a veto in the search for signals from rarer events, such as experiments to directly detect dark matter particles.

After the tremendous value of IceCube is sufficiently demonstrated, a possible future enhancement to IceCube may be to increase its reach at high energies. IceCube is too small to address the origin of the highest-energy cosmic rays, which will require an observatory that is larger by two to three orders of magnitude. A neutrino observatory large enough to collect hundreds of neutrinos that were created by the interaction of ultra-high-energy cosmic rays with the cosmic microwave background (the GZK effect; Greisen, 1966; Zatsepin and Kuzmin, 1966) would provide two unique discovery opportunities. First, the GZK neutrino spectrum and arrival directions are critical observations for determining the sources of the highest-energy particles in the universe. Second, the detections would extend the knowledge of neutrino properties. For example, by measuring the event rate as a function of incident angle, the opacity of Earth can be used to determine neutrino-nucleon cross sections at energies far beyond those probed at particle physics facilities.

A new technology would be required to build a larger array at a feasible cost. A promising technique is based on exploiting the Askaryan effect—the premise that high-energy electromagnetic showers in dense media give rise to a detectable radio frequency impulse (Askaryan, 1962). An array of antennas embedded in the top of the ice could be used to search for the burst of radio emissions produced by the interaction of an ultra-high-energy cosmogenic neutrino impinging on the ice (Askaryan, 1962). This technology would make it possible to instrument 100 km^2 of the South Pole ice cap.

What Is the Life Cycle of the Interstellar Dust and Gas Clouds from Which Stars Form? What Is the Frequency of Occurrence of Planets Around Other Stars? What Is the Star Formation History of the Universe?

These questions represent only a sample of the astrophysics beyond the study of the cosmic microwave background, for which the unique atmospheric properties and geographical location of Antarctica provide opportunities for dramatic advances. They are best pursued using far-infrared and submillimeter-wave observations of the gas and dust involved in the process of star formation, or by near-infrared and optical observations that exploit the possibility of 24/7 observing through the Austral night to conduct time-domain astronomy for exploring transient phenomenon, such as the search for exoplanets through gravitational microlensing events.

These opportunities require observations at wavelengths much shorter than those required for cosmic background studies, and at which the atmospheric opacity is considerably degraded by the residue water vapor. In the case of optical or near-infrared time-domain astronomy, minimal cloud cover and stable "photometric" conditions are required. To fully exploit near-infrared and optical observations, the telescopes need to be above the low-altitude atmospheric turbulent layer, caused by the temperture inversion, which would otherwise seriously degrade the image quality.

For these observations the summits of the high Antarctic domes offer potentially far superior performance than the South Pole (Burton, 2010). For small instruments, the high altitude and long duration of the circumpolar balloon platforms launched from McMurdo Station offer extraordinary observing opportunities. International efforts are under way in site testing for deployment of future astrophysical experiments at Domes A, C, and F. Dome A (4,083 m) is the highest location on the Antarctic plateau. In 2009 China began the construction of Kunlun station, including the installation of autonomous atmospheric site testing equipment. Astrophysics is the primary scientific driver for the station, with a 2.5-m infrared telescope and a 5-m THz telescope being planned. The French and Italian Concordia Station at Dome C (3,268 m) opened in 2005 for winter operation. The European Union-funded ARENA program endorsed a

2-m-class infrared telescope to be the first major astrophysics project at the station (ARENA, 2010). The Japanese Fuji Station at Dome F (3,810 m) was first used for wintering in 1995. Although the primary scientific purpose of the station was ice-core drilling, astrophysics is also now a part of its scientific plans.

These international efforts are testimony to the world-class astrophysics achieved in Antarctica and to the excitement of the future science opportunities in astrophysics there. The United States has much to offer and to gain from participating in the international pursuit of astrophysics from Antarctica. The scientific community has learned how to carry out challenging astrophysics projects from the successful program at the South Pole. Indeed the South Pole station itself would provide valuable testing and staging opportunities for experiments to be deployed at less developed sites, or for remote robotic astrophysical installations. International collaboration will also provide U.S. scientists access to the superb observing conditions available at other stations.

The study of cosmology and astrophysics from Antarctica has led to exciting discoveries over the past few decades. With the ever-increasing sensitivity of scientific instruments and the extraordinary observing conditions available from Antarctica and high-altitude balloons, new surprising discoveries that may point the way to future opportunities to learn about the universe can be expected in the next 20 years.

The Research Vessel NATHANIEL B. PALMER in Barilari Bay, Antarctic Peninsula. SOURCE: Adam Jenkins/NSF.

CHAPTER FOUR

Opportunities to Enhance Research in Antarctica and the Southern Ocean

As the foregoing chapters have noted, Antarctica and the Southern Ocean provide extraordinary opportunities to study questions that go deep within and across many disciplines. This chapter examines opportunities to enhance future scientific research in Antarctica and the Southern Ocean through collaboration; energy, technology, and infrastructure; and education. This chapter also describes a proposed initiative for an observing network with data integration and enhanced scientific modeling.

4.1 COLLABORATION

In the first half of the 20th century, many of the nations that were interested in Antarctica were primarily concerned with claiming territory. Since then, as Antarctica has become a haven for science, research in Antarctica and the Southern Ocean has grown into a large and successful international scientific enterprise. Throughout this evolution, collaboration has played a valuable role. This includes collaboration in several senses: across national borders, across disciplinary boundaries, between public- and private-sector entities, and between scientists and the logistical support providers who facilitate the conduct of science in these harsh environments. Each of these is explored in this section, but the general observation on the necessity of collaboration is as simple as stating that by working together new things can be done, and be done more affordably. Moreover, increasingly collaboration across any one of these areas encourages collaboration in others.

International Collaboration

One of the easiest places to see the growth in collaboration is among nations. The Antarctic Treaty process, led in part by the United States in 1959, has to date enrolled 48 countries, more than 20 of which operate more than 40 permanent, manned science bases on the continent (Box 4.1, Table 4.1, Figure 4.1). Many of these countries were

BOX 4.1 THE ANTARCTIC TREATY SYSTEM

The Antarctic Treaty System originated in 1961 during the height of the Cold War, and although the Cold War effectively ended more than two decades ago, the Antarctic Treaty System remains in force. The countries that are signatories to the Antarctic Treaty System are listed in the table below. One might argue, given the importance of Antarctica and the Southern Ocean for the conditions of the larger world, that the treaty system is now more important than ever. The Antarctic Treaty System provides the foundation for treating the continent of Antarctica as a scientific research zone, while excluding hostile military activity and territorial conquest. Subsequent additions to the Antarctic Treaty System of the Convention for the Conservation of Antarctic Marine Living Resource, which manages fishing in the Southern Ocean, and the Environmental Protocol provide explicit regulations to maintain the comparatively pristine conditions of the continent.

TABLE Signatories of the Antarctic Treaty System, Country and Date Joined (as of 2011)

Argentina	23-6-61*	Japan	23-6-61*
Australia	23-6-61*	Korea DPRK	21-1-87
Austria	25-8-87	Korea ROK	28-11-76
Belgium	23-6-61*	Monaco	30-5-08
Belarus	27-12-06	Netherlands	30-3-67
Brazil	16-5-75	New Zealand	23-6-61*
Bulgaria	11-9-78	Norway	23-6-61*
Canada	04-5-88	Papua New Guinea	16-9-75
Chile	23-6-61*	Peru	10-4-81
China	08-6-83	Poland	23-6-61
Colombia	31-1-89	Portugal	29-1-10
Cuba	6-8-84	Romania	15-9-71
Czech Republic	01-9-93	Russian Federation	23-6-61*
Denmark	20-5-65	Slovak Republic	01-1-93
Ecuador	15-9-87	South Africa	23-6-61*
Estonia	17-5-01	Spain	31-3-82
Finland	15-5-84	Sweden	24-4-84
France	23-6-61*	Switzerland	15-11-90
Germany	05-2-79	Turkey	24-1-96
Greece	08-1-87	Ukraine	28-10-92
Guatemala	31-7-91	United Kingdom	23-6-61*
Hungary	27-1-84	United States	23-6-61*
India	19-8-83	Uruguay	11-1-80
Italy	18-3-81	Venezuela	24-3-99

*Original signatory.
SOURCE: Information from Antarctic Treaty Secretariat.

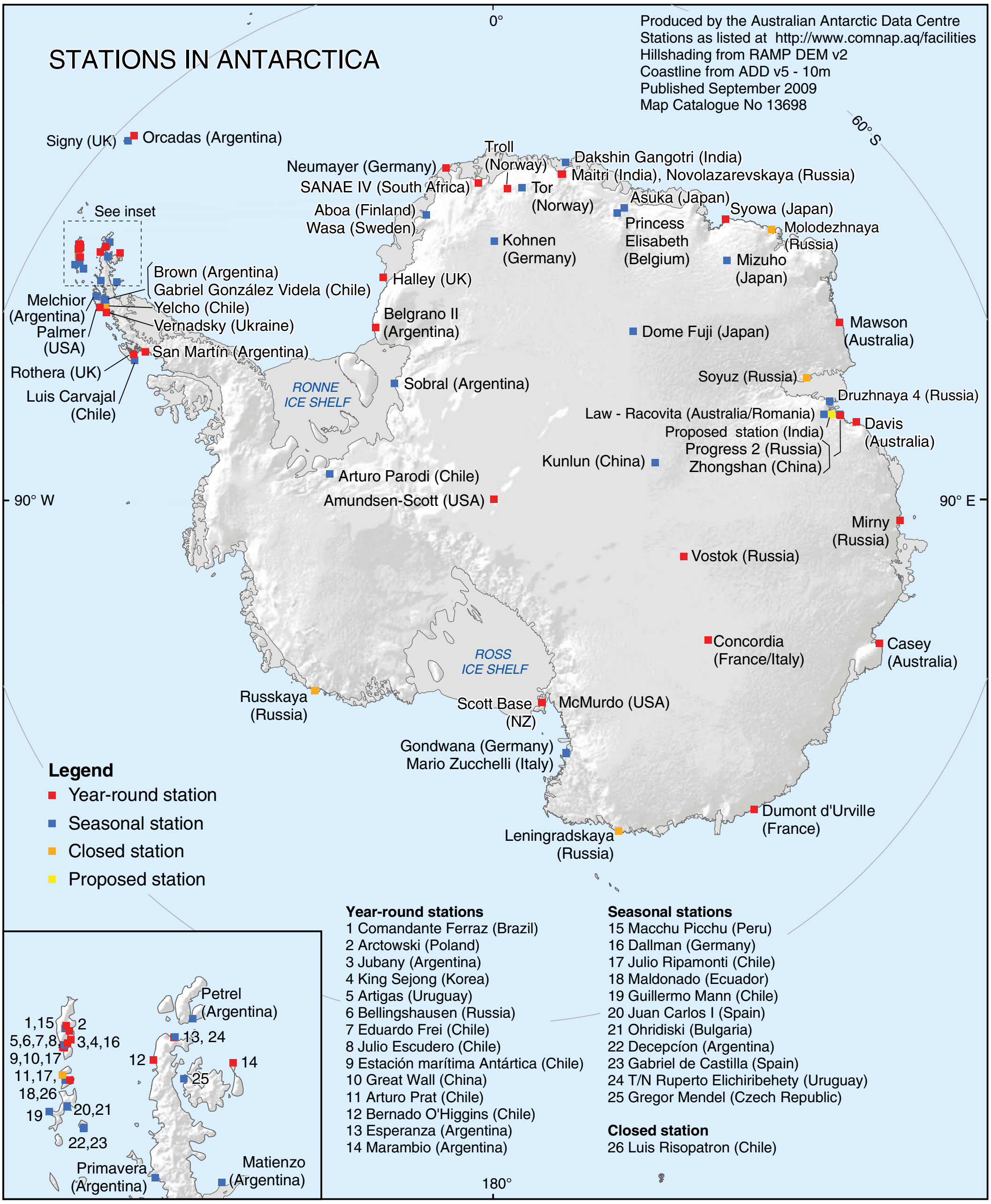
TABLE 4.1 Permanent Manned Stations in Antarctica: Country and Base Names (as of 2011)

Country	**Station**
Argentina	Belgrano II, Esperanza, Jubany, Marambio, Orcadas, San Martín
Australia	Casey, Davis, Mawson
Brazil	Comandante Ferraz
Chile	Arturo Prat, Bernardo O'Higgins, Eduardo Frei, Estación marítima Antártica, Julio Escudero, Rodolfo Marsh
China	Great Wall, Zhongshan
France	Dumont d'Urville, Concordia (with Italy)
Germany	Neumayer
India	Maitri, Bharathi (to open in 2012)
Italy	Concordia (with France)
Japan	Syowa
Korea	King Sejong
New Zealand	Scott Base
Norway	Troll
Poland	Arctowski
Russia	Bellingshausen, Mirny, Novolazarevskaya, Progress 2, Vostok
South Africa	SANAE IV
Ukraine	Vernadsky
United Kingdom	Halley, Rothera
United States	Amundsen-Scott, McMurdo, Palmer
Uruguay	Artigas

SOURCE: Adapted from COMNAP.

motivated by reasons of national pride to establish new stations to advance their national interests. But a broader perspective and increased emphasis on collaboration is now evident as nations consider the cost of running stations, the need for geographic flexibility, and the environmental regulations involved in operating stations since the Protocol on Environmental Protection (signed in Madrid in 1991) went into effect in 1998 (Orheim, 2011). In many ways, Antarctic science provides a glimpse of how national and international scientific collaboration can proceed successfully in the future.

Increased international collaboration has been driven by recognition that many Antarctic science questions are too large to be solved by any single nation. The committee has attempted to identify areas of science that will drive research in the coming decades in Chapters 2 and 3, drawn from a number of reports (see Box 1.2). Many nations that are active in Antarctic research have published future research priorities



Year-round stations
1 Comandante Ferraz (Brazil)
2 Arctowski (Poland)
3 Jubany (Argentina)
4 King Sejong (Korea)
5 Artigas (Uruguay)
6 Bellingshausen (Russia)
7 Eduardo Frei (Chile)
8 Julio Escudero (Chile)
9 Estación marítima Antártica (Chile)
10 Great Wall (China)
11 Arturo Prat (Chile)
12 Bernado O'Higgins (Chile)
13 Esperanza (Argentina)
14 Marambio (Argentina)

Seasonal stations
15 Macchu Picchu (Peru)
16 Dallman (Germany)
17 Julio Ripamonti (Chile)
18 Maldonado (Ecuador)
19 Guillermo Mann (Chile)
20 Juan Carlos I (Spain)
21 Ohridiski (Bulgaria)
22 Decepcíon (Argentina)
23 Gabriel de Castilla (Spain)
24 T/N Ruperto Elichiribehety (Uruguay)
25 Gregor Mendel (Czech Republic)

Closed station
26 Luis Risopatron (Chile)

FIGURE 4.1 Map of Antarctic research stations from various countries. SOURCE: Australian Antarctic Data Centre.

for the long term because such research requires heavy investments in logistics and infrastructure and necessitates long-term planning. A survey of plans of the European Polar Board (EPB), British Antarctic Survey, Alfred Wegener Institute (Germany), Australian Antarctic Division, and the Antarctic research organizations of New Zealand, Korea, and Norway is summarized in Table 4.2. The United States and the EPB, representing a consortium of European nations, are both involved in all elements of Antarctic research. Although the United States currently possesses the human capital, financial resources, and logistic strength to be able to take part in *all* segments of Antarctic

TABLE 4.2 Areas of Science Considered Priorities for Study in Antarctica and the Southern Ocean for the United States and a Sampling of Other Nations

	United States*	EU Polar Board	Australia	British Ant Survey	China	Germany	India	Korea	New Zealand	Norway
Climate change and impacts	X	X	X	X		X	X	X	X	X
Paleoclimate	X	X	X	X		X	X	X	X	X
Ice sheet and sea level change	X	X	X	X	X	X	X	X	X	X
Crustal structure and subglacial geology	X	X		X		X	X			X
Deep sea ecosystems	X	X		X	X	X	X		X	X
Earth system modeling	X	X	X	X		X		X		X
Astrophysics	X	X	X		X	X		X		
Space physics	X	X	X	X	X			X		X
Basic and applied life sciences	X	X	X	X	X	X	X	X	X	X
Atmospheric dynamics	X	X	X	X		X	X		X	X
Terrestrial ecology	X	X	X	X		X	X	X	X	X

*Priorities for the United States identified by the committee (Priorities for other nations and the EU Polar Board based on available documentation).

SOURCES: AWI, 2009; Australian Antarctic Division, 2011; British Antarctic Survey Science Programme, 2009; European Polar Board, 2010; Gupta, 2010; Lee, 2010; Ministry of Earth Sciences India, 2011; National Science Foundation, 2009; National Science Foundation Office of Polar Programs, 2011; New Zealand Antarctic and Southern Ocean Science Program, 2010; Polar Research Institute of China, 2006; Research Council of Norway, 2010.

research, the overlapping scientific priorities of the United States with those of other nations present numerous opportunities for collaboration.

Many new nations entered into Antarctic research in the 1980s, driven in part by interest in Antarctic mineral resources, national pride, and the chance to join an exclusive club of nations leading the world in scientific research. Internationally, the Scientific Committee on Antarctic Research (SCAR) has been supplemented by regional organizations such as the EPB and the Asian Forum for Polar Sciences. Antarctic science publications have been growing more quickly than publications in other areas of science, tripling between 1981 and 2009 (Figure 4.2) (Aksnes and Hessen, 2009). Although U.S. scientists contributed the largest portion of articles, this 2009 bibliographic analysis of 65,000 "polar" articles published in the peer-reviewed literature showed that the U.S. share declined from 34 percent in 1981-1983 to 24 percent in 2005-2007, and the share of the second-most-active country, the United Kingdom, declined from 17 to 11

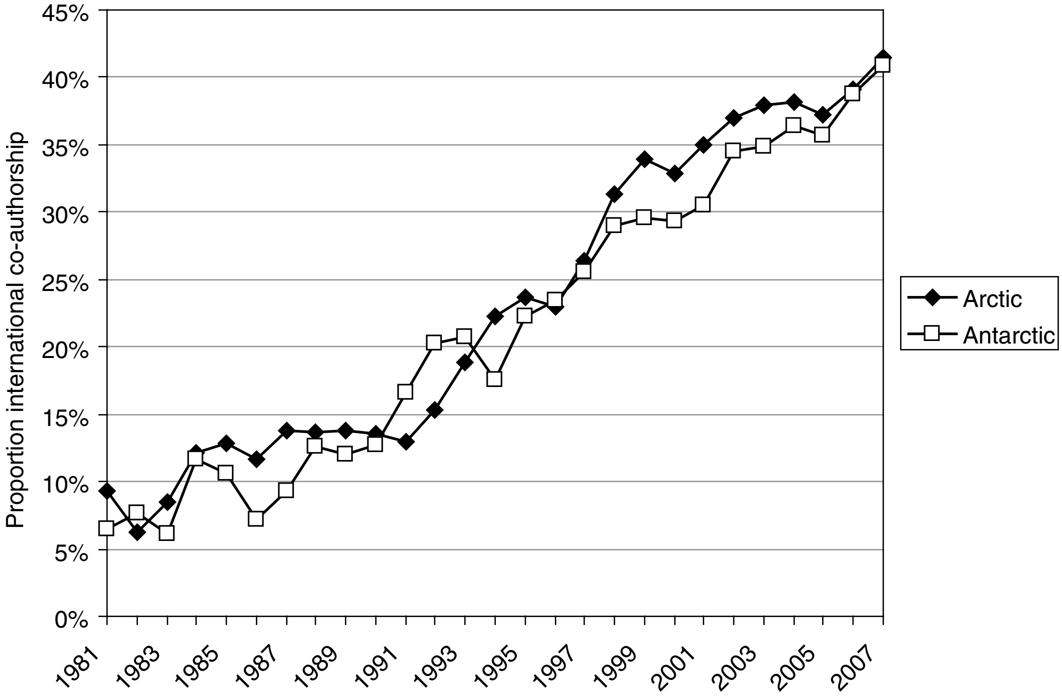


FIGURE 4.2 International co-authorship of Arctic and Antarctic publications, 1981-2007. SOURCE: Aksnes and Hessen, 2009.

percent. Australia and Germany held their own, while countries like Italy, Spain, China, and Argentina increased their shares. In short, there is a greater diversity of nations participating in Antarctic science. There is also noteworthy growth in partnerships: collaboration within European Union (EU) countries has increased from 27 to 35 percent, between scientists in the EU and other nations from 12 to 24 percent, and among non-U.S. and non-EU nations from 3 to 6 percent. The International Polar Year (IPY) from 2007 to 2008 led to increased international collaboration, as did the U.S. National Science Foundation (NSF) requirement that IPY awards involve international partnerships (Krupnik et al., 2011; National Science Board, 2010; National Science Foundation, 2010).

International collaboration in Antarctica has produced spectacular results. One example is the joint drilling and analysis of the Vostok ice core by scientists from France, Russia, and the United States that led to publication in 1999 of a 400,000-year record of proxy temperatures and carbon dioxide (CO_2) and methane (CH_4) concentrations. This was one of the most important climate research results of the past decade. Other examples of successful international collaborations include the following:

- EPICA[1] (European Program for Ice Coring in Antarctica) on Dome C and Kohnen station, which collects information on climate variations over the past 1 million years;
- ANDRILL[2] (Antarctic Geologic Drilling) project involving Germany, Italy, New Zealand, the United Kingdom, and the United States, which studies the evolution of the Antarctic ice sheets during the past 40 million years;
- Concordia astronomical observatory involving France, Italy, and others, which aims to open new spectral windows at infrared and submillimeter wavelengths;
- Gamburtsev solid Earth investigations involving the United Kingdom, the United States, Germany, Japan, Australia, and China, which studies this very large subglacial mountain range;
- CAML[3] (Census of Antarctic Marine Life) led by Australia, involving 17 ships and scientists from 20 nations, which investigates the distribution and abundance of Antarctica's marine life;
- AMPS[4] (Antarctic Mesoscale Prediction System) provides tailored numerical weather predictions that support aircraft operations, field programs, and fundamental Antarctic atmospheric research. It is a U.S. program but with active participation of 17 countries; and

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[1] See *http://www.esf.org/index.php?id=855.*

[2] See *http://www.andrill.org/.*

[3] See *http://www.caml.aq/.*

[4] See *http://www.mmm.ucar.edu/rt/amps/.*

- IODP[5] (Integrated Ocean Drilling Program) supported by 24 countries, which advances scientific understanding by monitoring, drilling, sampling, and analyzing subseafloor environments.

The organization of Antarctic research within countries can facilitate collaboration. In many nations, the presence of a central institute with responsibility for both logistics and science makes for rapid decision making once the case for cooperation has been accepted. Most nations engaged in Antarctic research need to collaborate to tackle large scientific questions. The U.S. Antarctic Program (USAP) has been large enough to undertake major projects alone, but, for reasons elaborated below, the USAP will probably collaborate more in the future to enable U.S. scientists to stay at the forefront of Antarctic and Southern Ocean science. Specifically, collaboration can benefit U.S. scientists when

- Research needs to be done in geographic areas where logistic support from other nations is practical and feasible;
- Other nations have instruments or other technical or logistic resources exceeding those available to U.S. scientists (e.g., see icebreaking capability below);
- Scientists in other nations are ahead of U.S. scientists and collaboration can raise the quality of U.S. Antarctic science; and
- The United States has a personpower shortage in given subject areas, and scientists from other countries can make up for that shortage.

U.S. collaborations with other strong Antarctic science communities can help achieve critical mass and density of observations to answer particular questions. Increasing international collaboration can be achieved without moving funds across national borders. Sometimes, nations can contribute in-kind portions of the total needs for a project, such as one nation supplying the aircraft and another supplying the fuel. The most important factors in increasing international collaborations are sufficient will to increase such collaborations and flexibility in meeting the needs of the science.

Interdisciplinary Collaboration

As explained in Chapters 2 and 3, science in Antarctica and the Southern Ocean is increasingly tied to research questions that cut across traditional disciplinary boundaries. A good example of this is the growing perspective of Earth system science that incorporates a wide set of the physical sciences, and the concept of ecological change

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[5] See *http://www.iodp.org/*.

that incorporates many of the life sciences. Of course, the changes in the physical systems affect the ecology, so these two broad realms of work are increasingly pulled together as well. As the policy implications of environmental change become apparent—the changing nature of fisheries in the Southern Ocean, for example—it becomes increasingly important to understand all aspects of the phenomena in question because mitigation strategies often have serious economic and social consequences and trade-offs. It is rapidly becoming unacceptable to ask policy makers to make difficult choices without good information on the consequences of their decisions.

Discovery, as well, is increasingly interdisciplinary, where even seemingly disparate fields come together around some projects. For example, the IceCube neutrino detector required the drilling of many deep holes in ice, and, as discussed elsewhere, drilling remains a major area of engineering investigation. Similarly, IceCube is highly dependent on cyberinfrastructure, as are most other areas of scientific inquiry, and research and development in cyberinfrastructure are important areas of cross-disciplinary inquiry.

Given the extensive logistical support typically required to do research in Antarctica and the Southern Ocean, the successful execution of interdisciplinary scientific work in this region often requires successful international collaboration. Addressing many of the future science questions in Antarctica and the Southern Ocean will benefit from integrated research projects and programs that are both international and interdisciplinary.

Collaboration Between the Public Sector and Private Sector

The private sector plays an important role in scientific research, and that role has been evolving and increasing in recent decades. The private sector makes major investments in scientific research: pharmaceutical companies, agricultural chemical and seed suppliers, automobile manufacturers, and many other kinds of companies invest heavily in research to create or improve products and services. As of now, the private sector does not perform much scientific research of its own in Antarctica and the Southern Ocean, but that may change in the future. Similarly, the private sector is a primary supplier of materials and equipment for scientific research of all kinds, including chemical reagents, laboratory animals, and special instruments used in research. As one example, more than 50 companies are listed as suppliers to the biotelemetry community.[6] Some of these companies got their start by developing telemetry devices for tracking animals in Antarctica and the Southern Ocean.

Historically, scientific work in Antarctica and the Southern Ocean was largely a public-sector affair. During the early days of U.S. research in the Antarctic region, the U.S. Navy provided most of the logistics support for U.S. scientific research. This has evolved over time to the point where logistical support is provided by contract with private companies. This is one example of the interaction of the private sector with research in Antarctica and the Southern Ocean.

There are undoubtedly challenges associated with opening the activities in Antarctica and the Southern Ocean to more private-sector involvement. The committee does not make a specific recommendation about the role of the private sector here; we simply note that this role is already changing and that it is doubtful that the situation will be reversed. The possibility of more collaboration across the public and private sectors can be viewed as an opportunity, and serious exploration of opportunities for and consequences of more public-private collaboration in the region is warranted.

Collaboration Between Science and Logistics Personnel

The Blue Ribbon Panel, which NSF has convened to look in detail at logistical issues, has an opportunity to evaluate the current approach of using a single large private contractor to support U.S. science in the Antarctic region, and to address the concerns this committee heard on the increasing difficulty and logistics-related stresses in conducting research in this region. The Blue Ribbon Panel can affect the future of science in significant ways by reconfiguring U.S. logistics to be more flexible, nimble, and synchronized with the needs of science. The rapidly evolving nature of the scientific questions facing society today demands this. Scientists working in Antarctica and the Southern Ocean want more direct input into the planning and conduct of logistics.

Although many of the positive efficiency aspects of shifts in logistical support in the past two decades have been obtained by moving from military to commercial operations, the Blue Ribbon Panel has an opportunity to consider how to improve logistical support so it enhances and expands science research and discovery capacities. The three U.S. bases are situated so as to foster access to much of the continent. The U.S. program possesses unique assets such as ski-equipped LC-130s and the heavy airdrop capability of the C-17. The Blue Ribbon Panel also has the opportunity to look into the places where the United States has fallen behind (e.g., in icebreaking capability)

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[6] See *http://www.biotelem.org/index.php?option=com_content&view=article&id=2&Itemid=2.*

and where international collaboration could increase efficiencies in logistical support. There is great future potential in emerging and innovative ways of conducting research, such as autonomous vehicles (underwater and airborne), miniaturization of sensors, development of novel sensors, engineering innovations for deep drilling systems, and innovative sampling strategies (e.g., instrumenting marine mammals). Improvements in communications, especially data transmission and continent-wide connectivity, will be crucial to support successful science in the future from the operational needs of field parties to the movement of large quantities of data northward to U.S. laboratories. Considerations for how to enhance the efficiency, flexibility, and user friendliness of Antarctic logistical support should include discussions of appropriate relaxation of rigid fieldwork rules and fostering morale in field and base scientists. Overall, the Blue Ribbon Panel has an opportunity to examine these issues in looking to the future of logistical support for science in Antarctica and the Southern Ocean.

4.2 ENERGY, TECHNOLOGY, AND INFRASTRUCTURE

There are significant opportunities related to energy, technology, and infrastructure that can facilitate the scientific research effort in Antarctica and the Southern Ocean and bring cost efficiencies to allow a greater proportion of funds to be used to support scientific research projects directly. This section highlights a few examples of major emerging technologies; Appendix C provides a longer list of new technologies that can potentially enhance scientific research in the coming two decades.

Energy

The Antarctic region is cold, where high winds (>160 km/h) and low temperatures (<−50°C) are common. During the winter the continent is frequently icebound, and severe storms and darkness prevent most air operations and make lighting and heating for personnel a primary challenge. The Antarctic Treaty System and its Environmental Protocols require that much of what is brought to Antarctica be shipped home, so supply chain and waste management requires significant effort. Science operations in the Antarctic and Southern Ocean are energy intensive, a fact long understood by explorers and scientists. As a result, managers in Antarctica and the Southern Ocean are always looking for innovations related to energy production and use. For example, during the 1960s a small nuclear plant was built at McMurdo Station in an attempt to provide more reliable electric power generation. (Note that the Antarctic Treaty does not prohibit peaceful uses of nuclear science or nuclear power.) Unfortunately, the 1.75 megawatt PM-3A reactor developed mechanical problems, including leaks, and the plant had to be decommissioned and dismantled (U.S. Naval Nuclear Power Unit, 1973). Although this particular innovation did not last, Antarctica has been and can continue to be an important testing ground for future energy innovations.

Currently, most of the energy for Antarctic science is provided by combustion of fossil fuels, primarily jet fuel and gasoline treated to withstand the low temperatures. These fuels are consumed for transportation, electric power generation, space heating, desalination and melting ice for potable water, washing, and other needs at both the field camps and the permanent stations. The fuel pipeline for much of the continent starts at McMurdo, where the station receives most of its annual 5.3 million gallons of fuel delivered by ship. Fuel is then transferred from McMurdo to airstrips and helioports via a flexible hose. Aircraft annually move over 600,000 gallons of jet fuel and gasoline to Amundsen-Scott South Pole Station to power diesel generators, provide heating, and fuel vehicles. Palmer Station has no permanent fixed-wing landing facilities and receives all its fuel via ship. In addition to cost, combustion of fossil fuels pollutes the air, and storage and transport can leak fuel into the water, ice, or ground.

Looking to the future, innovation in energy continues to be an active concern in Antarctica and the Southern Ocean. For example, a new overland traverse route using tractors and sleds promises to reduce the cost of fuel transport from McMurdo to South Pole Station. In another example, in 2008 Antarctica New Zealand and the U.S. Antarctic Program worked together to install three 330-kW wind turbines on the ridgeline of Crater Hill between McMurdo Station and Scott Base (Figure 4.3). The wind power generation system was integrated with the McMurdo and Scott power distribution network and has proven highly reliable despite the extreme weather conditions at McMurdo. Approximately 15 percent of McMurdo's and nearly 90 percent of Scott Base's electricity needs are now provided by this system. Analysis by the National Renewable Energy Laboratory suggests that expansion of wind electric power generation at McMurdo and extension of this capability to Amundsen-Scott South Pole Station could save as much as half a million gallons of fuel per year and produce net savings of $20 million over 20 years (Baring-Gould et al., 2005). It seems likely that adoption and adaptation of smaller, energy-efficient technologies will add significantly to energy savings in the region over time.

New science technologies discussed below will require energy. Remotely operated or autonomous sensor networks will play a critical role in data collection across a wide variety of scientific fields in Antarctic and Southern Ocean research. Energy is required for materials and personnel transport, facilities operations, and data collection, processing, storage, and transmission. A strategy that relies exclusively on fossil fuels and combustion will probably not be efficient and cost effective over the long run. In-

FIGURE 4.3 Three wind turbines located between McMurdo Station and Scott Base that provide energy to both stations. SOURCE: Mike Casey, NSF.

novations such as wind and solar power will likely play a role in many of the current energy-intensive activities, and battery technology, fuel cells, and other mechanisms for energy generation and storage should be explored in the challenging conditions of the Antarctic region. Overall the Antarctic and Southern Ocean region has the opportunity to continue to be an important testbed for new energy concepts for other extreme climates, such as the Arctic. This also offers a potential opportunity for public-private partnerships in research and development.

Technology

Previous chapters in this report have shown the need for observations to be made in more places and at more times in Antarctica and the Southern Ocean. The conditions in the Antarctic region are often challenging for observers and instruments alike. The advancement of technology, both in the instruments that make measurements and in the platforms that support those instruments, can help to overcome those challenges.

In addition to overcoming challenges, the emergence of new technologies can open up new capabilities. One example is the emergence of miniaturized computers, which has allowed small instruments to be attached to diving animals. These instrumented animals have measured the conductivity, temperature, and depth of the ocean in some areas where ice cover had previously impeded such measurements by ship or mooring (mentioned in Section 3.2). This is one example out of many where the exploitation of new technology has led to a scientific advancement in oceanography and animal ecology and physiology. It is important to remember that new technologies often appear "by surprise," meaning that cost-effective deployment comes after a considerable lag time from when the ideas behind the technology were first articulated and the proof-of-concept work was finished. A good example is the Internet. Work on what became the Internet began in the late 1960s, but relatively few people knew about it until the mid-1990s when the network was officially named the Internet (Abbate, 1999). The cultures of technical development are complicated, and one cannot simply expect new and useful technologies to appear as needed. A theme throughout this discussion of technology is that new capabilities—for energy, remote sensing, cyberinfrastructure, icebreaking, or any other activity important in the Antarctic and Southern Ocean—must be nurtured over significant periods of time, sometimes decades, before they prove their worth in the field.

Looking to the future, there are numerous emerging technologies that have the potential to expand, and even revolutionize, science's observational capacity. Three such examples are autonomous underwater vehicles (AUVs), long-duration balloons and air ships, and mobile drilling capacity for rapid drilling; see Figure 4.4. AUVs allow investigators to access difficult environments such as within cavities underneath ice shelves. Long-duration balloons and air ships allow instruments to access the upper portion of the atmosphere for extended periods of time, even potentially years at a time. Mobile drilling capacity, such as the FASTDRILL project, will allow for rapid drilling of multiple holes that significantly improves information output. Examples of platforms like these that provide access for measurements in more locations, with greater frequency, and at more times of the year will help provide needed data to address the types of science questions listed in Chapters 2 and 3. New technologies have the potential to affect all aspects of science, and a fuller, but by no means complete, list of emerging technologies is included in Appendix C. A continued effort to incorporate and adopt new technologies can ensure increased efficiency in U.S. research efforts.

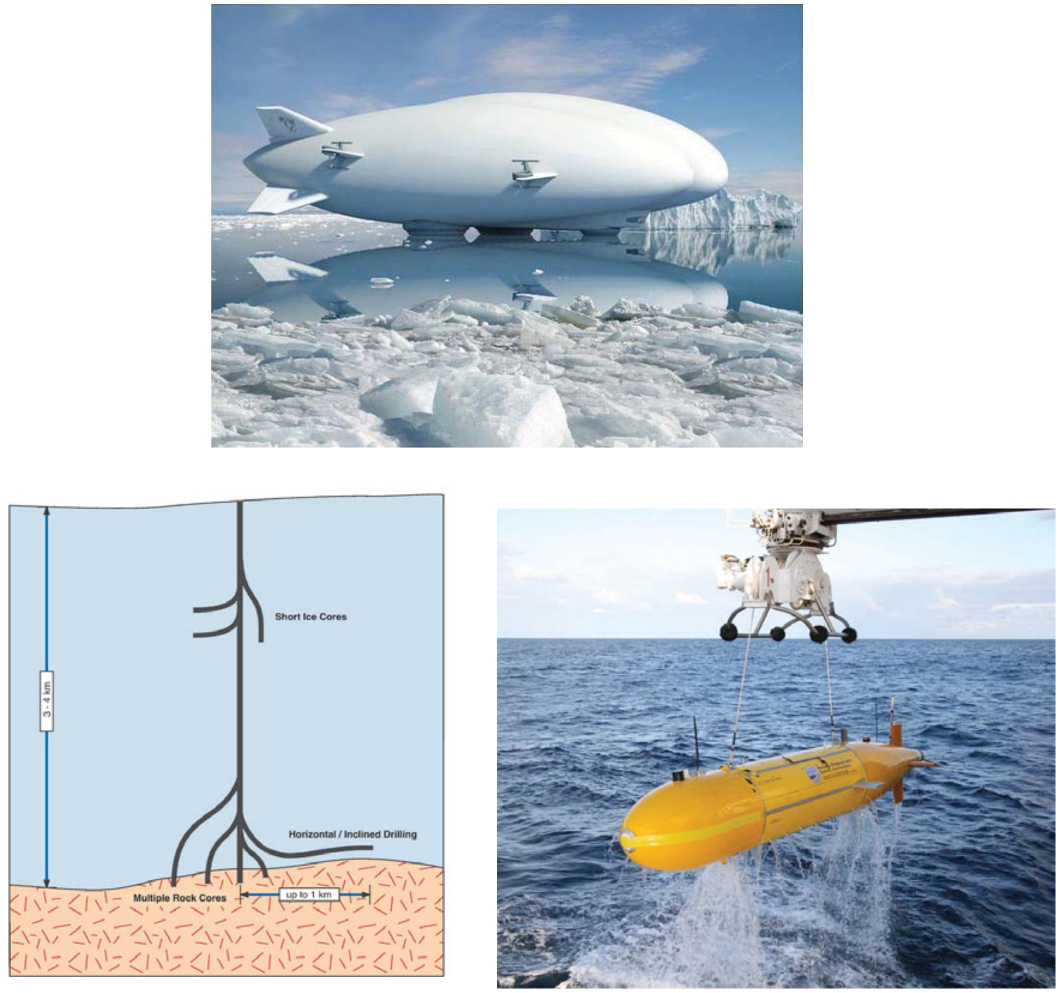

FIGURE 4.4 Medium-altitude blimp systems (top) can be self-sustaining, powered by solar and fuel cells. FASTDRILL (left) allows for the rapid drilling of multiple holes. The AUTOSUB (right) is propeller driven and programmable for navigation. SOURCES (from left to right): © Lockheed Martin 2008. Reprinted by permission; Clow and Koci, 2002; and National Oceanography Centre, Southampton.

Two special topics within this area are the use of research ships and icebreakers, both of which need to be considered for access to fully and partially ice-covered seas.

Research Vessels

Research ships have long been used for sampling of ocean temperature, salinity, plankton, and seawater chemistry, as well as the installation and servicing of moorings to monitor ocean properties and the launching of autonomous sampling systems. The expansion of physical and biological oceanography research in the Southern Ocean will require research ships that are capable of operating in fully and partially ice-covered seas.

Currently, much of the oceanography work in the Southern Ocean is performed from two privately owned research ships (the *Laurence M. Gould* and the *Nathaniel B. Palmer,* both leased by NSF from Edison Chousest Offshore, Inc.); these are able to navigate in the ice conditions around the Antarctic Peninsula but are not the polar class research icebreakers PC3 or PC5 (Appendix D, Table D.1) needed for scientific support around the Antarctic coast and ice-covered Southern Ocean. The U.S. Coast Guard cutter *Healy* can operate in ice-covered seas and has power and displacement greater than other icebreakers used for scientific research in the Arctic and Antarctica (e.g., *Oden* [Sweden], *Polarstern* [Germany]). There is a need to examine the fleet of research vessels in the United States, particularly with respect to ships that operate in fully and partially ice-covered seas; this is discussed in more detail in a previous NRC report, *Critical Infrastructure for Ocean Research and Societal Needs in 2030* (National Research Council, 2011c), and an analysis of U.S. Coast Guard capabilities (O'Rourke, 2011).

Heavy Icebreakers

Heavy icebreakers are a special class of surface ships that are essential to the conduct of science in Antarctica and the Southern Ocean, providing access for ocean and coastal research in heavy ice covered seas, and allowing fuel and supplies to reach research stations. They are complex, sturdy vessels that are inherently expensive. Icebreakers are discussed in more depth in Appendix D, with a brief summary provided here. Anticipated scientific research needs in Antarctica and the Southern Ocean will require the services of heavy icebreakers, not only to break ice and clear out harbors, but also to support research missions for less-capable polar research vessel icebreakers and act as helicopter platforms. In addition, scientific operations at McMurdo now totally rely on the annual resupply in late Austral summer of fuel and materials; this is done by transport ship and tanker and requires heavy ice-breaking capacity.

There is a critical shortage of U.S. heavy icebreaking capacity in Antarctica and the Southern Ocean at this time. The two U.S. Coast Guard heavy icebreakers, *Polar Sea* and *Polar Star*, are more than 30 years old and have exceeded their service lives. The *Polar Sea* is to be decommissioned in 2011. The *Polar Star* is undergoing engine repairs and refitting needed to extend this ship's service for a limited period; repairs are expected to be complete in 2013. As concluded by the 2007 NRC report *Polar Icebreakers in a Changing World,* the "operations and maintenance of the polar icebreaker fleet have been underfunded for many years" (National Research Council, 2007b).

The purchase of any new polar class icebreakers by the United States will be expensive. Alternatives for building heavy icebreaker capability include partnerships with other countries and leasing icebreakers flagged by other countries, such as the successful collaboration between the United States and Sweden using the icebreaker *Oden*. The arrangement with Sweden is not permanent, however, and the *Oden* will not be available for the McMurdo break–in during the 2011-2012 austral summer; thus, another polar class icebreaker must be engaged for this essential resupply mission. A contract has been signed by the NSF and the Murmansk Shipping Company to provide the Russian diesel electric heavy icebreaker *Vladimir Ignatyuk* to perform the McMurdo break-in for the 2011-2012 season, with options for two more years of support.

Other reports have discussed the need for the United States to have its own icebreaking capacity, including three previous NRC reports, a congressional analysis, and a Homeland Security audit (National Research Council, 2007b, 2011c, 2011e; O'Rourke, 2011; Richards, 2011). These documents conclude that there are strong national security and operational reasons for the nation to develop its own icebreaking capability. As stated in the *Critical Infrastructure for Ocean Research and Societal Needs in 2030* (National Research Council, 2011c) report, "the nation should recover U.S. capability to access fully and partially ice-covered seas." Based on the scientific research needs outlined in this report, the committee strongly supports the conclusion that the United States should develop sufficient icebreaking capacity, either on a national or international basis. Any arrangement should ensure that the U.S. needs in Antarctica and the Southern Ocean, for both research vessel support, and in particular the annual break-in supplying McMurdo, can be met by secure, reliable, and heavy icebreaking capacity.

Infrastructure

Science activity in the Antarctic region is dependent on facilities and on transport, and as noted above in the energy section, successful science depends on adequate provision of energy. Ships bring heavy cargo and fuel to support operations at Palmer Station and McMurdo Station. Aircraft bring personnel and equipment from Christchurch, New Zealand, down the 170° East meridian to McMurdo Station. From McMurdo, aircraft take personnel and equipment to the Amundsen-Scott South Pole Station or other locations, and supply materials and much of the fuel to those sites as well. The McMurdo-South Pole overland heavy traverse was established during the 2008-2009 season, and has continued each season. Many waste materials are required to be taken away from the inland sites, and eventually away from the continent.

Physical Infrastructure

Science activity in the Antarctic region is dependent on facilities and on transport, and as noted above in the energy section, successful science depends on adequate provision of energy. Ships bring heavy cargo and fuel to support operations at Palmer Station and McMurdo Station. Aircraft bring personnel and equipment from Christchurch, New Zealand, down the 170 meridian to McMurdo Station. From McMurdo, aircraft take personnel and equipment to the Amundsen-Scott South Pole Station or other locations, and supply materials and much of the fuel to those sites as well. The McMurdo-South Pole overland traverse is starting but is not yet established as a routine and reliable supply strategy. Many waste materials are required to be taken away from the inland sites, and eventually away from the continent.

Both transportation and facilities have improved dramatically over the past decades; an improvement that is easy to see given the existence of well-preserved huts left by the explorers of a century ago. It is reasonable to expect significant additional improvements in infrastructure in the coming years, and these improvements represent opportunities for improved efficiency and effectiveness. One of the most promising examples is the installation of wind turbines for electric power generation at McMurdo Station and New Zealand's Scott Base, discussed earlier. Similarly, ongoing improvements in materials technology have resulted in better building materials, clothing and outerwear, and scientific equipment.

One concern worth considering is the degree to which inherently harsh environments such as Antarctica and the Southern Ocean should be made to resemble settled areas elsewhere. A campsite does not necessarily require all the features of a modern city, and temporary field facilities for scientific work may be reasonably safe without meeting electrical and other code requirements for permanent buildings. Anecdotal evidence suggests that imbalances along these lines are common, with expectations for safety outweighing practicality. The health and safety of personnel are important, but overzealous development and enforcement of safety protocols can interfere with scientific work and add to the costs of supporting such work. A reasonable balance could be sought. The committee encourages the Blue Ribbon Panel to examine these issues as part of its review of the logistical support of science in Antarctica and the Southern Ocean.

The impacts of global human activity, such as increasing releases of greenhouse gases into the atmosphere and the resulting global climate change, far outweigh the impact researchers will have on Antarctica and the Southern Ocean. Yet stewardship of this fragile environment will require continual vigilance. The "footprints" of stations such as McMurdo or the South Pole Station should be kept as minimal as possible and researchers should strive to ensure that exploration does not lead to irreversible changes in the environment, such as possible contamination of subglacial lakes from drilling into these fragile environments.

Cyberinfrastructure

Scientific research in Antarctica and the Southern Ocean is already moving toward the deployment of extensive sensor networks that generate vast amounts of information. Remote sensing is now an important element of astronomy, physics, climate, oceanography, and biology. The kinds of novel sensors discussed earlier in this section and later in this chapter can usher in an era of "big data" for Antarctica and the Southern Ocean. Significant information processing capability would need to be located directly on the Antarctic continent to provide preliminary analysis of these data and to clean and compress the data for efficient transmission to and analysis by researchers and U.S. government agencies located in the United States and elsewhere.

Cyberinfrastructure support for research in Antarctica and the Southern Ocean is currently limited. Some facilities (e.g., the Amundsen-Scott South Pole Station) are often beyond the range of major communication satellites in geostationary orbit above the equator because of the curvature of the Earth. Intermittent satellite communication from such sites is provided from only those "failing" geostationary satellites that have gone far enough out of position to allow access. Low-Earth-orbiting communication satellites such as the Iridium System provide some data connectivity, but that connectivity is limited and expensive and will not provide the level of connectivity needed for future sensor networks. Future scientific research in Antarctica and the Southern Ocean would greatly benefit from "24/7" Internet connectivity. High-bandwidth capability to and on the Antarctic continent would require improved terrestrial and satellite communications infrastructure (Lazzara and Stearns, 2004). Cyberinfrastructure support would also aid in deployment of new instruments with computer-controlled mechanics for positioning and sampling, as well as scientific instrumentation with onboard information processing and data management capability. Such advances would expand scientific activity without an equivalent expansion of costs.

Given the importance of sensing networks, it is vital that the cyberinfrastructure needs for such networks be understood in advance of design and deployment. Cyberinfrastructure is not merely a complementary asset for such systems; it is in many cases the core of such systems and should not be left until it is too late to realize the essential needs it covers or the benefits it brings. As evidence of the emerging importance of cyberinfrastructure to all areas of science and engineering, several years ago NSF created an Office of Cyberinfrastructure under the Director. All polar research programs, and particularly those in Antarctica and the Southern Ocean, would benefit from incorporation of cyberinfrastructure planning in their overall planning.

4.3 EDUCATION

General Education

The report *Rising Above the Gathering Storm* (National Research Council, 2007c) raises the concern that the United States is not producing sufficient numbers of scientists and engineers to ensure a competitive future for the nation. Numerous measures of science education achievement in schools indicate that U.S. students are falling behind students from other nations, and that this could imperil the nation's future prosperity and security. Antarctic and Southern Ocean science can play a positive role in addressing this national need for science, technology, engineering, and mathematics (STEM) professionals and the general education of a scientifically literate citizenry. People of all ages are interested in the polar regions, and interest in polar science could have a similar mobilizing effect on students in the early 21st century that space exploration had in the latter half of the 20th century. An interesting example of this "polar appeal" is the remarkable reception the 2005 National Geographic film *March of the Penguins* received.[7]

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[7] See *http://www.nationalgeographic.com/marchofthepenguins/*; the film won an Academy award and grossed more than $120 million worldwide (*http://www.imdb.com/title/tt0428803/business*).

NSF supported a broad spectrum of educational efforts during the IPY. These programs targeted informal and formal science education at the K-12 level and aimed at improving the skills of classroom teachers, and they reached audiences across the United States and around the globe. An NSF-supported *NOVA* television special focused on recovering key climate records in the Ross Sea, and a number of radio programs on polar science were broadcast in the United States, the United Kingdom, New Zealand, Germany, and Australia. Polar-Palooza, a successful multimedia presentation with scientists as stars, toured U.S. science centers, museums, libraries, and schools. The IPY Research and Educational Opportunities in Antarctica for Minorities program took 15 undergraduate students, 5 graduate students, and 5 high school teachers on an ecological study of the Antarctic Peninsula. K-12 teachers made field trips with the Teachers and Researchers Exploring and Collaborating program, and developed online materials through WGBH Television's Teachers' Domain.[8] NSF has long operated the highly successful Antarctic Artists and Writers program that has done much to help popularize polar science and communicate it to the general public.[9] The program enables artists and writers to travel to the continent with the goal of increasing public awareness and understanding of the research that takes place there.

These kinds of efforts are a crucial part of the overall communication of polar science to society at large. They should be continued, and communicators of science to the general public should be seen as an essential part of the overall scientific enterprise. Major science initiatives, such as those in Antarctica and the Southern Ocean, can greatly benefit from education and public outreach components.

Any efforts undertaken by NSF or other agencies working in the Antarctic region would need to be informed by and supportive of national education standards to be effective for K-12 science education. The Next Generation Science Standards project is establishing new science education standards under the leadership of the National Academies and in collaboration with state departments of education. These standards will be adopted in many states and instruction will be aligned with those standards. Similarly, new standards for mathematics education and English-language arts have been released and widely adopted by states. Polar science can contribute directly in the areas of science and mathematics education, and more broadly to interdisciplinary themes. A good first step would be to convene one or more workshops to determine how polar science can contribute to the success of national education standards.

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[8] See *http://www.teachersdomain.org*.

[9] See *http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=12783&org=OPP*.

The Workforce Pipeline

Improved education is a vital "pipeline" issue. A new generation of polar scientists will be required to implement the vision laid out in this report and to work in science broadly. Some fraction of K-12 students will enter STEM careers, and some fraction of those will become the U.S. polar science leaders of tomorrow. It is important to develop enough strong scientists to take up the work in the Antarctic region, especially as international collaborations grow and advanced scientific techniques (particularly computation and simulations) enable new kinds of science, while broadening participation in science at all levels. The inherent lure of polar science might be sufficient to keep the pipeline going generally. The committee developed an online questionnaire for polar scientists as part of its work (see Appendix B for a fuller description of the questionnaire and responses). Questionnaire respondents reported by a 3:1 margin that they were able to find the needed students and postdocs. In addition, a majority of respondents felt that there existed a "next generation of scientists" who will be able to continue to advance their scientific field for the next 20 years (see Appendix B, Figure B.4). While concerns were raised about the variable quality of the workforce of the next generation, the first-order future of the Antarctic scientific community—simply having enough experts to do the science—appears to be secure.

The problem of broadening participation is more difficult to address. As fewer college students choose STEM fields, there is an increased need to attract STEM majors, including students from groups who have been historically underrepresented in science. In 2007, African-American and Hispanic students accounted for less than 4 percent (26 out of 653) of physics Ph.D.s awarded to U.S. citizens (Mulvey and Nicholson, 2010). Yet, such minority groups are growing as a fraction of the U.S. population.[10] Their participation in science is important because the new generations of scientists will be drawn from a student body comprised increasingly of these minority groups. To expand diversity in Antarctic research, the Antarctic research community needs to have a greater presence at venues with large numbers of minority students. The annual meeting of the Society for Advancement of Chicanos and Native Americans in Science (SACNAS) represents one such venue. SACNAS hosted Polar-Palooza[11] in 2008 and provided many students with their first opportunity to learn about the excitement of polar research.

The committee's questionnaire also provided insights into some of the reasons behind the difficulty of broadening participation. The questionnaire asked, "How did you get into Antarctic and/or Southern Ocean science?" and "Are similar pathways available

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[10] See *http://2010.census.gov/2010census/data/*.

[11] See *http://passporttoknowledge.com/polar-palooza/pp01.php*.

to others today?" Approximately half the respondents indicated that they began as students or postdoctoral researchers in a relevant field. These scientists obtained their start in Antarctic research by collaborating with established Antarctic researchers. Many of these respondents appeared concerned that Antarctic research is a "closed shop" and not particularly welcoming of outsiders. A "closed shop" would have serious implications for broadening participation in polar science: if the leaders in the pipeline are not themselves a diverse community, then special efforts will be required to broaden participation from new entrants. Established social networks are not the only path for entry into polar science, however. A significant number of respondents said they wrote independent proposals and were funded, and these respondents believed that any scientist who wants to participate in polar research can do so. Encouraging independent proposals from underrepresented participants is another possible avenue for broadening participation, and serious thought should be given to helping such participants to be competitive.

Although the current pipeline seems strong, important opportunities should be considered. Investment in proven models is a good place to begin. For example, the International Graduate Training Course in Antarctic Biology[12] has been a well-regarded summer school in Antarctic research for biology students at McMurdo Station for the past 16 years; students in the course have the opportunity to do laboratory and field-based research in Antarctica focused on biological adaptations in an extreme environment. Such efforts should be evaluated and, if warranted, expanded to include other fields for multidisciplinary research, while also incorporating lessons learned as well as the latest pedagogical approaches to promote student learning (e.g., Lopez and Gross, 2008). Graduate students, in particular, benefit from research-based instructional strategies that draw from research findings. Such students will form the next generation of university faculty, and they are likely to teach the way that they were taught. Making doctoral education more responsive to societal and educational needs is an important objective for all areas of science (Woodrow Wilson National Fellowship Foundation, 2005), and the polar science community should take advantage of the opportunity to develop innovative professional educational efforts that build on the interdisciplinary and unique aspects of Antarctic research.

Vision for the Future

A characteristic of education for polar science is the ad hoc and somewhat haphazard pattern shown of the efforts that have been mentioned in this section. All levels of

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[12] See *http://www.nsf.gov/events/event_summ.jsp?cntn_id=104292&org=ANT*.

education—K-12, undergraduate, graduate, and public education and outreach—require coordination if they are to have a lasting impact. A strategic plan for education in polar science would reduce the uncertainty and variation of programs from year to year. The NSF Geoscience Directorate (GEO) has developed an interdisciplinary portfolio strategy that incorporates the different pipelines by which people enter graduate study in the geosciences. Geoscientists often do not originate in the geosciences, but come from physics or chemistry, so pathways into and through the pipeline are likely to vary. GEO has established its own education program as a line item and appointed a dedicated Program Officer. This and similar strategies are worth examining. The NSF Office of Polar Programs (OPP) has extraordinary opportunities to influence education at all levels, and it is arguably among the best positioned of NSF's efforts to engage broad public participation in STEM-related learning. Such a program would be able to collaborate on an institutional level with programs within NSF's Education and Human Resources Directorate, leveraging the impact of Antarctic (and polar) science on many education programs. Any OPP educational plan would benefit from including a well-integrated component designed to recruit a diverse group of students into Antarctic research and to address opportunities in areas such as computational science education that will be increasingly important to science as a whole.

4.4 OBSERVING NETWORK WITH DATA INTEGRATION AND SCIENTIFIC MODELING

The preceding chapters highlight important scientific questions expected to drive research in Antarctica and the Southern Ocean over the next two decades. Because many other nations are tackling the same questions, there is a great deal of sense in working together. Answering these questions will require interdisciplinary approaches at the system scale that would be best addressed with a coordinated, long-term, international effort. Given the scope of its research program and support infrastructure in the Antarctic region, the United States has the opportunity to play a leading role in this effort. The committee has identified two new initiatives that are critical to this effort to achieve rapid and meaningful advances in science in Antarctica and the Southern Ocean in the coming 10-20 years: expansion of an observing network with data integration and improvements in scientific modeling capabilities.

Observing Network with Data Integration

From predicting sea level rise to understanding ecosystem response to environmental change, the preceding chapters of this report highlight the most important scientific questions that will be driving Antarctic research over the next two decades. A common theme throughout these chapters is the role that integrated and sustained observations will play in answering these questions. These problems are highly multidisciplinary, exist on a system scale, and cross multiple domains. The United States has the ability to help lead the effort that is required to address these questions. To be effective, this effort needs to go far beyond what can be achieved with expedition- and project-based data gathering. Therefore, the committee identifies an overarching need for NSF to help lead a coordinated international Antarctic observing system network encompassing the atmosphere, land, ocean, ice, and ecosystems, as well as their interfaces. This initiative should provide the framework for intensive data collection, management, dissemination, and synthesis across projects and across disciplines; lay the foundation for many future Antarctic and Southern Ocean observations; use models to evaluate and plan the optimal locations for observations; and maximize the scientific output from deploying resource-intensive observing platforms in such an extreme environment.

Examples of Observing Networks

The concept of an observing system is not new, particularly in the atmospheric and oceanographic sciences. There are strong precedents and valuable models for the multidisciplinary system the committee envisions. Ocean observing networks with shared common protocols, data formats and sensors, with joint operations from multiple countries have matured over the past several decades. Established systems that contribute to the Global Ocean Observing System,[13] which is focused on the physical properties of the ocean, include satellite observations, surface drifters and profiling floats ("Argo"), networks of moored instruments, networks of simple observations from merchant and military ships, and networks of specialized observations from research ships. Each of these individual systems includes international coordination, infrastructure, and commitment for long-term operations, usually with an integrated data system.

Many open-ocean observing systems were invigorated or implemented during the large international research programs of the 1980s and 1990s, including the Joint Global Ocean Flux Study (see example in Figure 4.4 of carbon records at the ship-based oceanographic station established near Hawaii in 1987) (Fasham, 2003); the Tropical Ocean-Global Atmosphere program, which introduced moored observations of temperature, salinity, currents, winds, and air-sea fluxes in the equatorial Pacific Ocean (now expanded to the Atlantic and Indian oceans) to enhance the prediction of tropical

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[13] See *http://www.ioc-goos.org/*.

climate variability (McPhaden et al., 2010); and the World Ocean Circulation Experiment, which initiated the global drifter, profiling float, and ship-based observations that have continued and expanded, mainly with observations of physical properties.

Within the United States, the Integrated Ocean Observing System (IOOS[14]) is a major interagency portal and umbrella for physical and ecosystem observations. The IOOS provides an excellent model for an integrated observing system in the Southern Ocean, especially if such a framework is international, because it is inconceivable that the region could be adequately observed without major international partnerships. As part of the U.S. IOOS, a large new NSF program, the Ocean Observatories Initiative[15] (OOI), will provide 25-30 years of sustained ocean measurements to study climate variability, ocean circulation, ecosystem dynamics, air-sea exchange, seafloor processes, and plate-scale geodynamics. The OOI infrastructure includes cabled seafloor observatory nodes, moored sensors, AUVs, and gliders, as well as the supporting cyberinfrastructure for data and communications (National Science Foundation, 2005). The large OOI is representative of the magnitude of just part of the effort that will be required for comprehensive observation of the Southern Ocean.

Looking to the future, the committee proposes a sustained, multinational, multidisciplinary effort to monitor ocean conditions in the Southern Ocean, including hydrography, levels of carbon dioxide (CO_2), and nutrients (Rintoul et al., 2011). Such an observing system would offer the opportunity for large-scale data collection covering huge areas of ocean (for an example of such a system, see Figure 4.5), producing large quantities of data that can be analyzed over time by researchers around the world. Community-based efforts for a Southern Ocean Observing System (SOOS; Rintoul et al., 2011) are well under way (Figure 4.6). Its present design addresses many of the major scientific questions identified in this report, including the role of the Southern Ocean in the planet's heat and freshwater balance, the nature and stability of the Southern Ocean circulation, the interaction of the Southern Ocean with the glacial ice sheets of Antarctica and its effect on their contribution to sea level rise, the stability of the Southern Ocean sea-ice cover, the impact of Southern Ocean carbon uptake regionally and globally, and the future of Southern Ocean ecosystems. Such efforts, or parts thereof, can form the nucleus of a comprehensive cross-disciplinary, system-scale, long-term Southern Ocean observing initiative.

In ecology, the U.S. NSF Long Term Ecological Research (LTER) Network is a coupled, multidisciplinary system of 26 observing sites, each focusing on a specific ecosystem (e.g., grasslands, coastal marine, forests), including the McMurdo Dry Valleys and

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[14] See *http://www.ioos.gov/*.

[15] See *http://www.oceanobservatories.org/*.

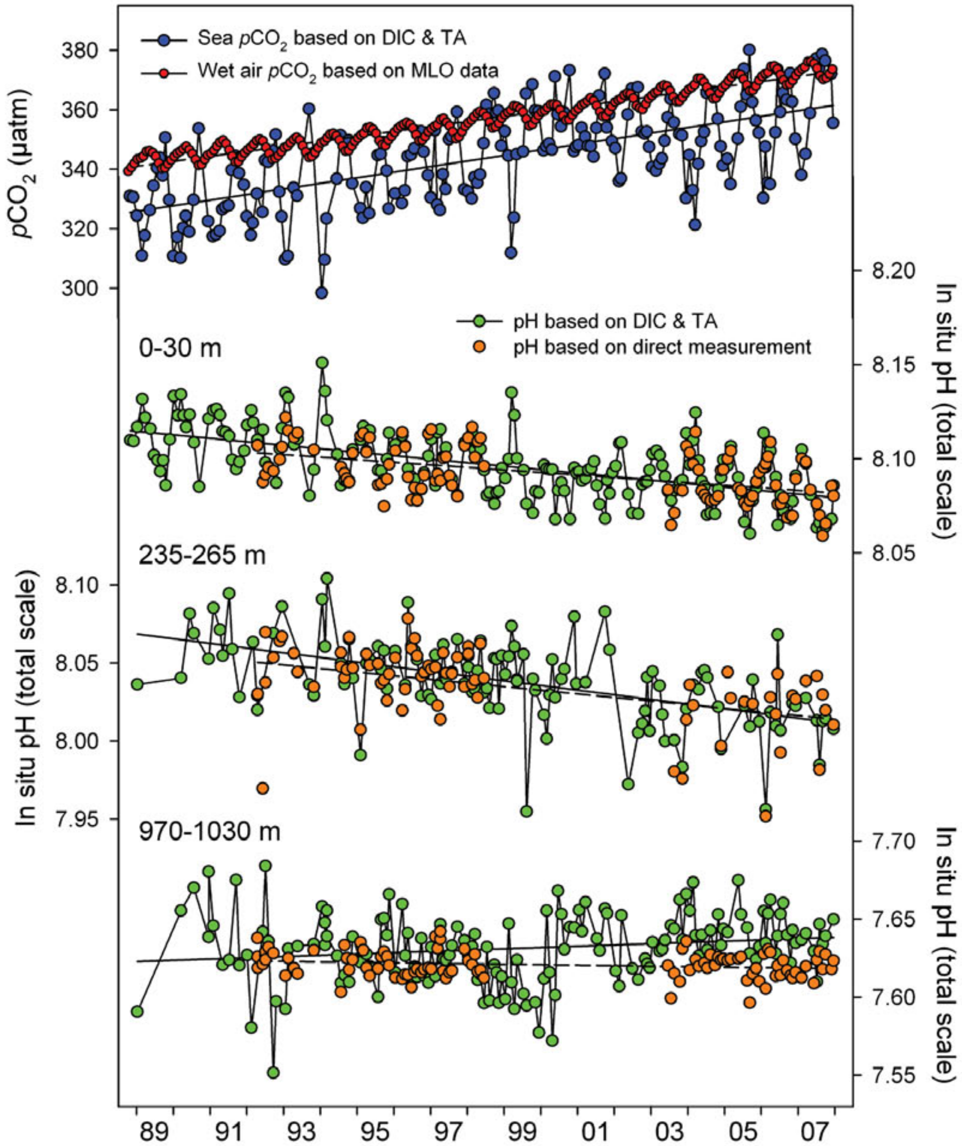

FIGURE 4.5 Time series of mean carbonic acid system measurements within selected depth layers at Station ALOHA, 1988-2007. (First image) Partial pressure of CO_2 in seawater calculated from DIC and TA (blue symbols) and in water-saturated air at in situ seawater temperature (red symbols). Linear regressions of the sea and air PCO_2 values are represented by solid and dashed lines, respectively (second, third, and fourth images). In situ pH, based on direct measurements (orange symbols) or as calculated from DIC and TA (green symbols), in the surface layer and within layers centered at 250 and 1,000 m. Linear regressions of the calculated and measured pH values are represented by solid and dashed lines, respectively. SOURCE: Dore et al., 2009, © 2009 National Academy of Sciences.

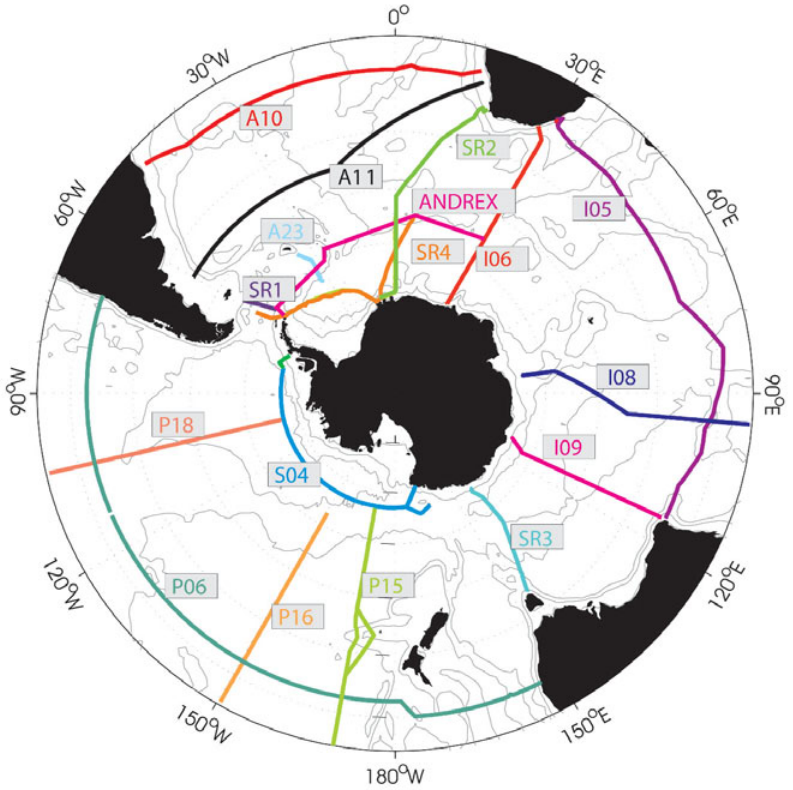

FIGURE 4.6 Repeat hydrographic section to be occupied by SOOS. Symbols indicate the WOCE/CLIVAR designations for each line. SOURCE: Rintoul et al., 2011.

Palmer LTER Sites in Antarctica (Hobbie et al., 2003). The LTER Network was established in 1980 with six sites that now have more than 30 years of sustained data collection. Sites share common measurements and participate in a unified data system. Some sites build on previously initiated time series such as the California Current Ecosystem LTER, drawing on the legacy and ongoing observations of the California Cooperative Fisheries Investigation started in 1950 (Ducklow et al., 2009). The LTER sites investigate a wide range of ecological phenomena, but common themes like climate change, biogeochemical cycling, and invasive species characterize many sites as diverse as a tropical rainforest and an Antarctic pelagic marine ecosystem. The LTER Network provides a model for just a part of the proposed Antarctic observing system (the ecological component, anchored by the Palmer and McMurdo sites).

There are a number of measurements that can only be made from space. Remote sensing allows the measurement of variables over greater geographic areas. The Integrated Global Observing Strategy initiated a Cryosphere Theme[16] as part of the IPY in 2007-2008. The summary report from 2007[17] contained a number of recommendations for future developments in remote sensing that could enhance the envisioned Antarctic observing system.

A closer model to the committee's vision for Antarctica and the Southern Ocean is the currently evolving Arctic Observing Network[18] (AON) that includes many of the needed elements. AON is an NSF-supported system of atmospheric, land-, and ocean-based environmental monitoring capabilities with four main objectives:

- record the full suite of environmental changes;
- understand the causes and consequences of the changes under way;
- predict the course, magnitude, and consequences of future changes; and
- develop adaptive responses to future change.

The need for an Arctic Observing System was conceived by the Arctic research community in response to system-scale changes in all domains of the Arctic system. It was included as a recommendation in the final report on the 1998 workshop *Opportunities in Arctic Research* that stated, "If we are to understand the implications and effects of the changes in the Arctic, we must first of all track them into the future by establishing long-term, systematic observation programs." It was developed and promoted during the design of Arctic Environmental Change programs such as the Study of Environmental Arctic Change (SEARCH) or the International Study of Arctic Change (Murray et al., 2010; Schofield et al., 2001) and the development of recommendations for Arctic research support and logistics (Schlosser et al., 2003). Major impetus for its implementation came from the IPY and the NRC report *A Vision for the International Polar Year 2007-2008* (National Research Council, 2004), which recommended that IPY "should be used as an opportunity to design and implement multidisciplinary polar observing networks that will provide a long-term perspective." Later, in a follow-up report from the Polar Research Board, *Toward an Integrated Arctic Observing Network* (National Research Council, 2006), a committee recommended that development of an Arctic Observing Network aided by Observing System Simulation Experiments should get under way immediately to take advantage of IPY. Currently in the United States, AON has 35 funded projects pursuing research on the Arctic atmosphere, ocean and sea ice, hydrology and cryosphere, terrestrial ecosystems, and human dimensions. A

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[16] See *http://igos-cryosphere.org/index.html*.

[17] See *http://igos-cryosphere.org/docs/cryos_theme_report.pdf*.

[18] See *http://www.nsf.gov/news/news_summ.jsp?cntn_id=109687*.

complementary international effort called Sustaining Arctic Observing Networks[19] is presently being implemented with the goal to coordinate and facilitate implementation of Arctic observing activities at the international level.

Vision and Goals for an Observing System

An Antarctic observing system—including in situ and remote measurements—would have many of the same goals as AON: to establish a new infrastructure for sustained observations capable of detecting and recording the full suite of environmental changes occurring over decades within the Antarctic system of atmosphere, oceans, land, and ice; to further the understanding of the causes and mechanisms of change and develop the capability to predict the course of future changes; and to better manage the continent for future generations. The envisioned observation system would also share a number of the same goals as the proposed Pan-Antarctic Observation System (PAntOS) that hopes to "deliver a coherent set of pan-Antarctic, long-term, and multidisciplinary observations focused on the entire chain of effects from geospace to Earth's surface."[20] PAntOS was proposed to be a SCAR Action Group in conjunction with the SCAR Open Science Conference in Hobart during 2006. The primary goal of the PAntOS Group was "to address the scope and implementation strategies for the follow-on development of the multidisciplinary Pan-Antarctic Observations Network encompassing the Antarctic Continent and the surrounding Southern Ocean."[21] Planning continued into 2007 but did not result in the formation of an Action Group and no activities have taken place since.

Inherent to this concept of an observational network is the need for sharing of data and information. Overall improvements by all institutes in the collection, management, archiving, and exchange of data and information will allow data that has been collected once to be used for multiple purposes by a variety of stakeholders reaching well beyond the scientific community. An observational network will require the efforts of more than one nation, and, as encouraged by the Antarctic Treaty, SCAR, and recently published science plans, it is important that data and information be shared at an international level. Initiatives like the Polar Information Commons[22] are beginning to address this issue. The United States has played a leading role in supporting international data sharing and should continue in this role. Internationally shared data sets can become assets that are greater than the sum of their national parts.

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[19] See *http://www.arcticobserving.org/*.

[20] See *http://www.scar.org/researchgroups/physicalscience/PAntOS_Plan_Rev1.pdf*.

[21] Ibid.

[22] See *http://www.polarcommons.org/*.

The increasing scope of Antarctic and Southern Ocean research envisioned for the coming years and decades will likely require diversification of its support. Presently, NSF is the primary agency supporting research in these regions, although current contributions from other agencies are adding significant capacity. The research activities proposed by this committee for the coming decades include components that will require a higher level of participation by other agencies, including mission-oriented or operational agencies. Without the latter, implementation and maintenance of a cross-domain, long-term, system-scale observing system for Antarctica and the Southern Ocean will be at best extremely difficult and would have a major impact on the ability to sustain a balanced portfolio of new research programs. The same holds for other components, such as enhanced development and application of new technologies. A multiagency approach should include participation by NSF, the National Oceanic and Atmospheric Administration (NOAA), NASA, the Department of Defense (Office of Naval Research), the U.S. Geological Survey, the Environmental Protection Agency, and the National Institutes of Health, as well as any other agency whose mission fits the vision for future research in Antarctica and the Southern Ocean outlined in this report. Effective coordination among agencies will be a key requirement for success of a future Antarctic research support structure.

Observing System Overview and Components

An observation system has three major components:

1. a set of observations of selected properties being made repeatedly at selected locations or in specified areas over a sustained period;
2. cyberinfrastructure for collection, communication, and curation of data; and
3. a network of scientists, technicians, and students to further develop the technology underpinning the system (e.g., novel and robust sensors), synthesize and analyze the data produced by the system, and predict future trajectories of the system grounded in observations.

The Antarctic observing system would be most beneficial if it encompassed the major elements of the Earth system: the atmosphere, oceans, land surface, ice, and both terrestrial and marine ecosystems that inhabit or are supported by these major geophysical systems. Sensor deployment should be guided by model-based observing system design and optimization whenever possible and take advantage of multisensor platforms wherever feasible (including use of existing platforms and observatories where possible). Data delivery should be timely—in real time or as close to real time as possible. As data transfer is currently achieved by manually downloading data periodically (often annually) or via low-bandwidth telecommunication systems (Iridium and Argos), a systemwide approach to improving data transfer could benefit both scientific observing needs and operational needs that rely on data transfer (e.g., operational weather data). Once assembled, data from observing systems should be widely available through data centers and/or web pages for scientific use including modeling, as well as for use by the broad stakeholder community. The design of an Antarctic observing system would benefit from a deliberate planning process, similar to that for AON. As an initial step, the major requirements for the observing system are outlined briefly in Appendix E.

Scientific Modeling

Any observing system will be incomplete without the simultaneous development of new models that can assimilate the observational data and provide sophisticated tools for data analysis and synthesis. For example, sea level projections due to ice changes come mainly from ice sheet models that lack the appropriate initial and boundary conditions with inadequate understanding of the underlying ice physics. Capturing system-scale spatial patterns in multiple domains including the ocean, atmosphere, sea ice, glacial ice, and biology requires modeling on multiple timescales. It is also important that empirical, theoretical/dynamical, and simplified modeling approaches be incorporated along with the execution of process studies to provide the scientific understanding from which to build better models.

Data assimilation allows the merger of diverse observation types that are irregularly dispersed in space and time (such as from the ground and space) into a coherent three-dimensional and time-dependent framework. The technique was first developed by the atmospheric science community for use in numerical weather prediction and is currently being extended to many other disciplines. A short-term prediction from a numerical model provides an initial estimate of the behavior of the system, and that estimate is further modified by additional observations.

Data assimilation has evolved through global retrospective analyses and reanalyses. For example, the latest reanalysis from the NOAA National Centers for Environmental Prediction features coupled assimilation of data on atmosphere, ocean, sea ice, and land surface (Saha et al., 2010). The next generation of reanalyses aims to develop an Integrated Earth System Analysis capability.[23] Possible components contemplated for inclusion are greenhouse gases, aerosols, ocean biogeochemistry, and ecosystems.

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[23] See *http://www.usclivar.org/Reanalysis2010.php.*

Global reanalyses are essential tools for investigating Arctic and Antarctic climate system behavior, but high-quality results are difficult to obtain for the Southern Ocean and Antarctica because of insufficient ground-based observations, challenges of assimilating the available satellite data, limited realism of the physical descriptions employed in the models, and the perception that this unpopulated part of the world is less important than other areas such as the tropics or the northern midlatitudes. Better reanalyses of the Southern Ocean and Antarctica would greatly benefit international efforts at modeling, leading to development of an Earth system reanalysis framework that enables both regional and global understanding.

Future conditions can be anticipated through models, and comprehensive Earth system models are the primary tools capable of projecting the behavior of the climate system as the atmospheric concentration of greenhouse gases increases. The outputs of these models are featured prominently in the Intergovernmental Panel on Climate Change reports (IPCC, 2007). Today the coupled behavior of the atmosphere, oceans, sea ice, and land is simulated. Among other components that are being or still need to be included are the dynamic behavior of ice sheets, the global carbon and nitrogen cycles, ocean and land biogeochemistry and ecology, the role of interactive aerosols, and the changing vegetation patterns. These global models have limited realism over the Southern Ocean and Antarctica, and significant effort is needed to develop accurate predictive capabilities.

The limited realism of the atmospheric simulations by Earth system models is illustrated by the rapid surface temperature increase over Antarctica that they simulate in contrast to the much more muted observed change (Monaghan et al., 2008). More accurate stratospheric simulations, including interactive stratospheric chemistry, are required to model the changing Antarctic ozone hole and the Southern Annular Mode. Improving Antarctic models also entails better representations of the Antarctic troposphere, including the ubiquitous stable boundary layer that, along with the surface topography, causes the katabatic winds. This necessitates high vertical resolution close to the ice sheet surface that is not available in any Earth system model. Higher horizontal resolution is required to resolve and place the strong coastal katabatic winds in the right locations for polynya formation. Antarctic clouds should not be modeled in the same manner as midlatitude clouds, but rather as tenuous ice clouds that nucleate on biological material and play an important role in determining the surface temperature and snow accumulation on the ice sheet. Similarly, future space weather models that use data assimilation will need diagnostic information about the ionosphere, as well as the underlying neutral atmosphere that can drive ionospheric dynamics.

Ice sheet models are starting to be included in Earth system models. Yet many aspects of ice sheet behavior are not well understood, such as ice streams, outlet glaciers, ice shelves and associated calving, and the flow of liquid water at the base. As a result ice sheet models currently show limited skill, but vigorous efforts at improvement are under way.[24] Progress in modeling Antarctic outlet glacier behavior will have the added benefit of being directly applicable to Greenland, where outlet glaciers are showing rapid change.

Earth system models do not capture the behavior of the Southern Ocean with much fidelity (Weijer et al., Forthcoming). Simulated sea ice behavior often shows large differences with respect to observations (e.g., Landrum et al., Forthcoming). Ice shelves are not included, so the formation of Antarctic Bottom Water is not well simulated. This is the densest water at the bottom of the global ocean and is part of the global oceanic overturning circulation that links the Southern and Northern hemispheres. This, along with Subantarctic Mode Water and Antarctic Intermediate Water, needs to be better understood to anticipate global climate change. Present models do not represent the transport across the Antarctic Circumpolar Current well, owing to their inability to resolve small-scale ocean processes. It is also important to understand the melting of ice shelves by warm ocean water (such as occurring in the rapidly retreating Pine Island Glacier) and their contribution to sea level rise, as well as the role of ice shelf retreat on the inland ice sheet.

For ecosystem models, a new generation of models is needed—one that can predict the effects of changes in species composition and ecosystem structure on ecosystem services (Reid, 2005), such as primary and secondary productivity, CO_2 uptake, and climate regulation, which are derived from properly functioning ecosystems. Current models lack species diversity, trophodynamic complexity, and realistic linkages between the lower trophic levels with their fast turnover times and upper-level predators that live for decades and range over thousands of kilometers, crossing ecosystem boundaries and coupling remote subsystems of the Antarctic system.

The many new physical processes that need to be understood at a process level and incorporated into models along with the fine spatial and temporal scales required indicate that regional climate system models will be required to make major progress in accurately predicting the broad-scale climate changes to be expected in Antarctica, not only for the long-term trends but also for the interannual and decadal variability. Successfully achieving such progress will require a major effort over the next 20 years. Regional Earth system models will need to be "nested" within the global Earth system

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[24] See *http://oceans11.lanl.gov/trac/CISM.*

models with simulation results flowing back and forth. Some work is already under way on this.[25] Improved Earth system models for Antarctica and the Southern Ocean are urgently needed to strengthen the simulation and prediction of global climate patterns.

Vision for the Future

The committee envisions an observing network with data integration along the lines of that in AON or the proposed PAntOS, along with a sustained modeling effort that plans and evaluates observation locations, synthesizes large data sets, and improves predictive capability looking into the future. Expansion of these activities holds great opportunity for improved productivity in science and will require resources and a careful planning process. These efforts are important for national and international collaboration, because the observation network and modeling effort described here are inherently interdisciplinary and will cross agency and institutional boundaries. This is very much in line with the goals of NSF as society enters the "New Era of Observation" as described by the NSF Director.[26] The committee endorses the development of an observing network and an improved intercoupled system modeling effort as the best hope in answering the pressing scientific questions facing the globe.

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[25] See *http://www.cesm.ucar.edu/working_groups/Polar/*.

[26] See *http://www.nsf.gov/news/speeches/suresh/11/ss110214_nsfbudget.jsp*.

A spring sunset near Palmer Station. SOURCE: Mindy Piuk/NSF.

CHAPTER FIVE

Future Directions in Antarctic and Southern Ocean Science

Explorers and scientists have worked to unlock the secrets of Antarctica for more than a century, and it has been just more than 50 years since the International Geophysical Year (1958-1959) ushered in an era of modern, internationally coordinated science. Yet the Antarctic continent and surrounding oceans still offer many untapped scientific opportunities. With advances in the understanding of the importance of the Antarctic region in the global system; advances in technology, computing power, and communications; and the continued geopolitical importance of having a scientific presence in the South, it is time to move into the next era of Antarctic and Southern Ocean science.

Over the past several years, evidence of a rapidly changing Antarctic environment has emerged from analyses of multiple data sets collected using a variety of different sensors. This information will be immensely valuable in expanding the understanding of climatic change across the globe. Antarctica and the surrounding Southern Ocean offer an unparalleled laboratory for studying environmental change and its global dynamics. In addition, the polar environment remains a unique place for scientific discovery, evidenced by the remarkable advances emerging from the efforts of more than 60 nations during the International Polar Year 2007-2008. These are discoveries that will alter the basic understanding of how the planet works and how the universe was formed. Moving forward in the coming decades, science in Antarctica and the Southern Ocean has the potential to lead to major advances in answering numerous questions of importance to science and society.

The United States is well positioned to continue as the preeminent research presence in Antarctica and the Southern Ocean by virtue of having a large national logistical support program and an exceptional pool of scientific talent upon which to draw. The South Pole Station, a major reconstruction project that required a significant portion of available resources of the U.S. Antarctic Program for much of the past decade, is completed. This reconstruction, along with the major effort required to construct the IceCube project, led to an imbalance in the resource allocation among the other areas of science seeking support. Now that the United States has a state-of-the-art research station high on the Antarctic ice sheet to compliment the stations at McMurdo and Palmer, there is an opportunity to strive to bring better balance in the support of all science and logistics priorities. The proposed observing network described in this report (Section 4.4) would facilitate some of that balance because many disciplines would benefit from the realization of such a network.

In this report, the committee has presented key science questions that the committee believes will drive research in Antarctica and the Southern Ocean in the coming decades, and the committee has highlighted several key opportunities to be leveraged to address those questions most efficiently. In this final chapter, the committee outlines six overarching recommendations that it believes are necessary to ensure success for the next generation of Antarctic science. The committee recommends that the United States

1. **Lead the development of a large-scale interdisciplinary observing network and support a new generation of robust Earth system models.** A broad-based observing system, including remote sensing as well as in situ instrumentation, is needed that can collect data that will record ongoing changes in the Antarctic atmosphere, ice sheets, surrounding oceans, and ecosystems. Such a large, sustained, and international effort will require a robust planning process and will likely require the leadership of at least one country; the United States could be the leader in this effort. Within the United States, the National Science Foundation (NSF) has the ability to take the lead in developing this observing network in close collaboration with other federal agencies having a fundamental interest in the polar environment, for example, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey. The goals of the observing network should be to measure and record ongoing changes, develop advanced understanding of the drivers of that change, and provide input for climate models that will enable the United States to project and adapt to the global impact evidenced by the changing Antarctic environment. Earth system models will need to incorporate the unique (and often unknown) conditions in Antarctica and the Southern Ocean in order to better project future changes to the planet more robustly.

2. **Continue to support a wide variety of basic scientific research in Antarctica and the Southern Ocean, which will yield a new generation of discoveries.** The Antarctic region provides a unique platform to perform basic science in a wide breadth of disciplines. In the coming decades future research directions will include discovering more about the climatic shifts that Earth has undergone in its history, the genetic understanding of diverse polar species and their adaptation to the rigors of life in Antarctica, and the predictabil-

ity of the weather in space, as well as the mystery of neutrinos and the origin and evolution of the universe. This research is poised to lead to remarkable new insights into the world and the universe over the next two decades.

3. **Design and implement improved mechanisms for international collaboration**. The complex nature and scope of both the changes to be studied and discovery-based basic science that will be conducted over the next 20 years in Antarctica and the Southern Ocean requires international teamwork. The International Polar Year (IPY) held from 2007 to 2008 demonstrated how successful international collaboration could work to foster discoveries and insights impossible for any single nation to complete. Even with the nation's unique logistical capabilities, the vast size of the Antarctic continent and ocean makes working with other nations and taking mutual advantage of their bases, ships, and transport systems both practical and advantageous. The logistical and scientific successes of the IPY demonstrated that the United States can appropriately support large collaborative international programs. The United States can best retain its leadership role in global science if it takes the lead in future international initiatives. Mechanisms to ensure timely and integrated international collaborative research would greatly enhance this effort.

4. **Exploit the host of emerging technologies** now and in the near future that can help facilitate all phases of research and logistics in Antarctica and the Southern Ocean. Technology has the ability to extend science's reach and revolutionize what is possible. A continued effort to incorporate and adopt new technology including cyberinfrastructure and novel sensors would ensure increased efficiency in U.S. scientific research efforts.

5. **Coordinate an integrated polar educational program.** The polar regions have powerful appeal to learners of all ages, and Antarctica could be used in the effort to help recruit, train, and retain a diverse and skilled scientific workforce for the future. The committee envisions building upon existing educational activities to develop a more integrated polar educational program that would encompass all learners including K-12, undergraduates, graduate students, early career investigators, and life-long learners. The polar education program should be based on the advances of modern educational research, incorporate experiences from other directorates at NSF, strive to diversify the population of students engaged in polar science, and take advantage of lessons learned from the IPY. The goal of this effort should be to engage the next generation of scientists and engineers required to support an economically competitive nation and foster a scientifically literate U.S. citizenry. A planning

process to design an integrated polar education program with other agencies with strong interests in the polar regions would be a logical beginning.

6. Finally, the conduct of the far-reaching and innovative work recommended in this report will require continued strong logistical support. The committee encourages the NSF-led Blue Ribbon Panel to develop a plan to support Antarctic science in the next two decades that will

    - **improve the efficiency** of the support provided by the contractor and enhance the oversight and management of the contractor by the scientific community;
    - **increase the flexibility** and mobility of the support system to work in a continent-wide and ocean-wide manner, using as much of the year and continent as possible, and fostering innovative "cutting edge" science; and
    - **maintain and enhance the unique logistical assets** of the United States, including the research stations, aircraft, and research vessels with increased icebreaking capabilities, and heavy icebreakers for reliable resupply of the U.S. Antarctic Program.

    Such adaptations will help the U.S. Antarctic Program continue to meet scientific research needs in Antarctica and the Southern Ocean over the next two decades.

CLOSING THOUGHTS

The Antarctic continent and surrounding ocean are unique sites for science to flourish. The science emerging from the U.S. Antarctic Program has provided new insights into how the planet is changing that have potential global economic and security ramifications. Scientific publications from Antarctica and the Southern Ocean routinely advance the basic understanding of this planet and beyond.

The Antarctic continent brings together scientists who push forward the frontiers of human knowledge, those who have recognized the rich opportunities for advancing fundamental knowledge on this vast ice-covered continent and the surrounding wild Southern Ocean. The Antarctic region contains unique natural environments; preserving these for experimental science requires a continued commitment to stewardship that should not be lost as science moves forward in the coming decades.

This report has highlighted directions that U.S. Antarctic and Southern Ocean science can and should move over the next 20 years. These efforts have the potential to produce thrilling new discoveries and a richer understanding of the planet and the changes it will face in the future. These discoveries will be possible only with a robust and efficient U.S. Antarctic Program.

Gersemia Antarctica, also known as soft coral, under the sea ice near McMurdo station, Ross Island. SOURCE: Rob Robbins/NSF

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APPENDIX A

Statement of Task

Under the auspices of the National Research Council (NRC), the Committee on Future Science Opportunities in the Antarctic and Southern Ocean will identify and summarize the changes to important science conducted on Antarctica and the surrounding Southern Ocean that will demand attention over the next two decades. The committee will assess the anticipated types and scope of future U.S. scientific endeavors and international scientific collaborations over a ~20-year period in Antarctica and the Southern Ocean. Membership should include leading polar scientists that span a wide range of expertise who actively participated in Antarctic research in recent years, and scientists with broad experience in global and international research. The committee should identify and summarize likely future science requirements of the U.S. research community, including the needs of the federal mission agencies that depend on U.S. Antarctic Program infrastructure and logistics. At present, those agencies are NASA, NOAA, USGS, DOE, EPA, the Smithsonian Institution and the Department of State, which relies on infrastructure support from the Program for official inspections of foreign facilities in Antarctica. The committee should

- build upon the work of other organizations (e.g., ICSU, SCAR, etc.), draw upon recent scientific achievements in Antarctica and the Southern Ocean including those reported during the 2007-2008 International Polar Year (IPY), and utilize previous workshops and reports (e.g., those from the NSF and NRC that pertain to future research directions in Antarctica);
- identify changes to anticipated types and scope of scientific programs for the United States in Antarctica and the Southern Ocean over the next two decades;
- examine appropriate opportunities for international Antarctic scientific collaborations based on recent U.S. experiences from the IPY and other anticipated activities;
- report any new emerging technologies should they be found while reviewing the scientific achievements that enhance the U.S. ability to realize important future opportunities or the application of new technologies that enable the collection of scientific data in more effective or efficient ways; and
- comment on the broad logistical capabilities and technologies that, from a science delivery perspective, would need to be improved or require major changes to enable the anticipated types and scope of future U.S. scientific

> programs, with the intent of informing the concurrent FACA Blue Ribbon Panel that will examine and have a central focus on logistical operations in Antarctica.

In carrying out its work, the committee is expected to draw on existing reports, results of national and international workshops, strategic plans of involved federal agencies, recommendations of professional scientific societies and other organizations, and any other sources it might find useful. The committee is not expected to set priorities among scientific research areas, nor is the committee to discuss budgetary issues. The primary goals are to identify important future research directions in the Antarctic and to inform the companion review looking at logistical planning and operations. Together these two studies are intended to help ensure that logistical operations are capable of supporting important forefront scientific research in Antarctica over the coming decades.

APPENDIX B

Summary of Online Questionnaire Results

During the study process, a short online questionnaire was distributed widely (see Figure B.1) to draw upon the expertise and experience of the polar community. The questions provided an opportunity for respondents to identify the most important science questions for the coming decades and to share thoughts on the "next generation" of polar scientists. Following a short set of general background questions (career stage, scientific discipline), questionnaire respondents were asked the following questions:

- *Within your own defined discipline*, please list 3 important scientific questions that you believe will drive research in Antarctica and the Southern Ocean *over the next 20 years.*
- *Across all disciplines*, please list 3 important scientific questions that you believe will drive research in Antarctica and the Southern Ocean *over the next 20 years.*
- Please list any technology, infrastructure, or innovative logistics that you believe will play a major role in future research efforts in Antarctica and the Southern Ocean (including new, emerging technologies).

FIGURE B.1 Geographic locations of questionnaire respondents.

- How did you get into Antarctic and/or Southern Ocean science? Are similar pathways available to others today?
- Are you able to find suitable candidates (number, quality) for the Post-Doc positions you have available? If not, why?
- Are you able to find suitable candidates for the graduate student positions you have available? If not, why?
- Is there a "next generation of scientists" who will be able to continue to advance your scientific field for the next 20 years?

The questionnaire was distributed to approximately 1,000 people via various Antarctic and Arctic email distribution lists. There were a total of 205 respondents representing a variety of disciplines and backgrounds. Questionnaire respondents included graduate students (pre-Ph.D.) and early-career scientists, midcareer scientists, and late-career scientists (see Figure B.2). Most of the respondents have conducted field work in Antarctica and the Arctic. A number of questionnaire takers have conducted fieldwork in the Southern Ocean, and there were also respondents who have worked on modeling in Antarctica and the Southern Ocean (see Figure B.3).

Respondents represented a range of disciplines that were grouped into eight categories, as shown in Table B.1.

Questionnaire respondents were asked to identify three important science questions that will drive research in Antarctica and the Southern Ocean over the next 20 years. Approximately 600 answers to this question were received and they were grouped

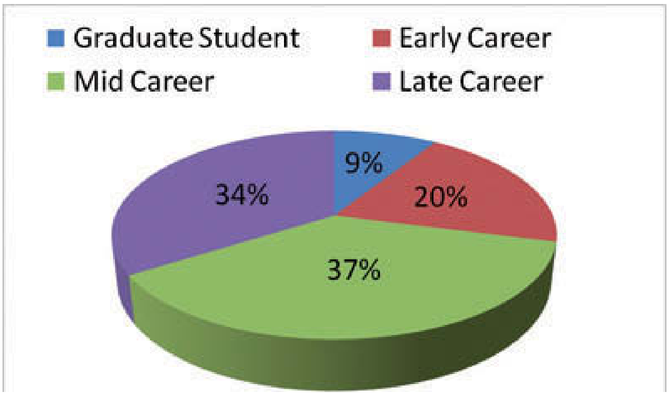

FIGURE B.2 Distribution of the various career stages of questionnaire respondents.

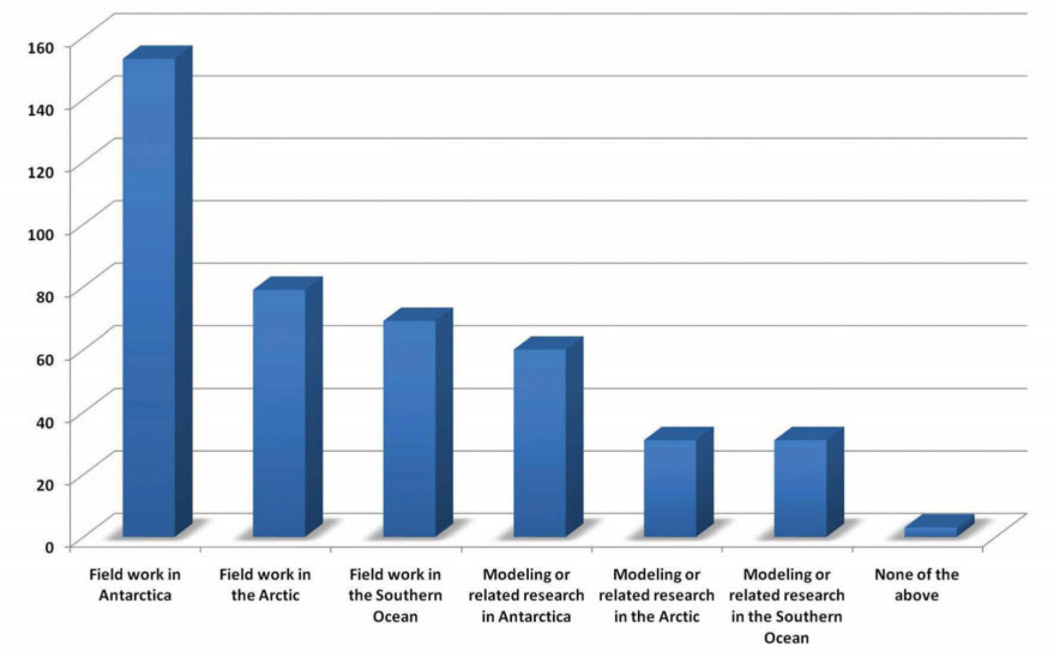

FIGURE B.3 Questionnaire respondents have conducted fieldwork in both Antarctica and the Arctic. Some have also conducted fieldwork in the Southern Ocean and are involved in modeling or related research. Note that questionnaire respondents were permitted to select more than one option to answer the question, "Where have you conducted research?"

TABLE B.1 Respondents Represented a Range of Disciplines That Were Grouped into Eight Categories

Discipline	Respondents (%)
Biology and ecosystems	36
Oceans and acidification	16
Geology	15
Astronomy and space physics	12
Ice and sea level rise	10
Atmosphere and climate	6
Technology	3
Other (incl. policy, psychology, art)	2

into the following 14 themes: global climate change and sea level rise, ice sheets, ice shelves, Southern Ocean, sea ice, paleoclimate, atmosphere and climatology, biology, space weather and astronomy, geology, interdisciplinary question, extreme environments, scientific process, and human elements.

Respondents who identified themselves as a principal investigator (PI) or co-PI were asked how they originally began their career in Antarctic science and if those pathways are still available to others today. Approximately one-third of respondents became involved as a graduate student and, if undergraduate and postdoctoral experiences are included, this makes up about 50 percent of respondents. About 15 percent indicated that they became involved via an established colleague, and 10 percent answered that they wrote a proposal that was funded.

PIs were also asked if they were able to find the postdocs and graduate students that they needed. Over half said that they were able to find postdocs and graduate students. When asked if there was a "next generation" of scientists that would advance the scientific field, approximately three-quarters said yes (see Figure B.4).

Although this exercise was useful to inform the committee about the lessons learned, general concerns, and future goals of a broad cross section of scientists (with various experience levels and disciplines), this was not a systematic survey and the results should not be used as an official statement for the scientific community.

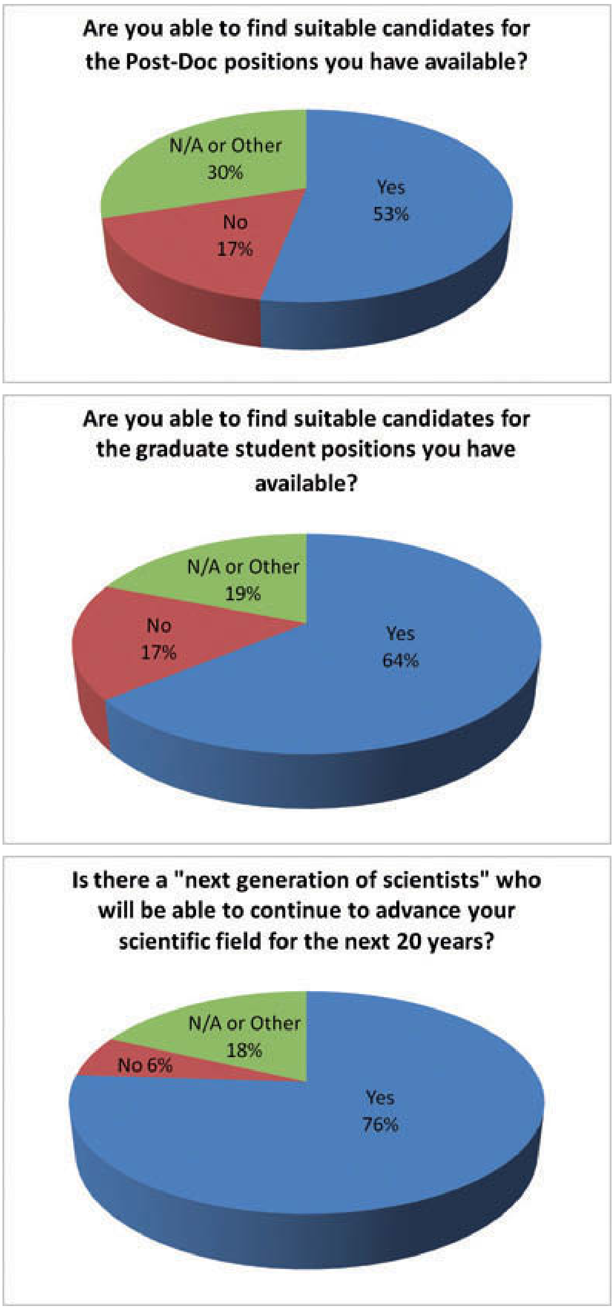

FIGURE B.4 Responses to the online questionnaire question regarding the availability of postdoctoral researchers, graduate students, and more generally a "next generation of scientists." The majority of respondents indicated that there is a next generation to carry the science forward in the coming decades.

APPENDIX C

Promising Technologies for Antarctic and Southern Ocean Science

Science has always been advanced by improvements in technology, often adapting technologies originally developed for other purposes and using them to advance research capabilities. Conducting scientific research in Antarctica and the Southern Ocean involves overcoming serious challenges from the environmental conditions and the remoteness of the continent. Scientists rely on various technologies to overcome these challenges, and, as new technologies emerge, they can unlock new opportunities for accessing new locations for research, obtaining new data, and other ways to improve scientific endeavors in this remote region. In the coming decades, new technologies will offer significant opportunities to improve, among other things, the instrumentation and infrastructure involved in scientific research in Antarctica and the Southern Ocean. Instruments that are smaller in size, including novel sensors that use less power, function during the Austral winter (the "cold and dark"), and can remotely transfer data will be needed to make observations in places and times that have been less accessible until now. An in-depth discussion of sensor development is beyond the scope of this report.

Improved instrument platforms will allow observations to be made in more places and at more times. This section, while not exhaustive, provides an exemplary list of several emerging instrument platforms that are worth examining.

FLOATS

Neutral buoyancy floats were conceived long ago (Swallow, 1955), and newer versions are now routinely used by the international oceanographic community, including RAFOS floats (SOund Fixing And Ranging, SOFAR spelled backward). Subsurface floats are now in wide use; they drift freely in ocean currents at depth and can periodically descend to 2,000 m and then ascend to the surface to report measurements of conductivity (salinity), temperature, and pressure (depth) from 2,000 m depth to the surface. Global coverage of ice-free regions has been achieved through the international

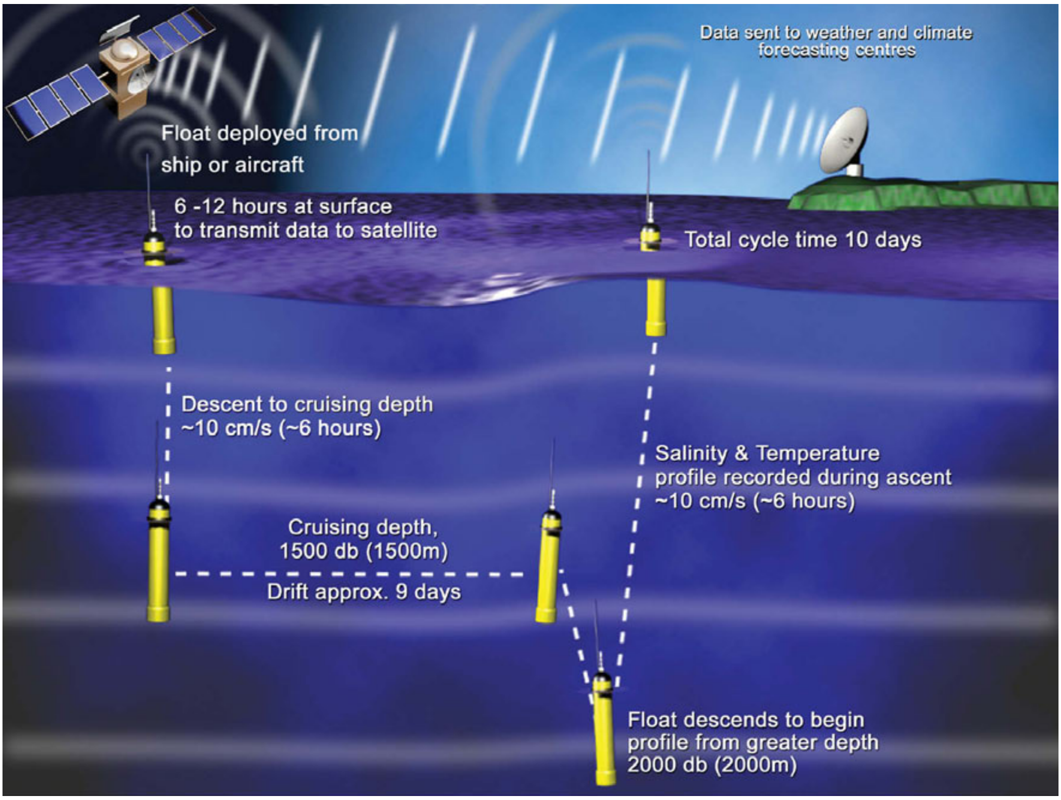

FIGURE C.1 An example of a currently existing oceanographic float that provides measurements of conductivity, pressure, and temperature from which salinity and depth are calculated. Additional sensors include oxygen, nitrate, optical properties, and soon pH. New floats designed for operation underneath ice shelves would have a protective bonnet over the antenna. SOURCE: Southampton Oceanography Centre.

Argo program (Figure C.1).[1] Additional sensors that can be incorporated, separately from the Argo program, include oxygen, nitrate, fluorescence, velocity, and soon pH; the capability to profile to a much greater depth is under development. An emerging technology of importance for the sea-ice-covered Southern Ocean is the long-duration float, which is programmed to profile repeatedly in ice-covered oceans without transmitting data on each ascent. The float uses a collision avoidance algorithm to test for ice or open water above it, and data transmission occurs only when the float can surface through open water. The precedents for this approach are two previous studies in Antarctica's Weddell Sea where an array of moored acoustic (RAFOS) sources

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[1] See *http://www.argo.ucsd.edu/index.html* and *http://wo.jcommops.org/cgi-bin/WebObjects/Argo.woa*.

exists to track under ice floats (Klatt et al., 2007) and a recent study along the Wilkes Land coast using 19 profiling floats with an ice avoidance algorithm based on the temperature gradient during ascent rather than a collision sensor (Wong and Riser, 2011).

AUTONOMOUS UNDERWATER VEHICLES

Autonomous underwater vehicles (AUVs) enable collection of pressure, conductivity, and temperature data in underwater areas that are difficult to reach, such as underneath fully or partially ice-covered waters of the Southern Ocean and the coastal areas of Antarctica. AUV use is increasing in oceanographic research (National Research Council, 2011c). Current propeller-driven AUVs have limited ranges, on the order of hundreds of kilometers, depending on their payload and operational speeds. A new AUV design employing buoyancy-driven propulsion has a significantly expanded operational range of thousands of kilometers (Bellingham et al., 2010); see Figure C.2.

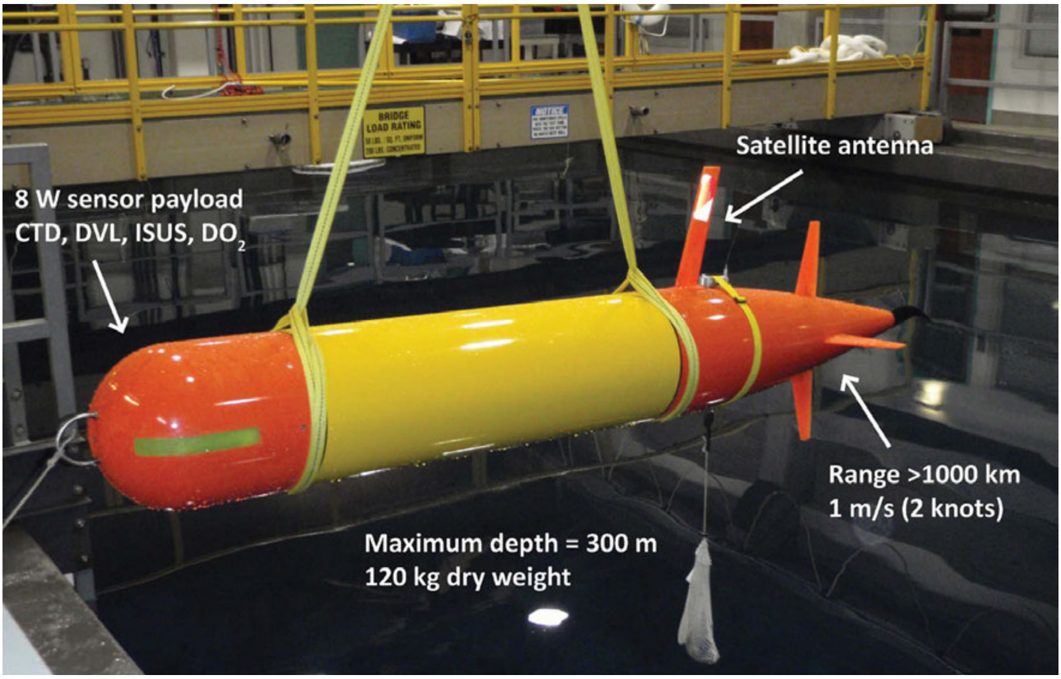

FIGURE C.2 An example of an emerging development in AUVs that has significantly longer operational range based on buoyancy-driven propulsion system. SOURCE: Bellingham et al., 2010.

Such advances enhance the opportunities for oceanographic and biological observations and process experiments, including measurements of phytoplankton blooms over the course of several weeks, or by transiting long distances to areas of interest.

INSTRUMENTED PELAGIC ANIMALS

The revolution in miniaturization has made it possible to equip pelagic animals such as seals, walruses, whales, sharks, tuna, and others with instruments to collect and report information on conductivity, temperature, and depth (using satellite-relayed data logging, or "CTD-SRDL"), as well as position from Global Positioning System (GPS). Data recorded during a dive are transmitted to satellites when the animal comes to the surface to breathe. Ice cover in the Weddell Sea makes it difficult to obtain data on the continental shelf and slope, especially in winter. During IPY measurements were taken from acoustically tracked floats and instruments carried by various types of seals; see Figure C.3. These provided data on seal movement (Figure 4.3) as well as CTD.

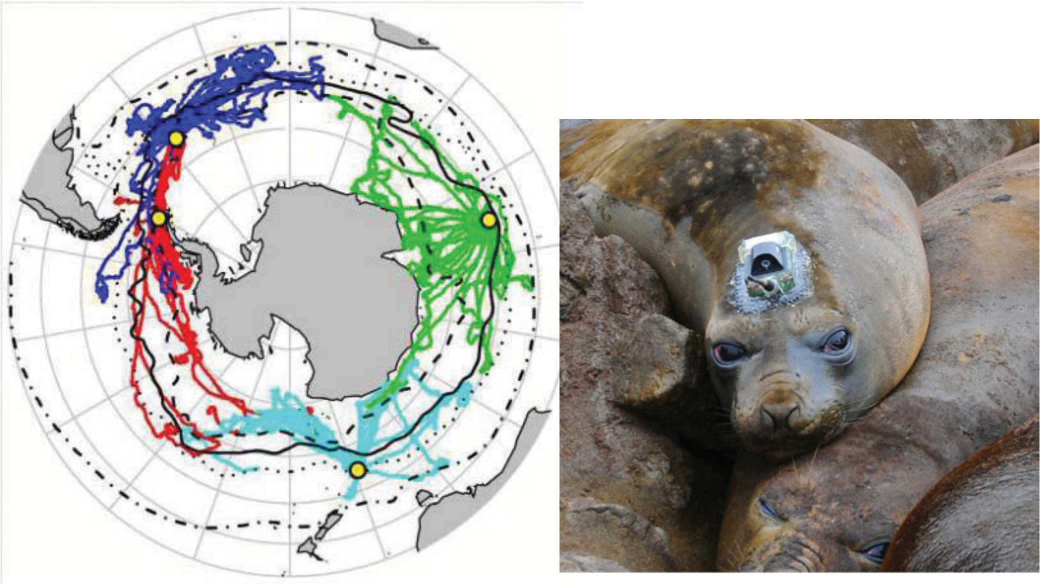

FIGURE C.3 Southern Elephant seal tracks from animal-mounted CTD-SRDL sensors (left) and an elephant seal with a transmitter (right). SOURCES: (left) Biuw et al., 2007. © 2007 National Academy of Sciences; (right) D. Costa.

The electronic tags were glued onto the fur and can stay on for several months before falling off when the animal molts. Although there is some evidence that shows the attachment of such devices can alter the water flow along a seal's body (Hazekamp et al., 2010), there is also evidence that suggests that these devices do not significantly affect the mass gain or survival of the seals (McMahon et al., 2008). Southern Elephant seals dive so deep that they can collect data from the water column down to 1,500 m, and they cover a large geographic area. Many dives are to the sea bed, thereby providing bathymetric data. High-precision mapping of ocean topography was recently demonstrated using such instrumented seals (Padman et al., 2010).

AIRCRAFT

Aerial platforms are used to support instruments that measure in situ components of the atmosphere, or remote sensing measurements "looking down" at Earth, or "looking up" into space. These platforms provide data in a critical gap between ground observations and satellite measurements. The Hercules C-130 has been a major tool for Antarctic research, transporting personnel, equipment, and fuel. First manufactured by Lockheed in the 1950s, the C-130 was modified for ski takeoff and landing (designated the LC-130) and continues to support Antarctic science missions because of its range, payload, and versatility. The LC-130 has recently been outfitted with a new mechanical arm to allow for RADAR and LIDAR instruments that are used to map ice elevation, ice sheet thickness, and bedrock topography (see Figure C.4). This is an example of using new technology to exploit an existing platform for enhancing scientific research.

FIGURE C.4 Hercules turboprop aircraft modified for Antarctica. Current design is LC-130 with modifications that allow LIDAR and RADAR observations of continental ice characteristics and thickness. SOURCE: E. Dunlea.

FIGURE C.5 Recent unmanned aerial vehicle designs. SOURCE: (left) NASA/Dryden/C. Thomas; (right) NOAA/PMEL.

UNMANNED AERIAL VEHICLES, DRONES, AND AIRSHIPS

In addition to manned aircraft, unmanned aerial vehicles (UAVs), often referred to as "drones," are beginning to be used for atmospheric measurements, remote sensing, and aerial image recording (see Figure C.5). Current UAVs have flight durations of minutes to hours, depending on size, payload, and flight altitude; they can fly patterns to sample specified areas and altitudes; and they are reusable. UAVs have already found their way into atmospheric composition sampling, measuring temperature, aerosols, and ozone (e.g., the GlobalHawk[2] mission), as well as seal census projects (e.g., ScanEagle[3]). Future use of UAVs would allow access to more remote areas. Future development of longer duration air ships could allow atmospheric observations to be made over the course of weeks to months (see Figure C.6).

DRILLING TECHNOLOGIES

Coring and access drilling provide tools for understanding Antarctic geology and paleoclimatology. Knowledge gained from previous drilling projects (such as the Deep Sea Drilling Project, the Ocean Drilling Program, and the Integrated Ocean Drilling Program) has been extended to the ANDRILL (Antarctic Geological Drilling) Program that involves more than 200 scientists from five countries.[4] Sediment coring is now done from ships in sea ice and from stationary sites on the ice shelf. Cores through more than 4 km of continental ice to bedrock have been collected, and drilling to two

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[2] See *http://www.nasa.gov/centers/dryden/research/GloPac/*.

[3] See *http://www.insitu.com/scaneagle*.

[4] See *http://www.andrill.org/*.

FIGURE C.6 Future vision of long-duration air ship; medium-altitude blimp system pictured. SOURCE: © Lockheed Martin 2008. Reprinted by permission.

known subglacial lakes is under way, with penetration expected in 2011. Significant research and development are still needed, however, to study subglacial lakes such as Lake Vostok and Lake Ellsworth (Rock and Bratina, 2004). In particular, improved technologies to minimize contamination and to deploy autonomous survey instruments are needed.

New drilling technologies are currently evolving and include examples such as the SHALDRILL (Shallow Drilling) project for ship-based coring along Antarctica's continental shelf, and the FASTDRILL project of mobile drilling capability to allow rapid drilling of arrays of deep (e.g., 4 km) holes through the continental ice sheet to bedrock at a local or continental scale (Powell et al., 2006). In fact, an NSF-supported workshop in 2002 recommended the development of advanced drilling technologies to reach bedrock beneath >2.5 km of ice. Methods such as hot-water drilling, coiled-tube drilling, and hybrid systems adapted to ice sheet drilling require additional engineering to enable multiple drill sites over the next 20 years. Improved technologies for rapid drilling will allow the production of multiple arrays of boreholes covering large areas (Tulaczyk et al., 2002).

APPENDIX D

Icebreaking Polar Research Vessels and Heavy Icebreakers

As outlined in this report and in previous National Research Council reports (NRC, 2007b, 2011c, 2011e), many of the proposed research activities of the next 20 years depend on having polar research vessel support in partially and fully ice-covered seas.[1] This includes setting and retrieving moorings for ocean and sea ice observations, as well as launching and retrieving autonomous underwater vehicles. Furthermore, a useful observing system will need to operate during the Austral winter, where icebreaker penetration of the winter icepack is the only feasible method for enabling a monitoring program in and near the ice shelves. Helicopters, which might be able to assist in some of this workload, are limited in range and in all-weather Antarctic navigation. In addition, the annual resupply ("break-in") of McMurdo Station requires the services of a heavy icebreaker. This resupply is essential for the functioning of the majority of U.S. research operations in Antarctica.

Despite this importance, the icebreaking capabilities of the United States are severely limited. As concluded by the 2007 NRC report (National Research Council, 2007b), "both operations and maintenance of the polar icebreaker fleet have been underfunded for many years, and the capabilities of the nation's icebreaking fleet have diminished substantially." The U.S. icebreaker capacity is limited to one polar research icebreaker, USCG *Healy* (Figure D.1(d)), and a privately owned research light icebreaker leased by the NSF, the *Nathaniel B. Palmer*. In addition, the NSF leases an ice-reinforced vessel, the *Laurence M. Gould,* primarily dedicated to support research operations in the Antarctic Peninsula area. The status of the icebreaker capabilities of the United States has been discussed in several previous NRC reports (National Research Council, 2007b, 2011c, 2011e), by a congressional analysis (O'Rourke, 2011), and in a Homeland Security audit (Richards, 2011). This issue involves both the U.S. Coast Guard (USCG) and NSF, and the history of authority over support for the Coast Guard heavy icebreakers (USCG and NSF, 2005). As outlined in these documents, there are strong national security and operational reasons for the United States to develop its own ice-

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[1] The icebreaking polar research vessel (PRV) targeted by the science community differs from a heavy icebreaker. The former is essentially a research vessel specifically designed to configurably perform a broad range of scientific activities in partially or fully ice-covered seas. A heavy icebreaker, as the name suggests, is a vessel with high horsepower and displacement designed to break ice in the most extreme circumstances.

breaking capability for use in both the Arctic and the Southern Ocean. As concluded by the 2011 NRC report *National Security Implications of Climate Change for U.S. Naval Forces*, "future U.S. national icebreaker assets should be defined as part of a holistic force structure that also accommodates ongoing National Science Foundation-sponsored polar research needs."

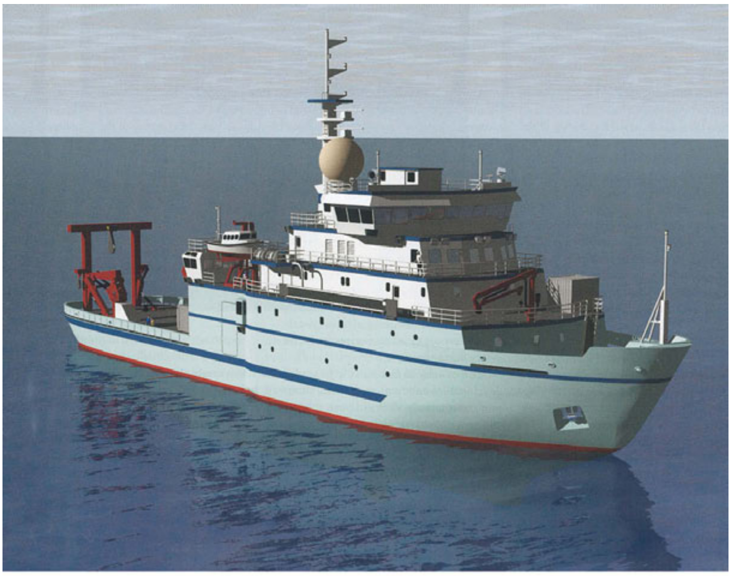
Icebreakers that can navigate in multiyear ice of Antarctica represent one of the most expensive infrastructures for Southern Ocean oceanographic and biological research and for access to coastal regions of East Antarctica as well as stations in West Antarctica and the vital resupply route to McMurdo. There are several options if the United States wishes to pursue its own national icebreaking capability. The range of heavy icebreaking capabilities appropriate for Antarctica year-round operations is PC 1 to PC 3 (classifications of icebreakers by icebreaking capabilities are shown in Table D.1). Ships, such as the *Varandey* (Figure D.1[a]), that can break ice, tow small icebergs, and clear harbors have construction costs of about $100 million, but they cannot adequately support research missions, act as helicopter platforms, or perform the McMurdo break-in. Replacement costs for each of the currently disabled U.S. Coast Guard heavy icebreakers, the *Polar Sea* and *Polar Star*, could be more than $700 million each with a construction time over 3 years after the funds are authorized. Less expensive modern research vessels strengthened for the ice such as the *Sikuliaq* (Figure D.1[b]), which is currently under construction for Arctic research, cost about $150 million and have capabilities to support research in unconsolidated seasonally light sea ice conditions and with limited endurance because of their smaller size. Specifications for NSF's new icebreaking Polar Research Vessel are currently under consideration by the University–National Oceanographic Laboratory System (UNOLS). The United States should explore options of various-sized icebreakers within a holistic fleet plan. The daily costs for research ship operations as evaluated by UNOLS in 2010 and 2011 is approximately $31,000, and the expected daily costs for a polar class (PC1-PC3) heavy icebreaker will be greater than $40,000.

Other alternatives for icebreaker support over the next 20 years include partnerships with other countries and leasing icebreakers flagged by other countries. For the past five seasons, the United States has leased the services of the Swedish ice breaker, Oden, to do the annual break-in to McMurdo Station. The international fleet of non-nuclear ships capable of penetrating ice fields heavier than first-year ice is very limited in number, and many of those ships have more than 30 years of service. Currently, there is a shortage of modern heavy icebreakers in all polar regions. Acquisition and operation of these platforms are very resource intensive. Thus, sharing icebreakers between two or more nations could be considered for the future. The model of sharing special-purpose research vessels has proven successful for scientific ocean drilling

FIGURE D.1 Examples of the attributes of a variety of icebreakers: (a) Russian (Lukoil, Ltd.) icebreaker *Varandey*, service ship, length 100 m, maximum power 16.8 MW from two azmuthing electric pods; (b) U.S. Coast Guard icebreaker *Healy* is designed for heavy ice and polar research missions of NSF, length 130 m and maximum power 22 MW; (c) NSF (University of Alaska, Fairbanks) owned *Sikuliaq*, research light icebreaker (PC6-7) to be launched in 2013; (d) USCG Polar Sea/Star, length 122 m, maximum power 45 MW (60,000 hp); in repair to 2013. SOURCES: (a) Chenghui, 2011, (c) Edgar, 2011, both reprinted with the permission of the Society of Naval Architects and Marine Engineers (SNAME); (b) and (d) U.S. Coast Guard.

(*continued*)

c.



d.

FIGURE D.1 Continued

TABLE D.1 Polar Class Descriptions

Polar Class	General Description
PC1	Year-round operation in all polar waters.
PC2	Year-round operation in moderate multiyear ice conditions
PC3	Year-round operation in second-year ice with old ice inclusions
PC4	Year-round operation in thick first-year ice that may contain old ice inclusions
PC5	Year-round operation in medium first-year ice with old ice inclusions
PC6	Summer/autumn operation in medium first-year ice with old ice inclusions
PC7	Summer/autumn operation in thin first-year ice with old ice inclusions

SOURCE: International Association of Classification Societies Ltd.

(e.g., *Joides Resolution*), and a case can be made that modern heavy icebreakers could be operated in a similar fashion. A first step toward shared use of heavy icebreakers could be a barter system. Ship time on heavy icebreakers could be bartered against ship time on other heavy icebreakers (this could prevent long transit times to the Southern Ocean or mismatch of icebreaking capacity for specific projects) or on open-ocean vessels. Such bartering agreements are working well in Europe. On the other hand, a U.S.-flagged polar heavy icebreaker with capabilities for year-round operations in Antarctica in combination with a dedicated icebreaking polar research vessel does anticipate requirements for the next 20 years of science in the Southern Ocean, U.S. responsibilities for Antarctic stewardship, and U.S. responsibilities for U.S. interests and the safety of U.S. personnel in Antarctica.

APPENDIX E

Components of an Antarctic and Southern Ocean Observing System

The committee has described the motivation for an Antarctic observing network with data integration and advanced scientific modeling in Section 4.4. This appendix further describes examples of several of the important observations that would be of greatest use in such a network providing information on the atmosphere, ocean, ice, and biology and biogeochemistry. The list is neither meant to be comprehensive, nor should the following be seen as a description of the final design of an Antarctic and Southern Ocean observing system. Detailing a comprehensive strategy for such an observing system was believed beyond the scope of this committee; any such strategy would be best done by an independently selected committee of specialists, especially with respect to cyberinfrastructure requirements that might need long lead times for development and deployment. For example, the development of the Arctic Observing Network required several steps from stating the need, to the recommendation, and finally to defining optimum design and implementation strategies. Such a process in other regions has required the engagement of several efforts by specially selected committees and working groups and has been documented in multiple reports over a period of a decade. Building on the experience of other observing system design efforts and using the work already invested into components of an Antarctic and Southern Ocean observing system could shorten the time needed for implementation of such a network.

ATMOSPHERE

For atmospheric observation, it is important to create a network that measures and reports a wide range of variables and can withstand the severe Antarctic environment. The Antarctic automatic weather station network started as a U.S. program in 1980 with only a few stations. It has expanded to more than 100 locations across Antarctica from 12 different nations.[1] Initially basic near-surface meteorological variables were measured, but the range of parameters monitored and topics tackled continues to

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[1] See *http://amrc.ssec.wisc.edu/aws/*.

grow. Applications of the data include investigations of specific atmospheric phenomena (like katabatic winds), climate monitoring, critical input for numerical weather prediction, and ground-based weather for aircraft landings. The network should be a core component for an Antarctic observing network.

Redundant, autonomous mobile sensors controlled by adaptive networks are well worth exploring for the Antarctic continent, while enhanced drifting buoys might be used in the sea ice zone and open ocean regions. Ground-based remote sensing involving radar, wind profilers, Doppler acoustic sounders, temperature profilers, cloud radars, and cloud LIDAR can improve upon data retrieved from current radiosondes. In addition, large numbers of simple dropsondes strategically released from high-altitude balloons could enhance data collection. Research aircraft are appropriate platforms for investigating atmospheric processes (e.g., cloud physics). In addition, it would be desirable to replace expensive, bulky, sensitive instrumentation maintained by expert technicians with simpler, more capable systems that can work in unmanned aircraft to routinely explore the behavior of the winds, temperature, moisture, and cloud fields in three dimensions.

Satellites over the Antarctic continent and Southern Ocean have great promise: radio occultation profiles from tracking the propagation of GPS signals through the atmosphere have proved useful over the Antarctic continent with all-weather capability and absolute calibration. Long-range planning for satellites is required. NASA's Earth Observing System (the Terra and Aqua satellites) and the more recent Cloudsat and CALIPSO missions have proven their value to science, but there are no adequate follow-up plans for when these systems exceed their design lifetimes. Data obtained on the atmosphere must be integrated into a coherent framework to support modeling.

OCEAN

Ocean observations can use both Eulerian (moored) and Lagrangian (moving) platforms. Eulerian measurements performed at strategically chosen locations, such as within straits, choke points, and boundary currents, would prove valuable. Improved moored sensors capable of conductivity-temperature-depth oxygen, nitrate, fluorescence, and acoustics and of flow cytometry of colored dissolved organic matter will be helpful. Devices with passive sonic recording of whales would improve the tracking of whales. Near-surface ocean platforms are in danger of damage from icebergs. Alternative sampling strategies including instrumented animals (seabirds, seals, whales), gliders, and autonomous underwater vehicles (AUVs) can mitigate this problem.

Lagrangian measurements can take place from a number of platforms, including profiling floats (e.g., Argo floats), gliders, and AUVs. Important oceanography measurements include currents, temperature, oxygen (O_2), CO_2, pH, turbidity, and nutrient levels. There is a critical lack of observations beneath floating ice shelves.

ICE

Observations of both glacial and sea ice are crucially lacking. Among the many measurements needed for glacial ice are three-dimensional englacial temperatures, basal conditions (e.g., frozen versus thawed bed, sediment at bed, subglacial lakes), geothermal heat flux, physical properties of ice (density, grain size, fabric), grounding line mapping, and ice thickness. A comprehensive measurement scheme will require many boreholes, cores (some continuous and others not), new drilling technologies, and new tools for englacial measurement. Airborne methods to measure ice thickness have already shown promise, but further work is required. Among other important variables to measure are accumulation rates, glacial surface temperatures, ice velocity, ice thickness, surface elevation, changes in grounding lines, and location of subglacial lakes. Acoustic depth gauges, surface density measurements, near-surface temperature profiles, and other strategies may provide valuable information for an observing network.

Sea ice observing will rely heavily on satellite measurements (ice extent, thickness for mass balance), drifting buoys (ice motion and ice mass balance), and in situ sampling (physical, chemical, and biological sea ice properties). Upward-looking sonars on AUVs can reliably measure sea ice thickness.

BIOLOGY AND BIOGEOCHEMISTRY

Answering a number of biology and biogeochemistry research questions on both land and ocean can benefit greatly from a network of observations. In the ocean, important observations include ocean-air $DPCO_2$; continuous flow, underway O_2-Argon and $D^{17}O$ from vessels; cabled observatories near coastal stations; and ocean color measurements from satellites (Behrenfeld et al., 2006), e.g., Wide Field-of-view Sensor (SeaWiFS)/Moderate Resolution Imaging Spectroradiometer (MODIS) (McClain, 2009). A recent NRC review of this situation concluded that the current ocean color time series from satellites is at risk and that NOAA and NASA should be encouraged to establish a working group modeled after the International Ocean Colour Coordinating Group

(IOCCG) to work toward a sustained ocean color data collection program from U.S. and non-U.S. sensors (National Research Council, 2011a).

On land, light detection and ranging (LIDAR) can be used to study permafrost at local scales, and monitoring stations could include microclimate information on soil temperature, water activity, carbon dioxide (CO_2), and pulsed amplitude modulation fluorometry. In freshwater, an observing network would benefit from in situ sensors to measure carbon, nitrogen, phosphorus, and stable isotopes of hydrogen, oxygen, and nitrogen, as well as dissolved CO_2 sensors and dissolved oxygen sensors. An oxygen (O_2) flux tower would provide important information. Inclusion of data from a network of terrestrial, aquatic, and glacial monitors could help define predictions of rates of land transformation and the resulting atmospheric and hydrologic feedbacks; these are important processes to follow as glaciers and permafrost melt, lakes overflow, or land is exposed.

APPENDIX F

Acronyms

ACC	Antarctic Circumpolar Current
ANDRILL	Antarctic Geological Drilling
AON	Antarctic Observing Network
AUV	Autonomous Underwater Vehicle
BARREL	Balloon Array for RBSP Relativistic Electron Losses
CH_4	Methane
CMB	Cosmic Microwave Background
CO_2	Carbon dioxide
EPB	European Polar Board
ESA	European Space Agency
GEO	NSF Geoscience Directorate
GPS	Global Positioning System
ICSU	International Council for Science
IGY	International Geophysical Year
IODP	Integrated Ocean Drilling Program
IOOS	Integrated Ocean Observing System
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
LIDAR	Light Detection and Ranging
LTER	Long Term Ecological Research
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
OOI	Ocean Observatories Initiative
OPP	Office of Polar Programs
OSTP	Office of Science and Technology Policy

PAntOS	Pan-Antarctic Observation System
PCO_2	Partial pressure of CO_2
RBSP	Radiation Belt Storm Probes
SACNAS	Society for Advancement of Chicanos and Native Americans in Science
SAM	Southern Annular Mode
SCAR	Scientific Committee on Antarctic Research
SEARCH	Study of Environmental Arctic Change
SOOS	Southern Ocean Observing System
STEM	Science, Technology, Engineering, and Mathematics
USAP	U.S. Antarctic Program
WAIS	West Antarctic Ice Sheet

APPENDIX G

Biographical Sketches of Committee Members

Warren M. Zapol (*Chair*), (IOM) is the emeritus Anesthetist-in-Chief at Massachusetts General Hospital (MGH) and the Reginald Jenney Professor of Anesthesia at Harvard Medical School. He is currently the Director of the MGH Anesthesia Center for Critical Care Research. A graduate of hte Massachusetts Institute of Technology (MIT) and the University of Rochester School of Medicine, Dr. Zapol's research efforts include studies of acute respiratory failure in animals and humans. Supported by the National Science Foundation, he has led nine Antarctic expeditions to study the diving mechanisms and adaptations of the Weddell seal. In 2003, he was awarded the Intellectual Property Owners Association's Inventor of the Year Award for the treatment of hypoxic human newborns with inhaled nitric oxide, a technique that he pioneered with his MGH team and now used to save the lives of 10,000 babies each year in the United States. In 2006, a steep mountain glacier in Antarctica was named for Dr. Zapol by the U.S. Board on Geographic Names. In 2008, he was appointed by President George W. Bush to the U.S. Arctic Research Commission.

Robin E. Bell is the PGI Senior Research Professor at the Lamont-Doherty Earth Observatory of Columbia University, where she directs polar research, education, and technology development programs. Dr. Bell is a geophysicist who earned her Ph.D. from Columbia University. Her research interests range from ice sheet dynamics, continental tectonics, and mass balance to subglacial ecosystems. She has studied the mechanisms of ice sheet collapse and the environments beneath the Antarctic Ice Sheet, including Lake Vostok. Dr. Bell discovered major subglacial lakes linked to the onset of fast flow in Antarctica and has advanced the concept of geologic control on ice stream dynamics. Dr. Bell was the Director of the ADVANCE program Columbia's Earth Institute that increased the participation and advancement of women scientists and engineers at the university through institutional transformation. She has also led nine major aero-geophysical expeditions to Antarctica and Greenland including the major International Polar Year (IPY) geophysical program to explore the interior of the East Antarctic Ice Sheet. She was instrumental in the development of the IPY 2007-2008.

David H. Bromwich is a Senior Research Scientist and Director of the Polar Meteorology Group at the Byrd Polar Research Center of Ohio State University. He is also a professor with the Atmospheric Sciences Program of the Department of Geography.

Dr. Bromwich's research interests include the climatic impacts of the Greenland and Antarctic ice sheets; global and mesoscale model simulations of the polar regions; the precipitation behavior of high southern latitudes, Greenland, and the Arctic basin; and the influence of tropical ocean-atmosphere variability on the polar regions. He has served on the National Research Council's Committee on Geophysical and Environmental Data and was previously a U.S. Representative of the Scientific Committee on Antarctic Research. Dr. Bromwich chaired the National Research Council's Committee on the Design of the Martha Muse Award to Support the Advancement of Antarctic Researchers. He is a member of the American Meteorological Society, the American Geophysical Union, the Royal Meteorological Society, and the Association of American Geographers. Dr. Bromwich earned his Ph.D. in meteorology from the University of Wisconsin, Madison, in 1979.

Thomas F. Budinger (NAE/IOM) is professor of the Graduate School at University of California, Berkeley; Senior Medical Scientist at the Lawrence Berkeley National Laboratory; and Professor Emeritus at University of California, Berkeley and San Francisco Medical Center. He was the founding Chair of the Department of Bioengineering at the University of California, Berkeley. He is currently Home Secretary of the National Academy of Engineering. Dr. Budinger received the M.S. degree in physical oceanography from the University of Washington, an M.D. in medicine from the University of Colorado, and a Ph.D. degree in medical physics from the University of California, Berkeley. He served as a U.S. Coast Guard Officer in the Arctic and Antarctic and was the Science Officer for the International Ice Patrol (1957-1960). Dr. Budinger's medical science contributions are for research on aging and heart disease. He has served NRC study topics ranging from imaging to radiation and warfighter protection. He is co-author of the text *Ethics of Emerging Technologies: Scientific Facts and Moral Challenges*. Recent awards include the Gold Medal from the American Roentgen Ray Society in 2009 and the Hal Anger Memorial Lectureship from the Society of Nuclear Medicine in 2010.

John E. Carlstrom (NAS) is the Subrahmanyan Chandrasekhar Distinguished Service Professor at the University of Chicago with the Kavli Institute for Cosmological Physic, the Astronomy and Astrophysics and Physics departments, and the Enrico Fermi Institute. He holds a joint position with the High Energy Physics Division at Argonne National Laboratory. In addition, Dr. Carlstrom leads the 10-m South Pole Submillimeter Telescope project. Dr. Carlstrom's Degree Angular Scale Interferometer in Antarctica revealed the microwave background's long-sought polarization. He has also led efforts to study imprints in the microwave background created by massive clusters of galaxies, and has done pioneering research on young solar systems. He has received NASA's

Medal for Exceptional Scientific Achievement. Dr. Carlstrom is a former member of the Astronomy and Astrophysics Advisory Committee (AAAC) that advises NSF, NASA, and the U.S. Department of Energy (DOE) on selected issues within the fields of astronomy and astrophysics. Dr. Carlstrom received his Ph.D. in physics from the University of California, Berkeley. He is a member of the National Academy of Sciences and the American Academy of Arts and Sciences, and he received a MacArthur Fellowship in 1998.

Rita R. Colwell (NAS) is a Distinguished University Professor both at the University of Maryland at College Park and at Johns Hopkins University Bloomberg School of Public Health and is Senior Advisor and Chairman Emeritus, Canon US Life Sciences, Inc.; President and CEO of CosmosID, Inc.; and former Director of the National Science Foundation (1998-2004). Her interests are focused on global infectious diseases, water, and health, and she has developed an international network that addresses emerging infectious diseases and water issues, including safe drinking water for both the developed and developing world. Dr. Colwell has previously served as Chairman of the Board of Governors of the American Academy of Microbiology and also as President of the American Association for the Advancement of Science, the Washington Academy of Sciences, the American Society for Microbiology, the Sigma Xi National Science Honorary Society, the International Union of Microbiological Societies, and the American Institute of Biological Sciences. Dr. Colwell has also been awarded 55 honorary degrees from institutions of higher education, including her Alma Mater, Purdue University, and is the recipient of the Order of the Rising Sun, Gold and Silver Star, bestowed by the Emperor of Japan, the 2006 National Medal of Science awarded by the President of the United States, and the 2010 Stockholm Water Prize awarded by the King of Sweden. Dr. Colwell holds a Ph.D. in oceanography from the University of Washington.

Sarah B. Das is an Associate Scientist in the Geology and Geophysics Department at the Woods Hole Oceanographic Institution. Dr. Das is a glaciologist whose research interests include the reconstruction of past climate from ice cores; understanding and measuring polar ice sheet mass balance and ice dynamics; exploring the interaction between the coupled cryosphere-atmosphere-ocean systems; and investigating biogeochemical processes in polar environments. She received a Ph.D. in geosciences from the Pennsylvania State University, and an A.B. in geological sciences from Cornell University. Dr. Das has led and/or participated in seven Antarctic and six Greenlandic field expeditions since 1995. She is active in training the "next generation" of polar scientists, teaching and mentoring pre-K through Ph.D students. She is also committed to sharing the excitement and importance of scientific discovery with the public, and has been a featured scientist on NPR, NOVA, at the Smithsonian National Museum of Natural History, and in the forthcoming book *Science on Ice*, among other outlets.

Hugh W. Ducklow is the Director of the Ecosystems Center at the Marine Biological Laboratory. Dr. Ducklow is a biological oceanographer and has been studying the dynamics of plankton food webs in estuaries, the coastal ocean, and the open sea since 1980. Dr. Ducklow has participated in oceanographic cruises in the Chesapeake Bay, the western North Atlantic Ocean, the Bermuda and Hawaii Time Series stations, the Black Sea, the Arabian Sea, the Ross Sea, the Southern Ocean, the Equatorial Pacific, and the Great Barrier Reef. He has been working on various projects in Antarctica since 1994. Currently, Dr. Ducklow leads the Palmer Antarctica Long Term Ecological Research Project on the west Antarctic Peninsula, where he is investigating the responses of the marine ecosystem to rapid climate warming. Although his research is primarily experimental and observational, he uses mathematical models and collaborates with modelers to gain deeper understanding and derive maximum benefit from the data we collect. Dr. Ducklow received his Ph.D. from Harvard University.

Peter Huybers is a Professor in the Department of Earth and Planetary Sciences at Harvard University. Dr. Huybers received a B.S. in physics in 1996 from the U.S. Military Academy at West Point, and a Ph.D. in climate chemistry and physics from MIT in 2004. He was a NOAA Postdoctoral Fellow in Climate and Global Change in the Geology and Geophysics Department at Woods Hole Oceanographic Institution (WHOI) from 2004 to 2006. Dr. Huybers has multiple research interests related to climate science: long-term climate cycles, annual temperature variations, and models to estimate historic temperatures based on the limited evidence available. He is the recipient of multiple awards, including a MacArthur Foundation Fellowship in 2009, a Packard Fellowship for Science and Engineering in 2009, the AGU James B. Macelwane Medal in 2009, a Harvard University Center for the Environment Fellowship in 2005, the MIT Carl-Gustaf Rossby Prize in 2004, and a National Defense Science and Engineering Graduate Fellowship in 2001.

John Leslie King is Vice Provost for Strategy and W.W. Bishop Professor in the School of Information at the University of Michigan. In January of 2000, Dr. King moved to the University of Michigan from the University of California at Irvine to be Dean of the School of Information. Dr. King spent 4 months in Germany in the spring and summer of 2005 at the Johann Wolfgang Goethe University in Frankfurt am Main, as Fulbright Distinguished Chair in American Studies. He was hosted by the Fachbereich Wirtschaftswissenschaften (the Faculty of Economics and Business) and the Institut fur Wirtschafts Informatik (Institute for Information Systems). Dr. King was elected a Fellow of the Association for Information Systems (AIS) in late 2005 and a Fellow of the American Association for the Advancement of Science in 2007. He received an honorary doctorate in economics and business from the Copenhagen Business School in 2009. Dr. King received his Ph.D. in administration from the University of California at

Irvine in 1977. His current research studies the relationship between technical change and social change, concentrating on information technologies and change in social institutions.

Ramon E. Lopez is currently a Professor in the Department of Physics at the University of Texas at Arlington. Dr. Lopez is a Fellow of the American Physical Society, was awarded the 2002 Nicholson Medal for Humanitarian Service, and was named the 2010 Society for Advancement of Chicanos and Native Americans in Science (SACNAS) Distinguished Scientist. He received his B.S. in physics in 1980 from the University of Illinois, and his M.S. and Ph.D. in space physics in 1984 and 1986, respectively, from Rice University. His current research focuses on solar wind-magnetosphere coupling, magnetospheric storms and substorms, space weather prediction, and the role of spatial intelligence in science education. He is the Co-Director for Diversity for the Center for Integrated Space weather Modeling (CISM), a Science and Technology Center funded by the National Science Foundation. Dr. Lopez is also the co-author of a popular book on space weather entitled *Storms from the Sun*, published by the Joseph Henry Press.

Olav Orheim is currently in charge of Norway's International Polar Year effort based at the Research Council of Norway. He was employed at the Norwegian Polar Institute from 1972 to 2005—from 1993 as Managing Director. From 1989 to 2005 he was also Adjunct Professor at the University of Bergen, teaching glaciology. Dr. Orheim received his Ph.D. in 1972 from The Ohio State University where he studied Antarctic glaciers and global climate change. He has had more than 30 field seasons in the Arctic and the Antarctic, and produced about 80 research publications covering glacier mass balance and climate, ice dynamics, icebergs, remote sensing, and politics of the polar regions. In 2003 he was Chair of the Norwegian Government's most recent review of Northern Policy. For a decade he has chaired various bodies under the Antarctic Treaty system, including the Legal and Institutional Working Group from 2005 to 2009. He has developed two much-visited Norwegian museums on glaciers and on polar regions. He is at present Chairman of the Board of five Norwegian entities, including the foundations Norwegian Glacier Museum in Sogn, the UNEP body GRID-A in Arendal, and the Polarship Fram, Oslo. He was in 2007 knighted under the Royal Norwegian Order of St. Olav.

Stanley B. Prusiner, (NAS/IOM), is Director of the Institute for Neurodegenerative Diseases and Professor of Neurology at the University of California, San Francisco (UCSF), where he has worked since 1972. He received his undergraduate and medical training at the University of Pennsylvania and his postgraduate clinical training at UCSF. From 1969 to 1972, he served in the U.S. Public Health Service at the National Institutes of Health. Dr. Prusiner is a member of the National Academy of Sciences, the Institute of

Medicine, the American Academy of Arts and Sciences and the American Philosophical Society, and a foreign member of the Royal Society, London. He is the recipient of numerous prizes, including the Potamkin Prize for Alzheimer's Disease Research from the American Academy of Neurology (1991); the Richard Lounsbery Award for Extraordinary Scientific Research in Biology and Medicine from the National Academy of Sciences (1993); the Gairdner Foundation International Award (1993); the Albert Lasker Award for Basic Medical Research (1994); the Paul Ehrlich Prize from the Federal Republic of Germany (1995); the Wolf Prize in Medicine from the State of Israel (1996); the Keio International Award for Medical Science (1996); the Louisa Gross Horwitz Prize from Columbia University (1997); the Nobel Prize in Physiology or Medicine (1997); and the National Medal of Science (2010).

Marilyn Raphael is a Professor in the Department of Geography at the University of California, Los Angeles (UCLA). Her research interests include the Santa Ana winds of California, global climate change and variability, climate modeling, atmospheric circulation dynamics, Southern Hemisphere atmospheric circulation and climate, and Antarctic sea-ice variability. Dr. Raphael received her Ph.D. in geography from The Ohio State University. She is a member of the American Geophysical Union, the American Meteorological Society, and the Association of American Geographers. She is Chair of the Department of Geography at UCLA and has served on a number of national committees including the NRC Committee for Climate Stabilization Targets for Atmospheric Greenhouse Gas Concentration, the Office Advisory Committee for the Office of Polar Programs of the NSF, and the national council of the Association of American Geographers.

Peter Schlosser is the Vinton Professor of Earth and Environmental Engineering and Professor of Earth and Environmental Sciences at Columbia University and Senior Research Scientist at the Lamont-Doherty Earth Observatory. He also is the Associate Director of the Earth Institute at Columbia University. He received his Ph.D. in physics at the University of Heidelberg, Germany, in 1985. Dr. Schlosser's research interests include studies of water movement and its variability in natural systems (oceans, lakes, rivers, groundwater) using natural and anthropogenic trace substances and isotopes as "dyes" or as "radioactive clocks"; ocean-atmosphere gas exchange; reconstruction of continental paleotemperature records using groundwater as an archive; and anthropogenic impacts on natural systems. He participated in seven major ocean expeditions, five to the polar regions.

Lynne D. Talley is a Professor of Oceanography at the Scripps Institution of Oceanography at the University of California, San Diego. Dr. Talley's expertise and research interests lay in general ocean circulation, hydrography, theory of wind-driven circulation, and ocean modeling. Dr. Talley has an extensive NRC committee background, having served previously on the Climate Research Committee, Global-Ocean-Atmosphere-Land System Panel, and Panel to Review the Jet Propulsion Laboratory Distributed Active Archive Center (DAAC). Dr. Talley was a National Science Foundation Presidential Young Investigator in 1987. Dr. Talley received her Ph.D. in Physical Oceanography from the WHOI/MIT Joint Program in Oceanography in 1982. She is a fellow of the American Academy of Arts and Sciences, American Geophysical Union, American Meteorological Society, and Oceanography Society.

Diana H. Wall is a University Distinguished Professor, Professor of Biology, and Director, School of Global Environmental Sustainability at Colorado State University. She is actively engaged in research to explore how soil biodiversity contributes to healthy, productive soils and thus to society, and the consequences of human activities on soil sustainability. She has conducted more than 20 years of research in the Antarctic Dry Valleys examining the response of soil biodiversity and ecosystem processes to environmental change. Wall Valley, Antarctica, was named for her achievements in 2005. Dr. Wall was a member of the U.S. Commission of UNESCO, is a member of the U.S. Standing Committee on Life Sciences for the Scientific Committee on Antarctic Research, chaired the SCOPE Committee on Soil and Sediment Biodiversity and Ecosystem Functioning, and co-chaired the Millennium Development Goals Committee of the Millennium Ecosystem Assessment. Dr. Wall was President of the Ecological Society of America, the American Institute of Biological Sciences, the Intersociety Consortium for Plant Protection, the Association of Ecosystem Research Centers, the Society of Nematologists, and Chair, Council of Scientific Society Presidents.