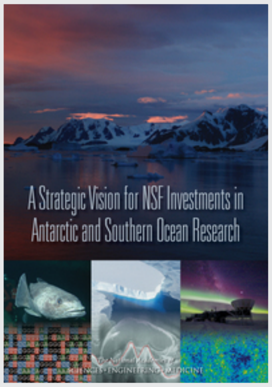

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Committee on the Development of a Strategic Vision for the U.S. Antarctic Program

Polar Research Board
Division on Earth and Life Studies

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

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions nor did they see the final draft of the report before its release. The review of this report was overseen by **W. Berry Lyons** (Ohio State University) and **David Karl** (University of Hawaii), 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.

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Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

Antarctic and Southern Ocean scientific research has produced many important and exciting scientific advances. Spanning oceanography to tectonics, glaciology to atmospheric chemistry, microbiology to astrophysics—the extreme Antarctic environment provides unique opportunities to expand knowledge about how the planet works and even the very origins of the universe. Research on the Southern Ocean and the Antarctic ice sheets is becoming increasingly urgent for understanding the future of the region and its interconnections with and impacts on many other parts of the globe. Antarctic science has global consequences.

Conducting research in Antarctica has always been a challenging endeavor. Ensuring safe field operations requires significant support, and accessing research bases requires specialized ships, runways carved from ice, aircraft equipped with skis, specialized helicopters, and over-snow vehicles. Despite these challenges, the U.S. National Science Foundation (NSF) provides researchers with broad access to the continent and its surrounding ocean. This research is supported through the three U.S. scientific stations (McMurdo, Amundsen-Scott, and Palmer), two polar research vessels (the *Lawrence M. Gould* and the *Nathaniel B. Palmer)*, and heavy icebreaker ships that ensure resupply access to stations and continuity of operations. Each year, more than 3,500 Americans are involved in research and logistical activities of the U.S. Antarctic Program (USAP).

The USAP, managed by NSF's Division of Polar Programs (NSF/PLR), supports U.S. scientific research and related logistics in Antarctica and aboard ships in the Southern Ocean. Although budgets vary from year to year, NSF/PLR invests approximately $70 million annually in scientific research and $255 million annually in infrastructure and logistics to support the research. The level of funding for infrastructure and the high ratio of logistics support personnel to scientists reflect the complexity and challenges of working in the far south.

The NSF requested that the National Academies of Sciences, Engineering, and Medicine convene a committee to develop, through widespread community engagement, a decadal-scale vision for NSF's Antarctic and Southern Ocean research—including research that is focused on the region itself, as well as research that uses the Antarctic as a unique platform for observing Earth's space environment and the universe. The Committee sought to identify priorities for strategic investments in compelling research and to identify the infrastructure most critical for supporting this research. (See Appendix B for the full Statement of Task.)

This report builds on a series of USAP advisory efforts in recent years, including a National Research Council study, *Future Science Opportunities in Antarctica and the Southern Ocean* (NRC, 2011a) and a special Blue Ribbon Panel study, *More and Better Science in Antarctica Through Increased Logistical Effectiveness* (BRP, 2012). In addition, this report is informed by extensive efforts to gather ideas from a diverse community of researchers across the United States. This included a widely advertised online forum and outreach sessions held at 14 locations across the country and at one international conference. The outreach effort spanned 11 months and engaged over 450 people.

The Committee's strategic vision for the major components of a robust USAP include the following:

- Continuation of a broad-based program that supports, across all major areas of Antarctic and Southern Ocean science, the curiosity-based research driven by proposals from principal investigators (PIs). The Committee did not attempt to recommend specific priorities for this category of research.
- A collection of larger-scale research initiatives that address particularly compelling scientific questions poised for significant advance but are (in size, cost, and complexity) beyond the scope of a PI-driven project. The Committee recommends here a very limited number of these topics as priorities for support—some of which, we suggest, merit substantial additions to NSF's existing research budget.
- Foundational elements that enable, support, and add value to all research activities—including core logistical and infrastructure needs (e.g., vessels, aircraft, field gear, research stations, laboratories, data transmission), strategic observational efforts, data management, and education and public outreach. The Committee suggests here an array of actions that NSF could undertake to strengthen these framework elements.

A CORE PROGRAM OF BROAD-BASED INVESTIGATOR-DRIVEN RESEARCH

Investment in a broad portfolio of research is essential for maintaining U.S. leadership in Antarctic and Southern Ocean science, and for ensuring that the nation is well positioned to take advantage of breakthroughs and to respond to new environmental challenges. The NSF/PLR model of supporting research across a broad spectrum of disciplinary areas, in response to proposals from across the research community, continues to be effective in sustaining and stimulating a vibrant scientific enterprise. Many of the ideas raised in the community input for this study are appropriate and compelling candidates for this category of "bottom-up" PI-driven research. But the Committee felt strongly that it should not define a priori what proposals for individual research projects should be favored; rather, such decisions should instead be left to the standard NSF review process.

In the Antarctic, even small research projects can involve significant logistical requirements for getting scientists into the field, and so it is important for NSF to identify opportunities for efficiency and coordination that best leverage logistical investments. This includes efforts to improve coordination in the collection, management, and analysis of observations. For example, many studies require observations of basic physical parameters (e.g., oceanic or atmospheric conditions), and efficiencies could be gained if these data were better shared among research teams or routinely obtained at key locations for shared use.

Recommendation: NSF should continue to support a core program of broad-based, investigator-driven research and actively look for opportunities to gain efficiencies and improve coordination and data sharing among independent studies.

LARGER-SCALE PRIORITY RESEARCH INITIATIVES

Given the costs and logistical challenges of accessing remote Antarctic and Southern Ocean regions of interest, we suggest that the traditional PI-driven research support be balanced with more directed, large-scale efforts aimed at concentrating a critical mass of human and financial resources on key research goals. Drawing upon both the community input and internal deliberations, the Committee identified, and recommends for consideration going forward, three main priorities for large research initiatives that require a coordinated "push" to make transformative advances, and that are beyond the scope of proposals submitted by individuals or small groups of investigators. To help provide a rigorous process for identifying these priority topics, the Committee developed the following evaluation criteria (Box S-1).

Recommendation: NSF should pursue the following as strategic priorities in Antarctic and Southern Ocean research for the coming decade:

I. **How fast and by how much will sea level rise? The Changing Antarctic Ice Sheets Initiative**
   - **A multidisciplinary initiative to understand why the Antarctic ice sheets are changing now and how they will change in the future.**

BOX S-1
Evaluation Criteria for Large Research Initiatives

Primary filter:

- **Compelling science:** research that has the potential for important, transformative steps forward in understanding and discovery.

Secondary filters (important criteria, but each one may not be met in every case):

- **Potential for societal impact:** research that yields information on near-term and/or long-term benefits for society.
- **Time-sensitive in nature:** research that involves systems/processes undergoing rapid change that need to be observed sooner rather than later; research that could help inform current public policy concerns.
- **Readiness/feasibility:** research that is poised to move forward quickly within the coming decade, in terms of needed technologies and community readiness.
- **Key area for U.S. and NSF leadership:** research for which the United States, and NSF in particular, is advantageously positioned to lead.

Tertiary filters (additional factors to consider):

- **Partnership potential:** research for which NSF/PLR investments could leverage investment by other federal agencies, other parts of NSF, or international partners.
- **Impacts on program balance:** research that would not cause significant adverse impacts on other projects by requiring disproportionate funding support, or logistical support.
- **Potential to help bridge existing disciplinary divides:** research that could provide opportunities to bring together disciplinary communities that seldom work together.

- **Using multiple records of past ice sheet change to understand rates and processes.**

II. How do Antarctic biota evolve and adapt to the changing environment? Decoding the genomic and transcriptomic bases of biological adaptation and response across Antarctic organisms and ecosystems.

III. How did the universe begin and what are the underlying physical laws that govern its evolution and ultimate fate? A next-generation cosmic microwave background program.

Below is a brief overview of the motivation, goals, and key steps forward for each of these topics. The first of these topics is the largest of the three, and in the Committee's judgment is the most urgent to pursue.

Strategic Priority I:
How Fast and by How Much Will Sea Level Rise?
The Changing Antarctic Ice Sheets Initiative

Ice sheets resting upon bedrock below sea level in both West and East Antarctica are vulnerable to a runaway collapse process known as marine ice sheet instability. This instability is thought to be triggered mostly by melting at the ice sheet edges by warm ocean water. Although this process has been identified and tested in models, it has not yet been directly observed; and it is not known how fast this runaway collapse might occur or what parts of the Antarctic ice sheet will be involved. But evidence is building that portions of the Antarctic ice sheet are becoming unstable and beginning to collapse, and that the pace of change has accelerated in recent years. There is an urgent need to understand this process in order to better assess how future sea level rise from ice sheets might proceed.

Understanding why and how the ice is changing now, and how fast it will change in the future, has critical implications for human society. As the West Antarctic Ice Sheet (WAIS) responds to a warming ocean and changing climate, it could contribute 2 to 4 m of global sea level rise within just a few centuries (with additional, much larger potential contributions from the East Antarctic Ice Sheet, but on unknown timescales). Protecting coastal infrastructure and ecosystems from this sea level rise is a massively expensive proposition, and understanding the likely rate and magnitude of sea level rise is critical to evaluating the level of societal response required.

The Committee thus proposes a major new effort to improve understanding of why the marine ice sheets of Antarctica, especially West Antarctica, are changing and how they will change in the future. This would be a multipronged research strategy that includes studies of both the ice sheet changes occurring today and of major ice sheet changes that have occurred in the past.

Component i: A multidisciplinary initiative to understand why the Antarctic ice sheets are changing now and how they will change in the future

> There are major gaps in scientific understanding of the processes and rates of ice sheet collapse, stemming from lack of observations in critical areas in the ocean and beneath the ice surface, and from still-evolving understanding of ice sheet/shelf dynamics and of critical changes in Antarctic climate and atmospheric circulation. Understanding the fundamental processes driving Antarctic ice sheet change requires a coordinated research effort with mea-

surements taking place over an extended time in critical regions. The initiative proposed here builds directly upon the recent history of U.S. leadership and investment in West Antarctic research. The key elements of this initiative include

- Multidisciplinary studies of key processes to advance understanding of complex ice, oceanic, and atmospheric interactions;
- Systematic measurement of key drivers of change in West Antarctica, for instance, including in situ observations of atmospheric and oceanic circulation, sea ice changes and influences, ice sheet flow and accumulation, and the sub-ice-shelf and grounding-line environment;
- Mapping the unknown terrains beneath the major ice shelves and the critical regions beneath the ice sheet, with technologies such as airborne radar, geophysical imaging, active seismic surveys, and sub-ice rovers, as well as traditional coastal and on-ice surveys; and
- Advancing development of coupled atmosphere–ocean–sea ice–ice sheet models optimized for the Antarctic environment.

This effort will require improved access to logistically challenging coastal regions of WAIS, which in turn requires research vessel, airlift, aerogeophysical, and over-snow traverse capabilities. It will require new technologies and sampling strategies, including advanced buoys and moorings, and autonomous instrumented submarines and surface sensor stations.

Component ii: Using multiple records of past ice sheet change to understand rates and processes

The detailed physical processes by which ice sheet collapse occurs are not well understood, and this lack of understanding translates directly into model uncertainties on the predicted speed and extent of future WAIS collapse. Resolving these uncertainties requires rigorous study of past rapid ice retreat events. The Committee thus proposes a well-integrated program of ice core, marine, and terrestrial studies that can directly inform and help constrain the models used to predict future evolution of WAIS.

The most recent WAIS collapse event is thought to have happened during the last interglacial period (Eemian) about 125,000 years ago. Paleorecords have been recovered from this period, but the low temporal resolution of these samples has frustrated attempts to constrain the rate of ice sheet collapse. For ice cores, pursuing annually resolved samples may yield particularly valuable evidence for establishing how fast Antarctic ice can melt. This initiative thus would include drilling one or more ice cores from sites on the margin of the presumed WAIS collapse region, where ice from the Eemian with annual layers is likely to still be preserved. A potential ice core site that is already well characterized and appears suitable is Hercules Dome, located at the boundary between East and West Antarctica.

This initiative would also include high-resolution sediment cores from marine basins at carefully chosen sites within and adjacent to the suspected WAIS collapse region. High rates of sediment accumulation are expected in open marine conditions; and it is thus reasonable to expect that annually or near-annually resolved intervals from collapse phases of the WAIS can be recovered in carefully selected records, providing new insights on how fast and how much West Antarctic ice melted during key historical intervals.

Determining the geographical footprint of past marine ice sheet loss by mapping the areal extent of the collapse region is also critical to estimating the volume of ice lost and hence the contribution to sea level rise. One promising approach is cosmogenic isotope exposure dating techniques on short bedrock cores taken from beneath the WAIS, which can indicate if the ice sheet was removed during a given time period, and in some cases how long the region was ice-free. These sub-ice datasets, along with cosmogenic and geochronological data from nearby moraines and glacial deposits that record ice margin positions, can be used to assess changes in WAIS ice volume over time.

This proposed *Changing Ice Initiative* has two main components that are distinct in terms of research strategies and geographical focus, but they cannot be advanced as isolated efforts. Ongoing interaction among these different research communities will yield the innovations that can elevate this initiative above and beyond the West Antarctic research carried out to date.

The USAP has supported a great deal of successful research on the changing Antarctic ice sheets over the past few decades, but the increased urgency of concerns about WAIS collapse necessitates greatly expanded multidisciplinary efforts among the U.S. research community and at the international level—with strong leadership and support from NSF. This research will ultimately provide critical guidance on when, where, and how society should adapt to rising sea levels. Although the costs of this research are large relative to the current budgets for NSF/PLR core programs, they are tiny relative to the projected costs of adaptation to and damage from sea level rise.

Strategic Priority II:
How do Antarctic biota evolve and adapt to the changing environment?
Decoding the genomic and transcriptomic bases of biological adaptation and response across Antarctic organisms and ecosystems.

For more than 30 million years, Antarctica and the Southern Ocean have been unique, isolated ecosystems with extreme climate conditions. The organisms confined within the Antarctic region have had to continually evolve to adapt to changing environmental challenges, making Antarctica a vast natural laboratory for understanding organismal evolution. As environmental change progresses, hastened in modern human times by global climate change and commercial fishing, there is compelling urgency to understand how Antarctic species and ecological interactions cope with the selective pressures.

Such questions have been widely studied through molecular biology, physiology, and ecology; but the fundamental unexplored frontier is the genomic information encoded within Antarctic organisms. Genome sequencing of populations of living species will reveal the magnitude of their genetic diversity, which is important in assessing their ability to adapt to environmental change. In addition, decoding transcriptomes and metatranscriptomes can provide information about an organism's functional plasticity and evolutionary capacity.

The importance of decoding the genomes of key Antarctic organisms to understand evolutionary adaptations and ecological success was recognized over a decade ago (NRC, 2003b). Since then, leaps in technological advances and large drops in costs have made genome sequencing highly feasible, with massively parallel sequencing infrastructures now widely available across research institutions and universities. Given such developments, the field is poised to make new discoveries in the following key areas: (i) Antarctic biodiversity and species interaction as an indication of their evolutionary potential, (ii) species' functional response to the changing Antarctic environment as an indication of their phenotypic plasticity, and (iii) evolutionary cold adaptation/specialization and future evolutionary and adaptive potential.

This initiative would involve biologists working on diverse species ranging from viruses to mammals, in a coordinated pulse of activity with a shared goal of decoding the genomic and functional bases of organismal adaptation in a changing environment. The effort would be inclusive of genomes and transcriptomes of individual species and species assemblages; and it could encompass ancient DNA, viruses, bacteria, and complex eukaryote species from major Antarctic habitats, including ice sheets, soils, outcropping rocks, surface and subglacial lakes and streams, the ocean, and sea ice. A priority focus can be given to keystone species and organisms/communities that are fundamentally important for addressing questions about Antarctic adaptation in the past and in the future.

NSF could implement this initiative in a series of calls for proposals designed to encourage interplay among lab-based genomic analyses, field-based environmental investigations, and collection of biological samples and environmental physical data—with concurrent support for bioinformatics advancements to aid in assembling and annotating the genomes to be analyzed.

This initiative can be based in part on analysis of already-archived biological samples, effectively advancing Antarctic biological research without taxing already-overstretched budgets and field logistics.

Strategic Priority III: How did the universe begin and what are the underlying physical laws that govern its evolution and ultimate fate? A next-generation cosmic microwave background program.

The cosmic microwave background (CMB) is the fossil light from the early universe of nearly 14 billion years ago. Measurements of the CMB have already provided remarkable insights into the makeup of the universe, determining the relative fractions of ordinary matter, dark matter, and dark energy, as well as the presence of the cosmic neutrino background. A key test remains, however—detection of the imprint on the CMB of gravitational waves generated during a process occurring in the first instants of the universe, known as Inflation. Such a detection would not only provide a spectacular confirmation of the Inflationary origin of the universe, it would open a window on physics at energy scales many orders of magnitude greater than could ever be probed with particle accelerator laboratory research, and it would provide evidence of the long-sought, but so far elusive, quantum nature of gravity.

A next-generation experimental program referred to as CMB Stage IV (CMB-S4) has been proposed to provide definitive measurements of the early universe, detecting inflationary gravitational waves, or at least setting limits that rigorously rule out some proposed models. The next generation of CMB measurements would also offer enough sensitivity to make precise determinations of the number and type of neutrino species, as well as the sum of their masses. The precision planned for these next-generation measurements will help unlock the story of the universe's evolution that as yet remains hidden in the CMB. These experiments address fundamental questions about our origins and the workings of the natural world that cannot be explained with current understanding of physics and thus demand further investigation.

This project would involve an array on the order of 10 telescopes installed at key locations around the world. Installing some of these telescopes at the South Pole will be a critically important part of the array, because the unique Antarctic environment makes it particularly valuable for obtaining the needed observations. The next-generation CMB experiment will be comparable to the current CMB research, in terms of its logistical "footprint" at the South Pole.

The CMB-S4 studies have been recommended by a major community-scale assessment—the "P5" Particle Physics Project Prioritization Panel, and this is seen as the next logical step in this rapidly progressing field of research. Taking the next step now will ensure U.S. leadership and continued return on NSF's investment in the South Pole CMB program. This effort would involve three NSF divisions (PLR, Physics, and Astronomical Sciences), the Department of Energy (DOE) Office of Science, and NASA, with potential for international partners as well.

FOUNDATIONS FOR A ROBUST ANTARCTIC AND SOUTHERN OCEAN RESEARCH PROGRAM

The Committee identified the following infrastructure and logistical support needs and other key issues as particularly critical for advancing the priority research initiatives, as well as supporting a wide array of investigator-driven research across PLR's core programs.

Access to remote field sites. The USAP has long been a leader in supporting deep-field research campaigns, and the community expressed strong desires to see continued support for these world-class capabilities. For the proposed *Changing Ice Initiative* in particular, it is essential to have expanded access to deep-field sites in West Antarctica, including work around and under the ice sheet edges. Critical target areas for U.S. efforts include the Amundsen Sea sector, the Ross Ice Shelf, and the grounding lines of the Siple Coast. Key needs include a deep-field camp and logistics hub, over-snow science traverse capabilities, ship support for research in ice-covered coastal areas (see below), all-weather aircraft access to McMurdo, and improved aircraft access to remote field locations. Given the reality that there are finite resources to transport material and personnel, careful planning will be needed to ensure that NSF's currently developing initiative to modernize McMurdo and Palmer stations does not constrain support for deep-field research activities.

Ship support. A prominent theme in the community input for this study was concern about ship-based support for the USAP. The United States currently has very limited heavy icebreaker support for research in Antarctic waters. The USCGC *Polar Star* is over 40 years old. The *Nathaniel B. Palmer* is approaching the end of its design service life and regardless is designed for only limited icebreaking. Despite more than a decade of assessment and planning efforts to address these limitations, no significant progress has been made thus far toward the acquisition of a new polar research vessel or icebreaker. This situation limits where U.S. scientists can conduct research and increases dependence on foreign vessels. To support the science priorities recommended by this Committee, and to retain a leadership role in both Antarctic and Arctic research, NSF will need to prioritize the acquisition of a next-generation research icebreaker, and in the near term will need to work with foreign research vessel operators to provide critically needed field opportunities for U.S. scientists. To maintain operations at U.S. Antarctic research stations and support all U.S. research carried out on the continent, progress must be made in acquiring one or more new polar class icebreakers.

Support for sustained observations. Long-term observations are essential for improving understanding of the natural environment and human influences on that environment. A call for expanded NSF support of sustained observational efforts was a common theme in the community input to this study, across widely varying disciplines. Some examples of frequently highlighted observing system needs include the Automatic Weather Station network, seismic and geodetic monitoring around the continent, improved ocean monitoring (e.g., surface and subsurface moorings, profiling floats, gliders), and instrumentation for characterizing long-term changes in solar variability and its impacts. Pursuing a comprehensive observing system across the full Antarctic continent, as recommended in the *Future Science Opportunities* report (NRC, 2011a), is still a worthwhile long-term goal, yet it simply may not be feasible to pursue at present. However, there are many practical and relatively low-cost steps that can be taken toward this broader goal by better coordinating, integrating, and strategically augmenting the wide array of observational efforts being carried out across the USAP. And the proposed *Changing Ice Initiative* offers excellent opportunities to develop regional building blocks of a broader Antarctic and Southern Ocean observing system.

Communication and data transmission capacity. Effective communications and information technology are critical to ensure safety in the field, operational support and management of manned and autonomous instrumentation, and daily bulk transmission capacity for scientific data. The proposed CMB-S4 program requires an increase in transmission rate up to the order of 1 terabyte/day in the coming decade. The *Changing Ice Initiative* raises new requirements for operational communications and bulk data transmission, for instance from deep-field camps and from autonomous instruments operating under the ice shelf.

Data management. None of the priority science recommended in this report can have lasting value if the underlying data are not preserved and accessible. Data management needs to be supported as an integral part of the scientific effort, which means supporting data itself as a valuable asset. The community input to this study revealed a widespread demand for more open and coordinated data collection and sharing, better use of existing data, and more integration of data across nations, disciplines, and data types. NSF/PLR can help the community sustain and develop data services to meet these demands, building on encouraging recent developments such as the formation of the Antarctic and Arctic Data Consortium and the Polar Data Coordination Network. NSF/PLR cannot address all the challenges alone or immediately, but there are many steps (discussed herein) that could be taken to realize scientific objectives more efficiently.

Coordination opportunities. The Committee's priority research initiatives all require some degree of new or expanded collaborative efforts among NSF/PLR and other divisions in NSF's Geosciences directorate (Atmospheric and Geospace Sciences, Earth Sciences, and Ocean Sciences), Directorate of Biological Sciences, and Directorate for Mathematical and Physical Sciences (Physics and Astronomical Sciences). There are also numerous opportunities for expanding NSF/PLR cooperation in key areas with other U.S. federal agencies (especially NASA, DOE, and NOAA), and with other countries' Antarctic and Southern Ocean research programs. Some areas that seem particularly ripe for expanding collaborative efforts include carrying out aerogeophysical, bathymetric, and seismic mapping exercises; performing biological sampling and survey efforts; planning ice core, marine-sediment, and geological drilling activities; improving representation of Antarctic and Southern Ocean processes in earth system models; expanding environmental sampling and instrument deployment from ships that service the various national bases around Antarctica; and supporting the Long-Duration Balloon studies and other large-scale astronomy/astrophysics and space weather research projects.

Education and public outreach. Antarctic science, with its inherent appeal to people's sense of discovery, is an underutilized element in educational curricula. NSF/PLR, together with other key partners, has important roles to play in supporting and developing Antarctic-themed resources for educators in K-12 and undergraduate classrooms, and likewise in developing public engagement and outreach resources for an array of informal educational institutions. An emphasis on using Antarctic datasets in classroom exercises and providing engaging experiences (e.g., personal stories from scientists in the field) can help people feel a sense of connection to the Antarctic and better appreciate the scientific and societal value of research in this remote part of the world. NSF can also help provide developmental opportunities in teaching and research for graduate students, postdoctoral researchers, and early-career Antarctic and Southern Ocean scholars—for instance, through targeted funding opportunities for research experiences, including international collaborations and institutional exchange, for undergraduates, graduates, postdocs, and educators.

Recommendation: NSF should prioritize the following actions to advance infrastructure and logistical support for the priority research initiatives recommended here—actions that will likewise benefit many other research activities supported under NSF/PLR's core programs.

- **Develop plans to expand deep-field access in key regions of the West Antarctic and Southern Ocean, including the following key elements: deep-field camp and logistics hub, over-snow science traverse capabilities, ship support for research in ice-covered Southern Ocean coastal areas, all-weather aircraft access to McMurdo, and improved aircraft access to remote field locations.**
- **Support the efforts of the Coast Guard to design and acquire a new polar-class icebreaker; and with the assistance of other research partners, design and acquire a next-generation polar research vessel. In the near term, work with international partners to provide ocean-based research and sampling opportunities through other countries' ice-capable research ships.**
- **Actively pursue opportunities for better coordinating and strategically augmenting existing terrestrial observation networks, and better coordinating national vessels to increase sampling of the Southern Ocean.**
- **Continue advancing efforts to improve USAP communication and data transmission capacity, including location/navigation for autonomous underwater instrumentation.**
- **Identify specific archives to manage and preserve data collected in all the core programs; encourage all funded projects to include personnel specifically tasked to address data management needs throughout a project's planning and execution; and work to both advance Antarctic-specific data management activities and advance cooperation with broader NSF-wide, national, and international data management initiatives.**

CONCLUDING THOUGHTS

NSF support for Antarctic and Southern Ocean research is vital for advancing the frontiers of human knowledge across many disciplines, for building an improved basis for understanding the earth system on a global scale, and for informing critical choices about how society might respond to major environmental changes over time. While there is an endless reservoir of exciting and important questions that Antarctic and Southern Ocean research could address, in the face of limited budgets for research and logistical support, the need for prioritization in allocating resources is real. The Committee hopes that the ideas raised here, which were richly informed and inspired by the input of researchers across the country, will provide a useful strategic framework for helping NSF leadership and staff make wise choices for the coming years.

CHAPTER ONE

Introduction

WHY WE DO RESEARCH IN ANTARCTICA AND THE SOUTHERN OCEAN

In January 1774, James Cook edged the *Resolution* into an unknown icy bay, farther south by hundreds of miles than any vessel had been at that time. Evidence of a massive continent to the south lay around the vessel in the form of huge icebergs and abundant penguins; but they could go no farther through the ice. He had traveled "as far as I think it is possible for man to go" at 71°10′ south latitude. The ship turned north, 90 miles away from an area later called Pine Island Bay. The only Antarctic samples recovered were chips of ice that provided desperately needed drinking water, as well as proof that land-based ice existed nearby. A sense of discovery and awe must have filled the crew as they drank the ancient polar water and imagined the landscapes yet to be discovered.

Now more than 200 years later, the Antarctic region is a hub of scientific discovery across multiple disciplines and a focus for science and infrastructure for many nations. The science carried out there plays a pivotal role in advancing the fundamental understanding of how Earth and the surrounding universe operate. As evidence for major shifts in Earth's climate accumulates, the role of Antarctica and the Southern Ocean as both drivers of and responders to global change is becoming increasingly apparent. The continued sense of discovery and awe, together with the increasingly urgent need to understand how these complex systems work, motivates the pursuit of science in Antarctica, along with the infrastructure and logistics needed to support it.

Profound discoveries emerge both from studies that focus on the Antarctic itself and from studies that leverage Antarctica as a unique platform for looking beyond. The recent identification of a microbial ecosystem native to subglacial Lake Whillans beneath the West Antarctic Ice Sheet is influencing our thinking about where life may exist on other planets. The recovery of the Vostok and Dome C ice cores that demonstrated the tight relationship between global temperatures and atmospheric carbon dioxide (CO_2) has framed policy debates about climate change. Precise dating of an ancient boulder has confirmed that the Antarctic and North America were once side by side as a centerpiece of the "supercontinent" Rodinia. Studies of krill, fish, whales, and penguins are helping us understand the complex food-web dynamics in the Ross Sea and Antarctic Peninsula. High-energy neutrinos captured as they passed through a

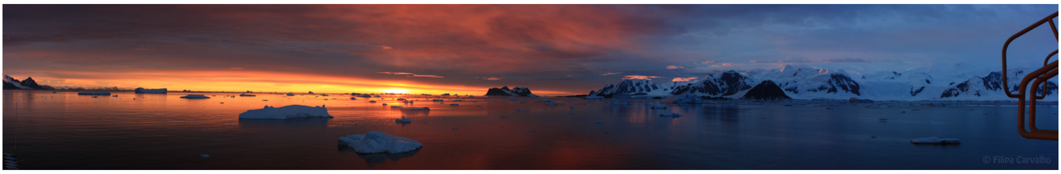


FIGURE 1.1 Photo taken near the Rothera research station in the West Antarctic Penninsula. SOURCE: Filipa Carvalho.

detector buried in a kilometer of ice at the South Pole tell of a source beyond our solar system. Precision measurements of the cosmic microwave background originating from the first moments of the universe have led to rapid advances in understanding the makeup and evolution of the universe, providing new insights into fundamental physics. The discoveries of Antarctic science reach back almost to the beginning of time and at the same time reach forward to enable understanding of what changes will occur in the future.

The Antarctic ice sheets and the Southern Ocean are now changing faster than James Cook, or even many modern-day scientists, could have imagined. Studies are finding a warming trend in the Antarctic Bottom Water that originates in the Southern Ocean and connects the Atlantic, Pacific, and Indian oceans through global circulation patterns. Satellite observations reveal both increasing velocities and decreasing elevation of Antarctic ice sheets. Cores drilled from Antarctic ice contain archives of how atmospheric composition has changed over time, helping us better understand how the climate system works. Sediment core observations of large and frequent changes in past Antarctic ice volume provide insights into how the ice sheet might change in the future. Changes in the ice sheets and the surrounding ocean are increasingly apparent, yet the processes driving these changes remain hotly debated. Understanding these processes is critical to developing accurate projections of how fast future changes will occur, and what impacts may be felt by the rest of the world.

OVERVIEW OF THE U.S. ANTARCTIC PROGRAM AND MOTIVATION FOR STRATEGIC PLANNING

The goal of this report is to help provide a strategic vision for NSF's investments in Antarctic and Southern Ocean research and infrastructure. For many decades, the United States has been the global leader in Antarctic and Southern Ocean research, driving major discoveries and advances in understanding the workings of planet Earth and the universe beyond. Currently, the U.S. Antarctic Program (USAP), managed by the National Science Foundation's Division of Polar Programs (NSF/PLR) supports U.S. scientific research and related logistics in Antarctica and aboard ships in the Southern Ocean (defined as the ocean south of 60°S). The goals of the program are to:

- Understand the Antarctic and its associated ecosystems;
- Understand the region's effects on, and responses to, global processes such as climate; and
- Use Antarctica's unique features for scientific research that cannot be done elsewhere.

Meeting these broad goals requires support for research over the entire Antarctic continent and the large Southern Ocean. NSF/PLR support for this research is currently organized through six major programs: (i) Astrophysics and Geospace Sciences, (ii) Organisms and Ecosystems, (iii) Earth Sciences, (iv) Glaciology, (v) Ocean and Atmospheric Sciences, and (vi) Integrated System Science, as well as an Antarctic Artists and Writers Program that aims to increase public understanding and appreciation of the Antarctic. Complementing the core science sections is the Antarctic Infrastructure and Logistics section, which maintains the Antarctic research stations, ships, and aircraft, and supports both NSF research and research conducted by other federal agencies. This section manages a large federal contract to the logistics provider (currently Lockheed Martin), and works closely with key U.S. military entities including the New York Air National Guard and the Military Airlift Command. Although budgets vary from year to year, the science sections are funded at a total of approximately $70 million annually, while the Infrastructure and Logistics section is funded at approximately $255 million annually.

The USAP benefits from the broad access that researchers are given to the continent and its surrounding ocean. As mandated by presidential order, the USAP operates three scientific stations on the continent: (i) McMurdo Station, located on the Ross Sea; (ii) Amundsen-Scott Station, located at the geographic South Pole; and (iii) Palmer Station, located on Anvers Island near the Antarctic Peninsula. Major airlift support to the continent through the McMurdo airfields is launched from USAP facilities in New Zealand; and staging facilities in Punta Arenas Chile support Palmer Station and provide the operational base for USAP research vessels. Continuity of operations at these stations and essential infrastructure upgrades require annual ship-based resupply, which in turn requires the services of a heavy icebreaker for break-in to McMurdo. This service traditionally has been performed by the U.S. Coast Guard ships *Polar Star* or *Polar Sea*, but in recent years has required leasing the services of other countries'

FIGURE 1.2 Examples of scientific explorations in Antarctica and the Southern Ocean. **A:** Scientists install cameras for the Extreme Ice Survey. SOURCE: Erin Pettit. **B:** Scientists install a high-frequency dipole antenna in East Antarctica to learn more about solar storms. SOURCE: Hyomin Kim. **C:** David Ainley studies Adélie Penguins in the Ross Sea. SOURCE: Jean Pennycook. **D:** NASA's Long-Duration Balloon site, Willy Field, McMurdo Station. SOURCE: NASA. **E:** Travis Pitcher working on the GPS monument at Bennett Nunatak, Antarctica. SOURCE: David Saddler. **F:** Students in an NSF-sponsored training course collecting a water sample through a hole drilled in the ice. SOURCE: Deneb Karentz. **G:** Scientists with a recently drilled ice core. SOURCE: Dan Dixon/ITASE.

icebreakers. The issue of icebreaking to support U.S. interests in Antarctica is discussed further in Chapter 4.

Over 3,500 Americans are involved each year in the program's research and logistical activities in Antarctica and the Southern Ocean. The level of funding for USAP infrastructure, as well as the high ratio of logistics support personnel to scientists, reflects the complexity and challenges of working safely and with consideration for the environment in the far south. Much of the infrastructure that supports cutting-edge Antarctic and Southern Ocean science is aging and in need of upgrading. In a time of tight science budgets, careful strategic planning is paramount for ensuring that new investments can both help contain future operational costs and maintain the safety of conducting Antarctic research.

ORIGIN AND GOALS OF THIS STUDY

The NSF/PLR leadership asked the National Academies of Sciences, Engineering, and Medicine to convene a committee to develop a "strategic vision" for NSF-supported Antarctic and Southern Ocean research for the coming decade. The Committee assembled to carry out this work includes experts in fields as diverse as astrophysics, biological sciences, ecology, geospace sciences, geology and geophysics, glaciology, ocean and atmospheric sciences, education, and data management. Members were selected to bring knowledge of existing and ongoing community planning for new endeavors, hands-on experience in Antarctic research, as well as new perspectives from outside the Antarctic science community. Committee biosketches are in Appendix A.

This study builds on a series of advisory efforts that began in 2010, when the White House Office of Science and Technology Policy and the NSF initiated a review to help ensure that the USAP supports the most important science in a manner that is as effective, efficient, innovative, safe, and environmentally friendly as possible. That review was conducted in two phases:

First, a broad scientific scoping effort was conducted by the Academies' Committee on Future Science Opportunities in Antarctica and the Southern Ocean, tasked to identify important scientific drivers that could shape the future of the USAP research. That committee was asked to highlight the full array of important science that can be done in the Antarctic and Southern Ocean, without suggesting any prioritization. The report, *Future Science Opportunities in the Antarctic and Southern Ocean* (NRC, 2011a), outlined eight high-level questions of critical importance to scientific research in Antarctica and the Southern Ocean over the next two decades. See Box 1.1 and Appendix C for

BOX 1.1
The High-Level Science Questions from
Future Science Opportunities in the Antarctic and Southern Ocean

Global Change

1. How will Antarctica contribute to changes in global sea level?
2. What is the role of Antarctica and the Southern Ocean in the global climate system?
3. What is the response of Antarctic biota and ecosystems to change?
4. What role has Antarctica played in changing the planet in the past?

Discovery

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

details. The Committee decided that this framework of eight questions still holds up well as an accurate reflection of today's science in Antarctica and the Southern Ocean. Thus we deliberately built upon that framework by trying to identify specific, implementable steps forward under each of those eight questions.

Second, a study was conducted by a special Blue Ribbon Panel that examined the logistics, management, and infrastructure needed to support the science identified in the *Future Science Opportunities* study. The resulting report, *More and Better Science in Antarctica Through Increased Logistical Effectiveness* (BRP, 2012), offers an array of recommendations that are summarized in Appendix D. The Blue Ribbon Panel highlighted the need for major reinvestment in the Antarctic and Southern Ocean infrastructure, especially at McMurdo and Palmer. The previous assessment of this type (Augustine et al., 1997) resulted in the rebuild of the South Pole station, followed by the installation of the 10-m South Pole Telescope and the IceCube Neutrino Observatory. These major infrastructure and instrumentation investments had significant impacts on Antarctic science for almost a decade. The lessons learned from these past experiences, together with the Blue Ribbon Panel's call for a new round of major infrastructure investments, and the potential for tight science budgets in the coming years, all point to the need for careful strategic planning for the next decade of USAP operations.

While these two previous studies laid an important foundation for setting big-picture goals for the USAP, NSF decided that an additional round of guidance would aid strategic planning and ensure that cutting-edge science is maintained during the next round of infrastructure modernization. This Committee was asked to build upon those earlier reports with recommendations for action that are fine-grained enough to be implementable on a practical level, and that are aligned with reasonable expectations for the resources likely to be available. The Committee was also asked to consider how NSF might set priorities among the many areas of research that are possible, given the realities that not all such research can be pursued at once.

The full Statement of Task for this study is provided in Appendix B. The recommendations presented here directly address the first two elements of this Task Statement: identifying priorities for strategic investment in compelling scientific activities, and analyzing the infrastructure needed to support this priority research. The Committee did not feel it had sufficient information or rationale, however, to fully address the third element of the Task Statement—evaluating how the current portfolio of program investments should change to achieve our strategic vision. Although the NSF/PLR staff did provide some information about the goals and types of research supported under the core programs, this information was limited and very mixed in terms of format and detail, and was only a snapshot of an evolving portfolio. The Committee felt this did not provide an adequate basis for recommending specific adjustments to the current portfolio. Likewise the Committee did not feel it was productive to call out specific existing grants that should be phased out, or to suggest specific limits on the number, size, or types of projects supported through the core programs—because this depends on how the program's annual budget changes over the course of the coming decade. And as discussed later, we are recommending that the core programs continue to base most investment decisions on how individual proposals fare in the standard peer review process, rather than being determined top-down by our Committee.

This report is built on an extensive effort to gather ideas from across the geographically widespread and disciplinarily diverse community of Antarctic and Southern Ocean researchers across the United States. The outreach efforts undertaken for this study spanned 11 months and engaged over 450 people. The major components were:

- An initial Town Hall session was held at the 2013 American Geophysical Union Fall Meeting, to announce the study and inform participants about the opportunities to contribute ideas.
- An online "Virtual Town Hall" website (online from March to November 2014) provided a place where anyone was able to submit ideas in writing. The

website was widely promoted via numerous list servers used among the polar research community and at relevant conferences and meeting sessions.

- A series of outreach sessions was held at 14 locations across the country. Some of these were stand-alone events held at universities and other locations identified as active "hubs" of USAP-related research. Others were shorter sessions held in conjunction with existing conferences and meetings. The dates and locations of these outreach events are listed in Appendix E. (See Figure 1.3.)

In all of these forums, participants were asked to: suggest research questions that are ripe for major advances in understanding and that could feasibly be achieved in the coming decade; identify specific technological, infrastructure, or data-sharing developments that are necessary to enable this research; and identify opportunities to advance this research through interagency cooperation, international cooperation, or other innovative arrangements.

The Committee also considered the results of the Scientific Committee for Antarctic Research (SCAR) "Horizon Scan" process (Kennicutt et al., 2014a,b), which was conducted in parallel with this U.S.-focused planning effort. For the Horizon Scan, scientists from around the world identified the most compelling science questions that

FIGURE 1.3 Photos from community engagement sessions held for this study.

will drive international Antarctic science forward in the next two decades. Through a combination of online input and a retreat of 74 experts from 22 countries, a total of 80 science questions were identified, and grouped under the following major topics: (1) Antarctic atmosphere and global connections and the Southern Ocean and sea ice in a warming world, (2) the ice sheet and sea level, (3) the dynamic earth beneath Antarctic ice, (4) life on the precipice, (5) near-Earth space and beyond—eyes on the sky, and (6) human presence in Antarctica. Several members of the Committee attended the Horizon Scan retreat, coauthored the reports, and provided input on linking U.S. planning with international efforts.

The Committee held six meetings to gather information, discuss and debate their views, and work on crafting this report. Those invited to speak at the meetings included numerous representatives of NSF, along with representatives of other federal agencies involved in the U.S. Antarctic Program, including the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the Department of Energy, the U.S. Coast Guard, as well as the State Department and the Office of Science and Technology Policy. In addition, briefings were provided from representatives of select research institutions, from other relevant National Academies' boards and studies, and from international organizations such as SCAR. See Appendix F for a full list of the meeting speakers.

Given the broad nature of this study, all Committee members had to evaluate and compare research needs across a wide array of topics that reached well beyond each individual's personal expertise. To foster a more informed process, the Committee members presented to each other a series of educational tutorials on key concepts, exciting recent developments, and remaining challenges for the many different fields of research anticipated to be addressed in this study.

Although this study and its recommendations are aimed primarily at NSF leadership, we hope it will be useful to an array of other audiences, including officials at other federal agencies that conduct research and operations in Antarctica and the Southern Ocean, examiners at the Office of Management and Budget, the White House Office of Science and Technology Policy, and congressional staff and committees. We hope the research community at large, which greatly helped shape the findings and recommendations presented here, will also find the report to be useful for a variety of educational and research planning purposes.

CHAPTER TWO

Opportunities and Challenges of Antarctic and Southern Ocean Research

OVERVIEW OF THE BREADTH OF ANTARCTIC AND SOUTHERN OCEAN SCIENCE

Scientific research in the Antarctic and the Southern Ocean has always been, and remains, a challenging endeavor. Access to the major research bases requires specialized ships, runways prepared on ice, and aircraft equipped with skis. The information connectivity that one takes for granted in the United States remains very limited at Antarctic research bases. Working safely in the extreme environment of the deep field, or in the often stormy waters of the open ocean, remains challenging for both people and technology. Yet despite the difficulties and expense of working in these extreme environments, the research supported by NSF produces a wide array of important and exciting scientific advances. The unique nature of Antarctic and Southern Ocean research can be appreciated through many different disciplinary perspectives—from oceanographic to tectonic to microbial to astrophysical. Highlighted here are some examples of the exciting developments and new scientific questions that have emerged from the U.S. Antarctic Program (USAP) research in recent years.

An ice-covered continent. Ice covers all but about 2 percent of Antarctica, and in places it is over 4 km thick. The ice sheets first grew in Antarctica over 34 million years ago as the Drake Passage opened and global atmospheric carbon dioxide (CO_2) levels dropped below ~1,000 ppm (as a result of erosion and weathering of the huge area of raw rock emerging as the Himalaya Mountains). Together, the ice sheets in East and West Antarctica hold the largest reserve of freshwater on the planet that if fully melted is capable of raising sea level globally by nearly 60 m. While continental in scale, ice sheet flow speed and thickness are affected by the underlying rock and sediment, the temperature of the surrounding oceans, and input of new snow from the polar atmosphere. Advances in our understanding of this integrated system have come from both individual studies and major international collaborative programs. For instance, individual investigator analysis of records from seismometers and exposed landscapes led to an understanding of how large ice streams and outlet glaciers drain the ice from the ice sheet interior toward the oceans, and how the movement of large icebergs is controlled by ocean tides. The large multinational collaborative framework provided by the International Polar Year led to the discovery of major subglacial water networks beneath Antarctica and their contributions to ice sheet dynamics. (See Figure 2.1.)

A tectonic keystone. Understanding the tectonics and geologic history of Antarctica is key to understanding continental assembly, to decoding how major species dispersed across the planet, to deciphering how the ice sheets have grown and collapsed in the past, and to understanding what controls the temperature of the base of the ice sheet and where it begins to flow fast. Twice the Antarctic continent has been at the center of a "supercontinent"—Rodinia over 1.2 billion years ago and Pangea 260 million years ago. The age and geochemistry of a boulder stranded at the edge of the ice (glacially transported from along the edge of the Transantarctic Mountains), provided strong evidence that Antarctica was adjacent to North America 1.2 billion years ago (Goodge et al., 2008). Marine sediments contain the record of how and when the ice sheet grew and have demonstrated how the ice sheet has collapsed many times in the past. Dating of the exposed rock and ancient deposits high in the Transantarctic Mountains have offered insights into past changes in atmospheric temperature and how the ice sheets and alpine glaciers responded to these changes. A large collaborative program that instrumented much of Antarctica with GPS instruments and seismometers (POLENET) found evidence for active volcanic systems beneath the West Antarctic Ice

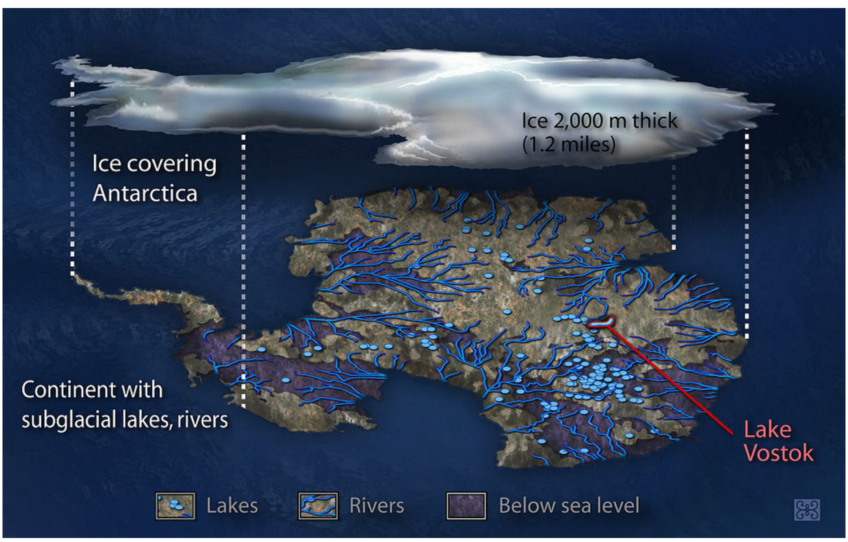


FIGURE 2.1 Subglacial aquatic system. SOURCE: Zina Deretsky, NSF.

Sheet, and observed vertical motion of the Earth's crust. Together with precise gravity measurements from the GRACE satellite, this has been crucial for quantifying the current rate of ice loss from Antarctica.

A frontier for exploration and discovery. Many of the places, processes, and ecosystems in Antarctica remain as unknown as other planets. The surface of Mars is known better than the topography beneath the Antarctic ice sheet and its floating ice shelves. The ocean cavities beneath Antarctica's peripheral ice shelves in particular are critical environments where warming ocean water and ice meet, and yet are almost completely unmapped and unmeasured. However, a few well-framed hypothesis-driven expeditions to study and sample new locations have resulted in major scientific advances. A U.S.-led multinational program discovered that rapid changes occurred in the seafloor ecosystem along the east and west coasts of the Antarctic Peninsula following ice-shelf and fjord-ice collapse, thus demonstrating how sensitive polar ecosystems are to change. The Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) program has recently recovered the first samples from a subglacial lake and from the grounding zone beneath the Ross Ice Shelf (Christner et al., 2014).

Novel records of past change. Sediments under the Southern Ocean and the Antarctic ice sheets preserve unique records of how the climate and the ice sheets have changed in the past. Scientists studying sediment cores drilled from beneath the Ross Sea (see Box 2.1) discovered that in the past, the ice sheets have been highly sensitive to rapid melting when atmospheric CO_2 concentrations are close to present-day values (Naish et al., 2009). They also found evidence of a remarkably warm period in Antarctica 15.7 million years ago. The marine algae and woody plants whose fossils and pollens were recovered indicate summer land temperatures up to 10°C (50°F) and sea surface temperatures as warm as 11.5°C (53°F) (Warny et al., 2009). Even more remarkable is the discovery that coastal East Antarctica 50 million years ago supported dense near-tropical forests, wherein winters were warm enough to be frost-free (Pross et al., 2012). A deep ice core recovered from the center of the West Antarctic Ice Sheet has provided a high-resolution record of abrupt climate change. And evidence of dramatic changes in atmospheric composition, gathered from air bubbles recovered from the ice core points to rapid, widespread changes in climate that occurred as the Northern Hemisphere ice sheets collapsed.

Ecosystems at the edge. The opening of the Drake Passage initiated unrestricted circumpolar oceanic flow over 30 million years ago, and this Antarctic Circumpolar Current (ACC) formed a nearly impenetrable barrier that organisms could not cross. The sequestered Antarctic biotic survivors confronted subsequent episodes of major climatic transitions over the next several million years. Unable to flee elsewhere,

BOX 2.1
Discovery of the Dynamic History of the Ross Ice Shelf

The Ross Ice Shelf is the largest ice shelf remaining on our planet. This floating expanse of ice (the size of France) is up to 1,000 m thick. Currently the Ross Ice Shelf buttresses the West Antarctic Ice Sheet and is holding back the flow of West Antarctic ice into the ocean. Whether the Ross Ice Shelf can disappear quickly and trigger a collapse of the West Antarctic Ice Sheet was an important open question until the NSF-supported project ANDRILL (Antarctic Geological Drilling) recovered key sediment beneath the ice shelf. The ANDRILL McMurdo Ice Shelf project maintained a melted borehole in the ice shelf near Ross Island, lowered a drill string to the seabed at 920 m below sea level, and recovered a nearly complete geological drill core extending a further 1,285 m into the Earth—a record that still stands in Antarctic drilling. This work has provided evidence of past episodes of ice shelf advance and retreat, and evidence of periods of open water and times when the ice shelf was in direct contact with the seabed.

The ANDRILL record demonstrates much greater dynamism in the Ross Ice Shelf than was previously known. The Ross Ice Shelf has retreated either partially or fully at least 30 times during the past 5 million years (Naish et al., 2009). The natural climate variations that caused these ice shelf retreat and advance events provide useful "sensitivity experiments" on climate change and ice sheet response. For instance, it is known that when major ice shelf retreat events occurred, Southern Ocean temperatures were no more than 3-4°C warmer than at present, and atmospheric CO_2 levels were less than those of today. This suggests that (after equilibrium response is achieved) we may already be committed to climate conditions that cannot support a fully extended Ross Ice Shelf, and thus may have surpassed a stability threshold for continental ice in West Antarctica.

Antarctic organisms have had to contend with continual environmental challenges and extreme conditions. Microbial organisms living in Antarctic ice, rocks, soil, sediments, ocean waters, sea ice, lakes, meltwater ponds, and subglacial environments must adapt to extreme freezing and/or arid conditions, prolonged dark-light cycles, or complete absence of light. While the pace of evolution of most all Antarctic life is poorly understood, complex multicellular organisms are thought to be particularly vulnerable, thus limiting their diversity in Antarctica. At sea, the rich diversity of fish species present in earlier eras is survived today by a single predominant group, the Antarctic notothenioid fishes. Their ancestors evolved antifreeze proteins, discovered by U.S. polar biologists, that allow them to survive in the freezing Southern Ocean. More recent studies demonstrated that this protein is both an antifreeze and an antimelt protein, meaning that the lives of high-latitude fishes are a balancing act of avoiding freezing and avoiding tissue damage from internalized ice crystals that do not melt (see Box 2.2).

BOX 2.2
Superheated Ice in Antarctic Fish

The antifreeze proteins (AFPs) of Antarctic notothenioid fishes have long been regarded as a textbook example of the power of evolutionary adaptive innovation to solve survival challenges from environmental change. AFPs bind and inhibit growth of ice crystals that enter fish, thereby preventing the fish from freezing and enabling them to thrive in icy, frigid waters. However, recent investigations show that these antifreeze proteins are also antimelt proteins (Cziko et al., 2014); that is, the AFPs that inhibit ice growth also inhibit ice from melting, even at temperatures well above the expected melting point. Such "superheated" ice occurs inside Antarctic fishes in their natural environment. A decade-long temperature record of a McMurdo Sound fish habitat site revealed that because of the AFP-induced superheating, seasonal seawater warming may not melt internal ice over the fishes' lifetime. Microscopic blades of AFP-stabilized ice crystal could therefore accumulate to injurious levels in tissues. The life-saving AFPs are thus an evolutionary double-edged sword. This paradigm-shifting observation serves as a rare, concrete example of the imperfection and trade-off accompanying evolutionary processes, and a further reminder of the extreme challenges to survival in the harsh Antarctic environment.

FIGURE Antarctic notothenioid fish *Trematomus bernacchi*i (emerald notothen) finding safety in anchor ice formation on shallow bottom of McMurdo Sound, Antarctica. SOURCE: Kevin Hoefling.

Land of weather extremes. Antarctica is the highest, coldest, windiest, and driest continent on Earth, and is linked with weather events elsewhere on the planet, over a variety of timescales. The highly reflective ice surface and long, dark winter lead to the formation of a cold, dense air layer adjacent to the surface, creating a continent-wide, gravity-driven airflow pattern known as katabatic winds. In some coastal regions this airflow layer converges to generate extremely persistent and intense winds, for example, at Cape Denison in Adélie Land, considered the windiest place on Earth (Wendler et al., 1997). The influence of the katabatic airflow reaches deep into the overlying atmosphere, anchoring a clockwise cyclonic circulation high above the ice sheet. Air rising from Southern Ocean storms close to Antarctica moves up and toward the center of this cyclone. As it cools radiatively, it sinks, sustaining the northward katabatic flow from the central plateau. This "polar direct cell" is a major feature of the large-scale atmospheric circulation of the Southern Hemisphere. As air moves upward and poleward, nearly all of its moisture is lost, leaving the high interior with little precipitation and few clouds, which intensifies cold air production. The temperature contrast between the cold Antarctic atmosphere and warmer regions to the north generates westerly winds over the Southern Ocean, whose variations have a profound impact on the formation of sea ice, generation of bottom water, air–sea exchange of CO_2, and climate variability across the Southern Hemisphere and many parts of the Northern Hemisphere.

Wind and currents in the Southern Ocean. The Antarctic Circumpolar Current (ACC), which is driven by the circumpolar westerly winds, plays a unique role in linking the Atlantic, Pacific, and Indian oceans (see Figure 2.2). Around Antarctica, Upper Circumpolar Deep Water derived from the ACC penetrates and interacts with the ice sheet margins, initiating more melt and rapid ice flow. The ACC itself is an important region for ocean mixing and air–sea exchange of heat and gases, including fluxes of CO_2 and dimethylsulfide. The ocean eddies and currents play a role in the formation and modification of many different water masses that link the region to the global thermohaline circulation. Antarctic Bottom Water forms close to the Antarctic coast, becoming a well-defined dense and cold water mass that fills the deepest basins of the global ocean. Studies indicate that because of climate change, this Antarctic Bottom Water has been warming and decreasing in volume over the past few decades, which could have major implications across the world's oceans (Purkey and Johnson, 2012). With near-zero primary production on the Antarctic continent, the entire Southern Ocean ecosystem depends on nutrient- and sunlit-driven food production within sea ice and upper ocean waters, which are shaded by sea ice and mixed by currents and winds. Rapidly changing physical conditions are impacting Southern Ocean biogeochemistry and food supply, but the actual processes underlying these impacts remain mostly

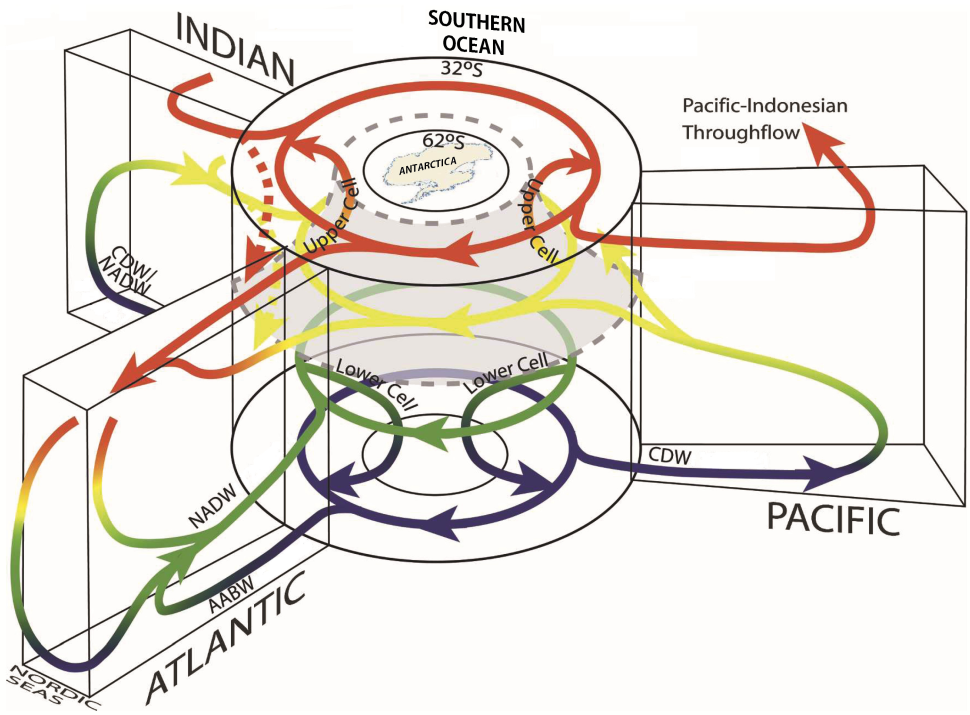


FIGURE 2.2 Illustration of how Southern Ocean circulation is linked to global oceanic dynamics. NADW = North Atlantic Deep Water; CDW = Circumpolar Deep Water; AABW = Antarctic Bottom Water. SOURCE: Lumpkin and Speer (2007).

unstudied. New NSF-sponsored initiatives such as the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project will greatly expand our understanding of such issues (see Box 2.3).

A world-class astrophysical laboratory. The South Pole offers an unparalled ground-based platform for studying the evolution and structure of the universe. The region's dry and stable atmospheric conditions and uniformity of weather provide a critical advantage for astrophysics research that involves deep, large-scale observations at infrared, submillimeter, and millimeter wavelengths. For instance, the 10-m South Pole Telescope (SPT) and the BICEP and Keck telescopes are designed for observing the faint, diffuse emission from the cosmic microwave background, which provides a wealth of information about the origin and evolution of the universe. In 2002 the first detection of the polarization of the cosmic microwave background was made from

BOX 2.3
SOCCOM: Understanding Southern Ocean Biogeochemistry

The Southern Ocean plays a globally significant role in the cycling of carbon, nutrients, and heat; and modeling studies project that changes in the Southern Ocean may profoundly influence future climate trends (Frölicher et al., 2015). But the remote, harsh nature of this region has hindered the collection of needed observations over relevant spatial scales. Current global models are too coarse to resolve critical features of the ocean circulation, and the limited observations make it difficult to assess model skill.

SOCCOM is an NSF-sponsored program, initiated in 2014, that will help elucidate the role of the Southern Ocean in global climate. Biogeochemical sensors mounted on autonomous floats will allow sampling of factors such as nutrients, pH, and phytoplankton biomass in the upper 2,000 m of the ocean, with a temporal resolution of 5 to 10 days. The data will be made available in real time, allowing anyone to conduct research throughout the lifetime of the project. SOCCOM will deploy 200 floats with a projected lifetime of 5 years, throughout the Southern Ocean.

Freed from the constraint of needing a ship to collect measurements, researchers will obtain broad coverage of Southern Ocean biogeochemistry. New ice-capable floats also extend coverage to the poorly studied sea ice region south of the polar front. These developments will aid the development of global climate and ocean models.

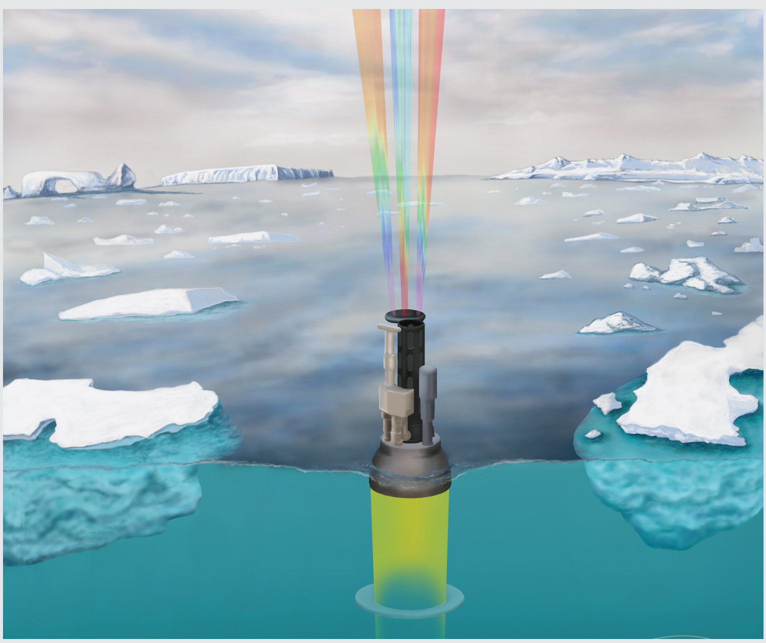


FIGURE Rendering of a SOCCOM float. SOURCE: Monterey Bay Aquarium Research Institute.

the South Pole (Kovac et al., 2002), and in 2013, the SPT made the first detection of B-mode polarization of the cosmic microwave background (Hanson et al., 2013). The IceCube Neutrino Observatory at the South Pole, encompassing a cubic kilometer of ice, searches for nearly massless subatomic particles called neutrinos. The IceCube team recently observed the first astrophysical high-energy neutrino detections (see Box 2.4).

INTRA- AND INTERAGENCY CONTEXT FOR NSF'S ANTARCTIC AND SOUTHERN OCEAN RESEARCH

Many of the research topics and activities carried out through NSF's Antarctic and Southern Ocean research programs are inextricably linked to broader global-scale research questions. Several examples illustrate these linkages:

- The Southern Ocean waters surrounding Antarctica play a critical role in global oceanic circulation and in uptake of heat and CO_2 from the global atmosphere. Better quantifying atmosphere–ocean exchanges across the Southern Ocean will help us better understand global energy, heat, and chemical constituent budgets. Southern Ocean mixing processes also play critical roles in ocean biology, for instance, in the Antarctic Convergence Zone where cool Antarctic water encounters warmer subpolar waters. This is a region of mixing and upwelling, where high nutrient levels yield a rich ecosystem with bacterioplankton, phytoplankton krill, and other organisms that support higher trophic levels.
- Antarctic climate changes observed in recent decades, especially warming of the Antarctic Peninsula and across West Antarctica (e.g., Nicolas and Bromwich, 2014) are influenced by a number of long-distance atmospheric linkages known as "teleconnections" (see Figure 2.3). One major teleconnection is the interplay between the strengthening and poleward migration of the westerly winds over the Southern Ocean (which happens in the positive phase of a periodic variation known as the Southern Annular Mode [SAM]), and the El Niño-Southern Oscillation (ENSO) which arises in the tropical Pacific. The strengthening and migration of the winds has caused a slight cooling over most of the continent and warming of the northern Antarctic Peninsula. Over West Antarctica the influence of the shifting winds weakens, and the remote atmospheric effects of tropical atmospheric variations predominate. The tropical ENSO impact on West Antarctica is amplified when the SAM and ENSO oscillations are in phase with each other, and the impact is damped when the two oscillations are out of phase.
- Solar-terrestrial research informs scientific understanding of how short-term and longer-term variations in solar output affect Earth's "space weather"

BOX 2.4
IceCube Neutrino Observatory

The IceCube Neutrino Observatory, a set of detectors located at the South Pole designed to capture signs of high-energy neutrinos, was completed in 2010. The international project includes roughly 300 physicists from 44 institutions in 12 countries. Funded by NSF and agencies from around the world, IceCube is a unique tool to detect neutrinos that pass through the deep, clear ice of Antarctica. It is made up of 5,160 digital optical modules suspended on 86 strings within a cubic kilometer of ice. When neutrinos interact with the ice, they create electrically charged secondary particles. The observatory detects neutrinos through the short flashes of blue light (called Cherenkov radiation) that these secondary particles produce as a result of traveling through the ice faster than light travels in ice. The tracks of the light could give scientists information about the type of neutrino involved and its origins, providing insights into high-energy cosmic events such as supernovae, black holes, gamma-ray bursts, active galactic nuclei, and other extreme phenomena. In 2013, scientists observed the first evidence for astrophysical high-energy neutrinos with energies at the 100-TeV level, including events with energies at the peta-electronvolt level—the highest-energy neutrinos ever detected (IceCube Collaboration, 2014).

Now that IceCube has detected astrophysical neutrinos, opening the field of neutrino astronomy, the collaboration envisions a major upgrade to the detector array to increase the rate of detection and the sensitivity to high-energy astrophysics events, by increasing the volume of instrumented ice by a factor of 10 (IceCube-Gen2 Collaboration, 2014). They also envision lowering the energy threshold for neutrino events to enable precision neutrino physics experiments by increasing the density of detectors in the core of the array (Precision IceCube Next Generation Upgrade (PINGU; IceCube-PINGU Collaboration, 2014). Radio-based neutrino detectors that also take advantage of the unique quality of the ice sheet at the South Pole, most notably the Askaryan Radio Array (Allison et al., 2012), are being proposed as complementary efforts to allow extension of neutrino astronomy to yet higher energies.

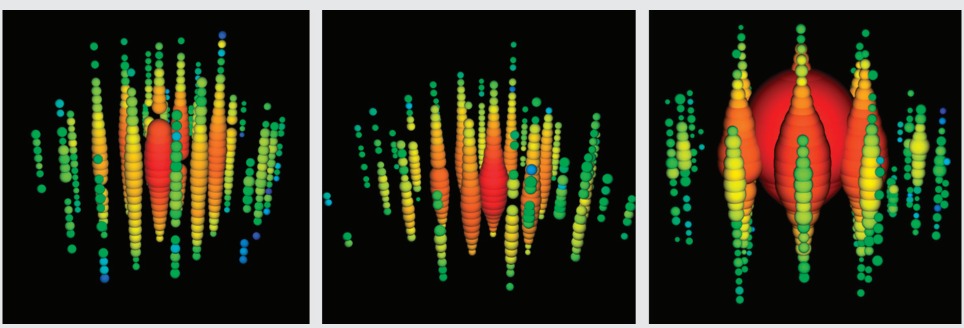


FIGURE Rendering of the results from IceCube's detection of the highest-energy neutrinos ever recorded. SOURCE: IceCube South Pole Neutrino Observatory.

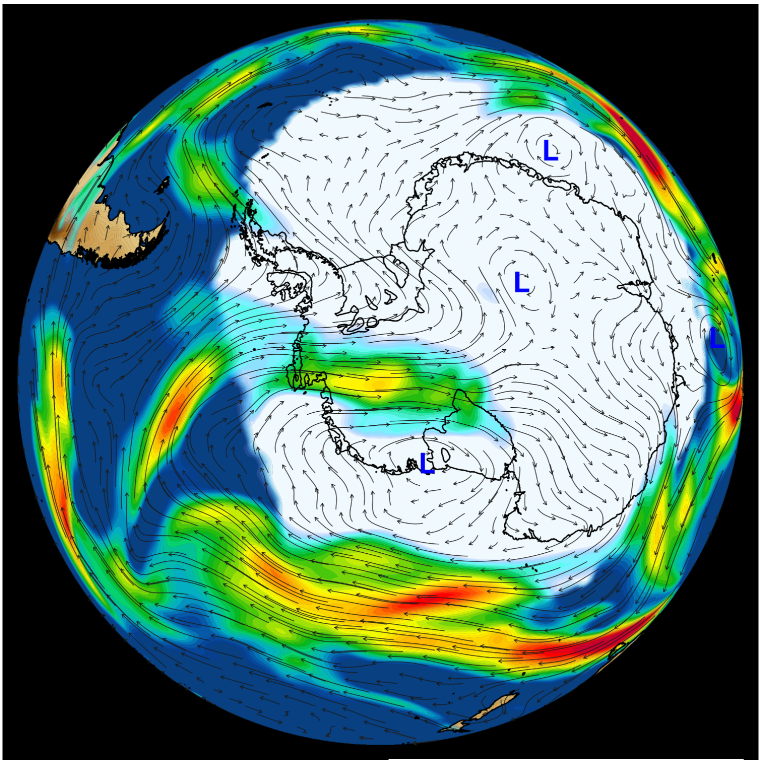


FIGURE 2.3 Map showing a deep low pressure system centered over the eastern Ross Sea on October 19, 2014. The system brought large amounts of warm marine air, clouds, and precipitation into West Antarctica. Arrows show wind flow and colors show wind speed in the middle part of the atmosphere. Data from ERA-Interim reanalysis. SOURCE: Julien Nicolas, Ohio State University.

and its climate variations over scales of decades to millennia. Because these solar influences affect the entire globe in complex patterns, monitoring such impacts requires globally distributed networks of observational equipment. (See Figure 2.4.) For instance, arrays of magnetic observatories are deployed at dozens of locations around the world, to investigate the dynamic variations of the field produced by the changing electrical current systems in the magnetosphere and ionosphere. The polar regions, and Antarctica in particular, are particularly critical nodes in these networks, and these Antarctic-based observational sites would be much less valuable if not planned and utilized as part of the broader global networks.

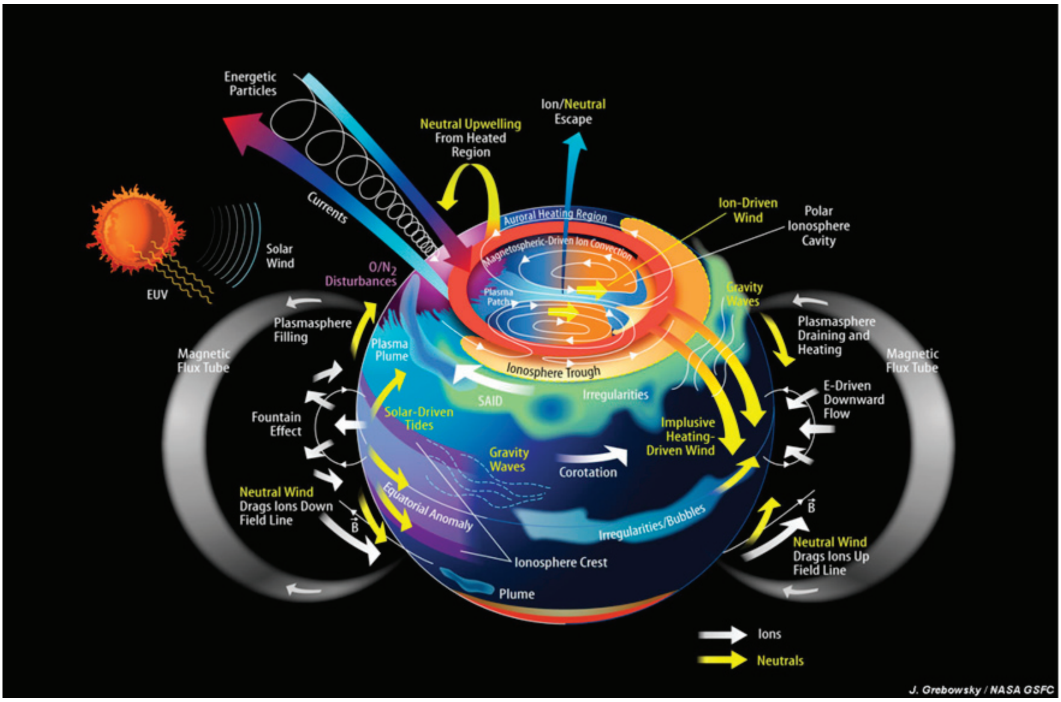


FIGURE 2.4 Illustration of the coupled atmosphere–ionosphere–magnetosphere system and processes that control dynamics across the system. SOURCE: J. Grebowsky, NASA/GSFC.

- Cosmic microwave background studies and the IceCube Neutrino Observatory at the South Pole are key experiments in multiagency, multinational efforts to understand the fundamental workings of time and space, and the origin and evolution of the universe. These experiments complement work being done around the world, in high-energy physics collider experiments, dark matter searches, large surveys of the sky across the electromagnetic and particle spectra using ground-based, balloon-based, and satellite platforms.

NSF/PLR research focuses on the region poleward of 60°S latitude, but the ocean, the atmosphere, and the energetic particles reaching Earth from outer space do not recognize such boundaries, as the examples listed above help illustrate. For this reason, PLR research overlaps with key topics of interest to other divisions in NSF's Directorates for Geosciences, Biological Sciences, and Mathematical and Physical Sciences. A variety of cross-divisional research support opportunities do exist, but there are some contexts in which bureaucratic divisions within NSF can act as a barrier to advancing critical integrative research and observations. Some key opportunities to overcome these barriers are discussed in Chapter 4.

Collaboration with other U.S. federal agencies is likewise critical for advancing Antarctic and Southern Ocean research, given the costs and challenges of gaining logistical access to the region, and NSF's essential role in facilitating this access. Although the Committee was tasked to advise strategic priorities just for NSF, there are, of course, other U.S. federal agencies that play important roles in the USAP. Some examples include:

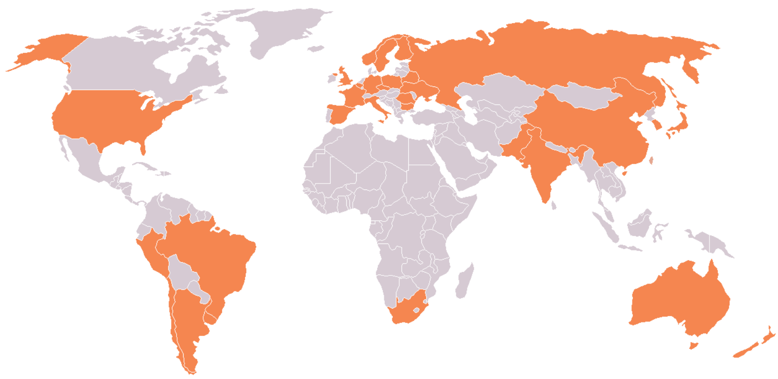
- **NASA's** Operation IceBridge utilizes research aircraft equipped with monitoring instruments to characterize annual changes in thickness of sea ice, glaciers, and ice sheets. IceBridge fills a gap in polar observing needs until launch of the ICESat-2 satellite.
- **NASA's** Long-Duration Balloon Program (with logistical support from NSF) uses large unmanned helium balloons to provide an inexpensive means to place payloads into a space environment, taking advantage of the unique atmospheric circulation over Antarctica. This helps in the development of new technologies for NASA's spaceflight missions and enables important scientific observations in fields such as x-ray/gamma-ray, infrared, and submillimeter-wave astronomy; cosmic rays; and upper atmospheric studies.
- **NOAA's** Global Monitoring Division operates an Atmospheric Research Observatory at the South Pole, as part of an extensive global network of sites where air samples are collected weekly and analyzed for greenhouse gases, halocarbons, stable isotope tracers, and volatile organic compounds. The South Pole site also collects in situ observations of aerosols, radiation, and surface and column ozone. These data help us understand long-term trends, seasonal variability, and spatial distribution of key atmospheric constituents.
- **NOAA's** Antarctic Ecosystem Research Division oversees the Antarctic Marine Living Resources Program, which does research that contributes to ecosystem-based management of fisheries that impact krill, finfishes, krill-dependent predators, and other components of the Antarctic ecosystem. This program supports the U.S. contribution to the Commission for the Conservation of Antarctic Marine Living Resources.
- **DOE's** Climate–Ocean–Sea Ice Modeling project develops high-performance, multiscale models of the ocean, sea ice, ice sheets, and the ocean and cryosphere components of the Community Earth System Model and Accelerated Climate Model for Energy. The goal is to improve modeling of high-latitude climate change and its impacts on ice sheets, sea level rise, sea ice changes, Southern Ocean circulation, and high-latitude ocean–ice ecosystems.

- **DOE's** Lawrence Berkeley National Laboratory has been an essential contributor in designing and developing the neutrino detectors used in IceCube. Berkeley Lab's National Energy Research Scientific Computing Center also contributes its supercomputing power to filtering the signals and analyzing the data from IceCube as well as processing the data from the 10-m South Pole Telescope.
- **DOE, NASA, and the National Institute of Standards and Technology** have contributed to the development of the superconducting bolometric detector arrays used on cosmic microwave background cameras deployed to the South Pole. DOE Office of Science will likely be a major contributor with NSF to the next-generation ground-based cosmic microwave background program.
- **DOE'S** Atmospheric Radiation and Monitoring (ARM) program is supporting, in conjunction with NSF, the ARM West Antarctic Radiation Experiment to study Antarctic clouds, which are poorly characterized in climate and weather prediction models. The effort will operate at McMurdo Station for 1 year and for a few summer months in West Antarctica, and related efforts may later be carried out over the Southern Ocean.
- **The U.S. Geological Survey (USGS)** has worked in Antarctica for over 60 years, starting in 1947 with geophysical and geologic surveys and in 1957 with topographic mapping. More recently, the USGS has been involved in marine, airborne, and satellite studies, as well as mapping and coring of the ice sheet; and, working jointly with NSF, the USGS oversaw the U.S. Antarctic Resource Center—the nation's most comprehensive international collection of Antarctic aerial photography, maps, charts, satellite imagery, and technical reports.

The research and monitoring efforts of these other agencies are often linked to, and sometimes directly contribute to, NSF-sponsored research. As discussed in Chapter 4, the community engagement discussions point to a variety of ways in which interagency cooperative efforts could be expanded to better leverage resources toward reaching USAP research goals.

INTERNATIONAL COLLABORATION IN ANTARCTIC AND SOUTHERN OCEAN RESEARCH

Antarctica is the only continent on Earth set aside just for international cooperative science, and international cooperation in scientific research is a cornerstone of the Antarctic Treaty System. At present, 30 nations have Antarctic-based research facilities (see Figure 2.5). The NSF has a long history of leading, engaging in, and supporting international collaborative research in Antarctica. A few illustrative examples are:



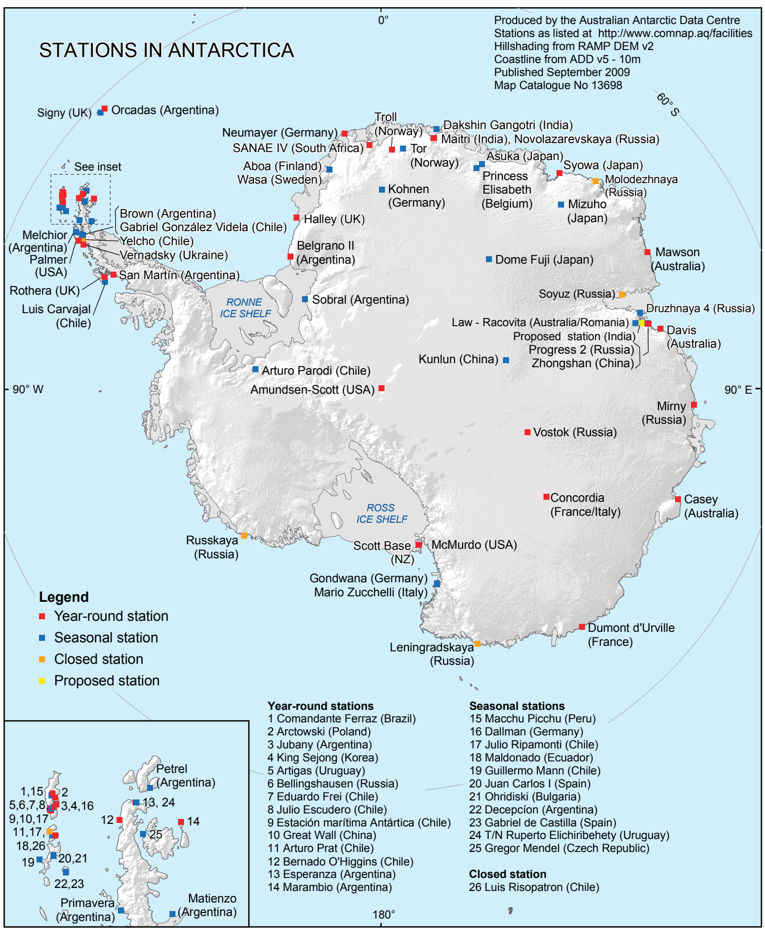


FIGURE 2.5 *Top:* Countries that have one or more research stations in Antarctica. SOURCE: Wikipedia. *Bottom:* All countries' Antarctic research stations. SOURCE: Australian Antarctic Data Centre.

- International research dating back to the International Geophysical Year 1957-1958 led to the remarkable discovery that the Antarctic ice sheet is more than 2 miles thick.
- Our fundamental understanding that global climate change, temperature, and pCO_2 levels have moved together over the past 800,000 years was a result of pioneering ice core research at Vostok Station, jointly supported by the United States, Russia, and France, and of the European Project for Ice Coring in Antarctica (EPICA).
- NSF collaborated closely with New Zealand, Italy, and Germany in the ANDRILL project to recover cores that demonstrated the rapid collapse of the West Antarctic Ice Sheet many times in the past 5 million years.
- During the 2007-2008 International Polar Year, a seven-nation team of scientists led by the United States surveyed the largest unexplored mountain range on the planet (hidden by the ice) and discovered new dynamical processes at the base of the ice sheet.
- The Polar Earth Observing Network (POLENET), which collects GPS and seismic data from autonomous observing systems across the Antarctic ice sheets, has been supported by participation by or contributions from 28 nations.
- The IceCube detector that recently made groundbreaking observations of astrophysical neutrinos involves collaborators from institutions in 12 countries, with significant additions to U.S. funding support coming from Belgium, Germany, Japan, and Sweden.

NSF and the U.S. research community have also been participating in recent international efforts to improve observations and understanding of the Southern Ocean. For instance:

- The Southern Ocean Observing System seeks to coordinate and expand the efforts of all nations that gather data from the Southern Ocean, with the specific aim of developing a coherent and efficient observing system that will deliver the observations required to address key scientific and societal challenges.
- The World Climate Research Program's Climate and Ocean: Variability, Predictability and Change (CLIVAR) Program hopes to expand the Argo profiling float program with additional sensors and floats capable of working under the ice, and enhancing observations such as subsurface moored arrays, mobile platforms such as gliders and wave gliders, biogeochemical floats, moored biogeochemical observations, and the establishment of crucial under-ice acoustic tracking of floats, gliders, and other autonomous underwater vehicles.
- The Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) is an international program that reoccupies basinwide ocean sections on

decadal timescales for hydrographic and biochemical studies. A number of GO-SHIP transects go through the Southern Ocean and/or terminate at the Antarctic coast. Several nations use their ships that resupply Antarctic bases to also collect temperature and salinity profiles and observations of ocean currents and surface meteorology and air–sea fluxes.

- The NSF's Ocean Observatories Initiative has deployed two Southern Hemisphere ocean observatories, at 55°S/90°W and at 42°S/42°W. Each site has four moorings, including a surface mooring and up to five ocean gliders, multidisciplinary instrumentation, and capacity to add more sensors. These observatories provide opportunities for collaborative studies with observatories being established by other nations (e.g., the Australian Integrated Marine Observing System's surface mooring south of Tasmania; the Japanese Science and Technology Agency surface mooring near the Antarctic coast). They also provide important contributions to the Global Climate Observing System, the Global Ocean Observing System, and other international efforts to develop a global array of sustained ocean observing sites.

The specific mode of international cooperation supported by NSF varies widely—from informal collaboration between individual scientists, to formal proposal calls that specifically outline the need for international partnerships. For instance, during the International Polar Year 2007-2008 the NSF funding call required international collaboration and robust scientific partnerships. For some large programs, NSF program managers led the process of convening international peer review panels and negotiating subsequent cost-sharing and proportional scientific participation.

U.S. marine scientists have long enjoyed opportunities to sail on other nations' Antarctic research vessels either as part of official joint projects, or as "ships of opportunity" when individual scientists work with international collaborators. For instance, numerous U.S. scientists have pursued NSF-funded research on board the German research icebreaker *Polarstern*. Some countries, such as South Korea, fund U.S. scientists to join their sponsored programs. In turn, U.S. Southern Ocean projects often include overseas participants. For instance, International Ocean Discovery Program drilling proposals for the Southern Ocean are always reviewed by an international panel of experts, and U.S. funding to operate the vessel is comingled with contributions from over 25 nations. There is potential for expanding coordination in use of the various national ships for underway meteorological and oceanographic sampling, for deployment of drifters, floats, and gliders; and possibly for establishing mooring sites along ship transits.

The United States also has a long history of international collaboration in logistical support for Antarctic and Southern Ocean research. NSF has worked extensively with New Zealand and Italy in the western Ross Sea, has collaborated on several occasions with Argentina and Chile in studies along the Antarctic Peninsula, and is developing relationships with South Korea and China as these nations establish new bases in Terra Nova Bay close to McMurdo. The British Antarctic Survey has been a close partner with NSF in projects from the difficult-to-access Amundsen Sea and deep interior of East Antarctica, to the western Antarctic Peninsula where they are a formal partner in NSF's Palmer LTER (Long Term Ecological Research) program.

The United States was a driving force behind the creation of the Antarctic Treaty and continues to support Treaty System activities, including COMNAP (Council of Managers of National Antarctic Programs) and SCAR (Scientific Committee for Antarctic Research). A large number of U.S. scientists participate and play leadership roles in SCAR activities and projects. These activities, as well as the relationships that have developed through alliances in SCAR, mean the United States is well positioned to play a leadership role in further developing international scientific and logistical cooperation.

Antarctica remains one of the most challenging places on Earth to work, and many research efforts remain beyond the scope of any single nation. International collaboration will continue to be critical for making new advances, and sharing expenses across multiple national funding entities increases the probability of implementing large programs. Specific needs and opportunities for expanding international cooperation are discussed further in the following chapters.

STRATEGIC FRAMEWORK FOR NSF INVESTMENTS IN ANTARCTIC AND SOUTHERN OCEAN RESEARCH

In considering all the factors that make research in the Antarctic and Southern Ocean such a unique and challenging endeavor, the Committee developed a conceptual vision of the major components that make up a robust U.S. Antarctic Program. It includes three major components:

- A broad-based program that supports curiosity-based research driven by proposals from Principal Investigators (PIs) across all major areas of Antarctic and Southern Ocean science—currently organized under six main PLR Antarctic science programs.
- A small number of high-priority larger-scale research initiatives that address particularly compelling scientific questions poised for significant advance within the next decade, but which are beyond the scope of a single PI-led

project. These require a coordinated effort, resource commitment, and targeted, upgraded logistical support.

- A set of foundational elements that enable, support, and add value to all research activities. These include, for example,
  - — Core logistical infrastructure needs (e.g., vessels and aircraft) in support of access to research sites; and continued maintenance and improvement of science support items such as laboratory facilities and data transmission capacities;
  - — Maintenance of strategic observational efforts, including NSF leadership in coordinating and expanding international and interagency activities;
  - — Comprehensive management of Antarctic research data, and active education and public outreach efforts—both of which can significantly expand the return on investment for all PLR research activities.

The next chapter discusses the first two of these components, including our recommendations for the high-priority, large-scale research initiatives. Chapter 4 addresses the last component (the foundational elements), with recommendations for what is most needed to support the priority research areas, and to be well positioned to respond to innovative new directions in any aspect of Antarctic and Southern Ocean science.

CHAPTER THREE

Suggested Research Priorities for the Coming Decade

This chapter discusses the first two major components in the Committee's strategic vision for NSF investments in Antarctic and Southern Ocean science. The first section describes our rationale for recommending continuation of the current "bottom-up" mode of support for research across a broad base of topics. The second section offers our recommendations for a very limited set of research priorities to support as large-scale community-driven initiatives in the coming decade.

MAINTAIN A CORE PROGRAM OF INVESTIGATOR-DRIVEN RESEARCH ACROSS A BROAD BASE OF TOPICS

A number of previous NRC reports (including *Rising Above the Gathering Storm* [NRC, 2007], chaired by Norman Augustine) have outlined why it is in the nation's best interest to support basic science research across a broad spectrum of disciplinary fields. Although there are strategic reasons for the United States to take a leadership role in targeted areas of science and engineering, it is impossible to predict where the next major breakthroughs or advances will happen. Thus to ensure that the nation is well positioned to take advantage of such breakthroughs, it is important to be engaged in all core areas of scientific research.

This recommendation also holds true for research supported in the U.S. Antarctic Program (USAP). It is in the national interest for U.S. researchers to be active in all basic areas of Antarctic and Southern Ocean science, since it is unknown when or where critical advances will occur in the future, and likewise unknown when or where future major environmental changes may emerge. The Committee thus fully endorses NSF's Division of Polar Programs (NSF/PLR's) well-tested model of supporting research across a broad spectrum of topics, in response to the ideas that emerge in proposals from the research community. Indeed, numerous participants in our community forums voiced concerns about the dangers of NSF moving away from this bottom-up model of research support. For instance, one respondent stated: "NSF must remain nimble and responsive. More mission-driven, large-team based science . . . will be at the expense of being responsive to new ideas and exciting discoveries that we don't even know about yet. These discoveries are often made by single or small groups of

PIs thinking outside the box, or with a crazy new idea, or even just making the first observations from a new place. There has to be continued support for that, financially and logistically."

The Committee agrees with this sentiment and notes that many of the important scientific breakthroughs that have occurred in Antarctic and Southern Ocean science have come from relatively small-scale, hypothesis-driven, curiosity-inspired research (see Box 3.1). Nonetheless, the balance of "small" versus "large" science takes on a unique cast in the context of USAP field research. There is no truly "small science" in the Antarctic—given the significant logistical needs and costs associated with getting any researchers into the field in that part of the world.

In this context, we suggest that NSF's traditional broad-based research support strategies be balanced with more directed, larger-scale efforts aimed at ensuring that a critical mass of human and financial resources is concentrated on meeting key research goals over a limited period of time. With the large costs and logistical challenges

BOX 3.1
Transformational Space Research in Antarctica

A historical example of "curiosity-based," investigator-driven Antarctic research is the transformational work of Robert Helliwell and colleagues in the 1950s. They were investigating radio discharges produced by lightning in the very low frequency (VLF) range. During the investigations they heard persistent whistling sounds initially thought to be a flaw in the equipment. After many years investigating these phenomena, an experimental program was developed to launch controlled VLF waves and explore their characteristics upon reception in the opposite hemisphere. Since the wavelength of VLF signals is huge, a very long antenna is required. A 21.2-km-long antenna based at Siple Station, Antarctica, transmitted VLF radio signals into the magnetosphere, and they were observed in the opposite hemisphere in Canada.

These experiments led to the understanding that the region of cold plasma surrounding the Earth (the plasmasphere) has a profound effect on the waves. Waves at this frequency propagate upward into space, and the velocity of the VLF waves through plasma is dependent upon the frequency and the plasma density. A lightning bolt launches waves at many frequencies that propagate upward along the magnetic field and are observed in the opposite hemisphere. The higher frequencies moving through the plasma surrounding the Earth travel faster and are heard first, followed by the lower frequencies, thus producing the falling tone that sounds like a whistle. These phenomena are now called "whistlers." Through this work, fundamental discoveries were obtained about how radio waves can be used to investigate the plasma environment around the Earth. This research began an era of investigation that is still vibrant and active.

involved in accessing certain regions of interest (e.g., remote coastal or mountainous terrain, subglacial environments), large organized campaigns can provide major economy-of-scale benefits. NSF/PLR has always maintained some degree of balance between the smaller bottom-up research activities and the larger programmatic-level campaigns; and thus our Committee's overall vision does not differ significantly from PLR's existing strategies in this regard.

The suggested priority topics discussed below focus on relatively large research initiatives—efforts that seem likely to require a coordinated "push" in order to move forward at a sufficient scale and time frame. In other words, these are not the types of research activities that are likely to proceed of their own accord through the traditional process of proposals submitted by individuals or small groups of investigators. PI-driven proposals should indeed continue to receive support, and many of the research ideas raised in our community input process are the appropriate scale (and are indeed compelling candidates) for this category of bottom-up research. Those ideas are not all individually discussed here in this report, but the full collection of that input may serve as a rich database of ideas and inspiration for PLR program managers.

A theme that arose often in our community discussions and is relevant to a wide array of PI-driven research is the need for improved integration and coordination in the collection, management, and analysis of in situ observations. Two good examples of this relate to coordination of science in McMurdo Sound and the Ross Sea region—areas that have been the focus of intense study for decades by U.S. researchers (see example in Box 3.2). For instance, the integration of existing research activities could be greatly aided by creating a Ross Sea "Research Coordination Network." This could provide a mechanism to support workshops that foster new collaborations and address interdisciplinary topics, to identify novel networking strategies and collaborative technologies, and to develop community standards for data and metadata. This would also link well with efforts of the international Southern Ocean Observing System, which has identified the Ross Sea region as a key area for enhancing regional-scale cross-disciplinary research.

A related example raised in our community discussions illustrates how coordinated data collection and management can eliminate duplication and improve research efficiency. Many ecological studies around McMurdo Sound (and likewise around Palmer Station) require collecting basic physical oceanographic observations such as temperature, salinity, and pH profiles, as context for interpreting biological observations. Typically, individual research groups each collect such observations themselves; but a possible alternative is to maintain a few autonomous observing assets on moorings and floats that collect standard physical oceanographic data in key locations over the

BOX 3.2
Adélie Penguin Impacts on Food Webs in the Ross Sea

Research has revealed that foraging by Adélie penguins from Ross Island colonies can greatly impact the food web throughout the Ross Sea (Ainley et al., 2006; Ainley, 2007; Smith et al., 2014). The Ross Sea has a high abundance of predator species (e.g., 40 and 25 percent of the world's Adélie and Emperor penguins, respectively), but has an unexpectedly low abundance of zooplankton such as krill. During summer, foraging by penguins appears to reduce the abundance of krill and fish within the foraging ranges of the penguin colonies. This leads to the food web having an inverted hourglass structure, with krill and small fish being the restricting "waist" through which the food web must flow.

The Ross Sea top predators (e.g., whales) reduce the abundance of their prey, and through competition these predator and prey species affect each other's abundance. For instance, reduction and then recovery of baleen whales in the late 1970s induced population responses in the penguins; and recent reduction in the Antarctic toothfish population has led an to increase in the penguins' population. The food web in the Ross Sea is thus driven in a top-down manner. This shows a distinct contrast from the much-studied western Antarctic Peninsula (a region where top predators are far less abundant than in the Ross Sea), where all of the forcing of the food web occurs in a bottom-up direction—that is, from phytoplankton up to the top predators.

course of a field season. If properly managed, these data could then be used by numerous studies, and without the burden of collecting such duplicative information themselves, those studies would have lower overall costs.

Recommendation: NSF should continue to support a core program of broad-based, investigator-driven research and actively look for opportunities to improve coordination and data sharing among independent studies.

SUPPORT A FEW STRATEGICALLY CHOSEN LARGE RESEARCH INITIATIVES

The Committee was charged to identify priorities for NSF/PLR research support, drawing upon the ideas collected from the research community at large and upon the judgment of the Committee itself. This type of prioritization exercise of course presents a daunting challenge—especially given the huge diversity of compelling research topics that are addressed in Antarctic and Southern Ocean research. But in a time of relatively flat budgets and rising infrastructure and operational costs, hard choices must be made by NSF. This study aims to ensure that those choices are driven by a strategic perspective and by a broad base of ideas and opinions.

This sort of prioritization exercise is inevitably a subjective process to some degree. To provide some structure and objective rigor to this analysis, the Committee agreed upon a set of criteria to evaluate the many different options that arose in our community outreach. This list was developed by examining all the many types of evaluation criteria that have been used in similar exercises carried out by other NRC study committees over the past several years, and tailoring that list to best fit the context of Antarctic and Southern Ocean science. The selected criteria are listed below. "Compelling science" was seen as the primary filter, as all candidate topics must meet this standard. The subsequent criteria were viewed as important but not always necessary in every case.

- **Compelling science:** research that has the potential for important, transformative steps forward in understanding and discovery;
- **Potential for societal impact:** research that yields information of near-term and/or long-term benefits for society;
- **Time-sensitive in nature:** involves systems/processes undergoing rapid change that need to be observed sooner rather than later; research that could help inform current public policy concerns;
- **Readiness/feasibility:** research that is poised to move forward quickly within the coming decade, in terms of needed technologies and community readiness;
- **Key area for U.S. and NSF leadership:** research for which the United States (and NSF in particular) is advantageously positioned to lead.

Additional factors that were considered:

- **Partnership potential:** research that will allow NSF/PLR to leverage investment by other federal agencies, other parts of NSF, other international partners;
- **Impacts on program balance**: research that will not cause significant adverse impacts on other projects by requiring disproportionate funding or logistical support;
- **Potential to help bridge existing disciplinary divides:** research that will provide opportunities to bring together disciplinary communities that seldom work together.

Weighing the ideas that arose in the community input against these evaluation criteria, and building on their own expertise and judgment, the Committee identified a short list of topics to recommend as priorities for NSF/PLR investment, listed below. The first of these topics is the largest of the three, and in the Committee's judgment is the most urgent to pursue.

Recommendation: NSF should pursue the following as strategic priorities in Antarctic and Southern Ocean research for the coming decade:

I. How fast and by how much will sea level rise?
- **A multidisciplinary initiative to understand why the Antarctic ice sheets are changing now and how they will change in the future.**
- **Using multiple records of past ice sheet change to understand rates and processes.**

II. How do Antarctic biota evolve and adapt to the changing environment? Decoding the genomic and transcriptomic bases of biological adaptation and response across Antarctic organisms and ecosystems.

III. How did the universe begin and what are the underlying physical laws that govern its evolution and ultimate fate? A next-generation cosmic microwave background program.

For each of these topics, we offer below a brief description of the fundamental scientific questions to be addressed, and the ways in which the topic meets our key evaluation criteria. We also offer some details on how these different initiatives might conceivably move ahead in the coming years—although in all cases, working out the detailed implementation plans will require subsequent rounds of engagement and deliberation between NSF leadership and staff and the relevant research communities.

Strategic Priority I
How Fast and by How Much Will Sea Level Rise?
The Changing Antarctic Ice Sheets Initiative

Background Context and Motivation

Twenty thousand years ago, massive ice sheets covered Chicago, Albany, Toronto, and Oslo. Rapid episodes of ice retreat and subsequent rise in global sea level are recorded by proxy indicators in terrestrial deposits and sediments throughout the North Atlantic, and in ice and sediment cores from Greenland and Antarctica. At times the rates of sea level rise were at least 1 m per century, and probably faster—but exactly how fast is not well known.

Today three large ice sheets remain on our planet, one in Greenland and two in Antarctica—the West Antarctic Ice Sheet (WAIS) and the East Antarctic Ice Sheet (EAIS). Mapping of the ice has long shown that large areas of the WAIS and some regions of the EAIS lie on bedrock well below sea level. These regions, known as marine-based ice sheets, are the most responsive to climate change. The coastal areas of the northern WAIS and major portions of the EAIS (as well as the deep glaciated fjords of Greenland) are all in contact with the warming ocean today, and a rapid, large-scale response has begun. Increased ice flow, thinning ice, and a major fraction of the ongoing sea level rise are all consequences of this interaction. If the marine-based ice from both East and West Antarctica were fully melted, it would contribute over 20 m to global sea level rise. Understanding how and how fast these ice sheets could collapse is thus critical for understanding how future sea level rise might proceed.

Theory predicts certain marine-based ice sheets are subject to a runaway collapse process known as marine ice sheet instability (MISI) (Hughes, 1981; Mercer, 1978). For MISI to occur, the bedrock must slope toward the interior of the ice sheet, so that the water depth increases as the ice front retreats away from the sea. If warming water or other changing climatic conditions initiate a retreat of the ice front, the water depth beneath the front and the thickness of the ice both increase, and this in turn increases the speed of the ice flow. Faster flow leads to thinning of the ice sheet, and the ice becomes ungrounded (floating), causing further retreat and setting up a positive feedback mechanism that leads to even more rapid ice loss.

In West Antarctica, particular interest thus centers on areas where the bedrock slopes most strongly toward the interior of the ice sheet, making it susceptible to MISI. No modern analog to WAIS collapse has actually been observed, and so the detailed physical processes by which collapse occurs are not well understood. This lack of understanding translates directly into model uncertainty on the predicted speed and extent of WAIS collapse. But satellite observations have confirmed that in certain areas of the WAIS, glacier loss is accelerating, the ice sheet surface is lowering rapidly, and overall the ice sheet is losing mass at an accelerating pace. (See Figure 3.1.) Evidence is also building that these key areas are becoming unstable and beginning to collapse (Joughin et al., 2014; Rignot et al., 2014). A region of particular concern is Thwaites Glacier in the Amundsen Sea sector, because available modeling shows that loss of Thwaites would in turn lead to the loss of all marine ice in West Antarctica (Pollard et al., 2015). Some models suggest that such a scenario is now inevitable and could occur rapidly, but there is still active debate on this question (Alley et al., 2015; Favier et al., 2014; Joughin et al., 2014; Parizek et al., 2013; Pollard et al., 2015). Most importantly, it is unclear whether this collapse might occur within 200 years or 2,000 years.

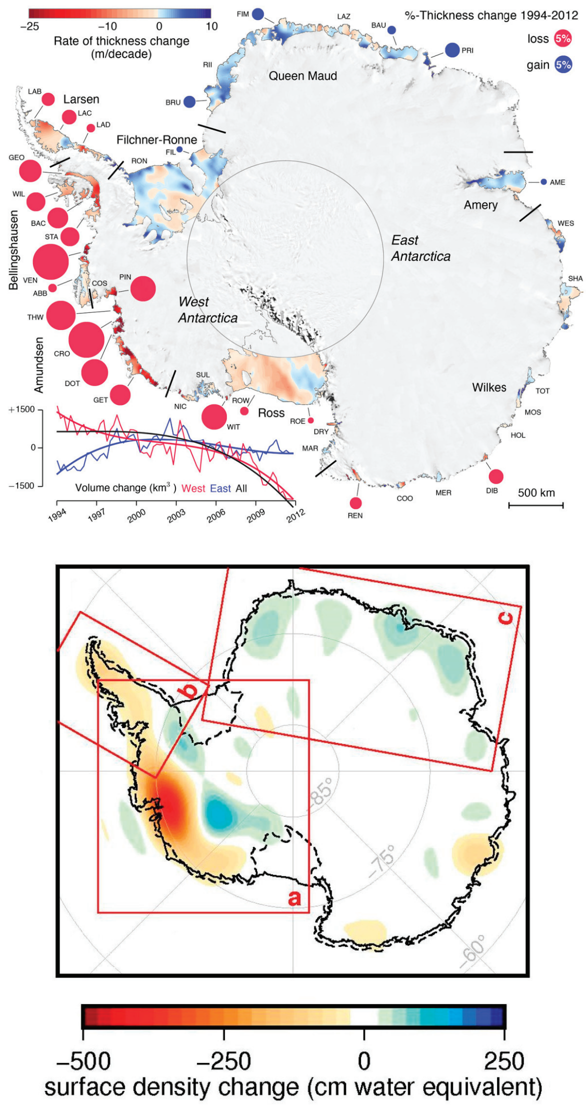


FIGURE 3.1 *Top:* Change in thickness and volume of Antarctic ice shelves from 2002 to 2012. Rates of thickness change (meters/decade) are color-coded from −25 (thinning) to +10 (thickening). Circles represent percentage of thickness lost (red) or gained (blue). SOURCE: Paolo et al., 2015. *Bottom:* Change in the mass of the Antarctic ice sheet from 2003 to 2014, based on data from the GRACE satellite mission which measures gravity changes. In the past 11 years, the Antarctic ice sheet lost 92 billion tons of ice per year. The vast majority of ice loss was from West Antarctica's Amundsen Sea region (box a) and the Antarctic Peninsula (box b). The ice sheet on East Antarctica (box c) primarily thickened during that time. Color scale indicates mass (equivalent to centimeters of water) of the land ice, with red denoting the largest loss and blue denoting the largest gain. SOURCE: Harig and Simons (2015).

Understanding how sea level may rise as the WAIS responds to a changing climate is critical for evaluating the level and urgency of societal response that will ultimately be required. Estimates of overall sea level rise from the most recent Intergovernmental Panel on Climate Change report range from 26 to 98 cm in this century (IPCC, 2013), but recent modeling studies suggest that far more rapid rates are possible and perhaps even likely (Alley et al., 2015; Bamber and Aspinall, 2013). Slower collapse scenarios (extending over millennia) may mean that society will have significant time to adapt, whereas rapid collapse scenarios imply a potential need for massive investment in infrastructure to protect coastal infrastructure and ecosystems in the United States and globally (Box 3.3)—as well as attention to issues such as displaced populations from flooded areas and intrusion of saltwater into freshwater aquifers.

Moreover, the rise of sea level around the globe will not be uniform. Relative to the global average, the United States is particularly sensitive to a change in sea level from West Antarctic ice loss. When ice mass is lost from an ice sheet, the ocean is pulled less strongly toward that coastline, which *lowers* sea level near the ice sheet and *raises* sea level elsewhere by a larger amount. Studies have found that due to these gravitational effects, ice loss from the WAIS will be amplified along the East and West coasts of North America by about 25 percent (Mitrovica et al., 2009; NRC, 2012).

BOX 3.3
Costs of Sea Level Rise

Actual costs of future sea level rise, the costs of both direct impacts and of possible adaptation actions, are notoriously difficult to determine. This is because of the difficulty of separating costs of sea level rise from other impacts associated with climate change, and because outcomes depend heavily on the exact magnitude and rate of sea level rise, as well as many other factors, for example, population statistics, socioeconomic scenarios, damage functions, discount rates, types of damages, and types of protection strategies used in any given modeling study.

For illustrative purposes however, we note that one recent study looked at costs of sea level rise and associated storm surge on U.S. coasts. They found that depending on the scenario used, the total (undiscounted) costs of adapting to sea level rise and increasing storm surges were in the range of $840 billion to $1.1 trillion by the end of the century (Neumann et al., 2015). Another study looking at global-scale impacts found that without adaptation, sea level rise by 2100 could lead to annual losses of 0.3–9.3 percent of global gross domestic product; and that the global costs of protecting coasts would require investment and maintenance costs of $12 billion to $71 billion per year by the end of this century (Hinkel et al., 2014). Both studies found that the costs of taking adaptation actions, although huge, were far less than the costs of impacts resulting from no adaptation actions.

West Antarctica was first identified as a critical and potentially unstable part of Antarctica through USAP-supported research on the Ross Ice Shelf, the Siple Coast, and the ice sheet interior. Subsequent research investments in the West Antarctic region—including campaigns on Pine Island Glacier, the Whillans Ice Stream, WAIS Divide, and the Amundsen Sea Polynya International Research Expedition—have provided a strong foundation for the United States to lead the critical research challenges that must still be addressed in this region. For example, the United States:

- Has a research community that has published numerous high-profile scientific studies on the region's evolving climatic, cryospheric, and oceanic conditions (e.g., Dutrieux et al., 2014; Holland et al., 2010; Jacobs et al., 2011; Joughin et al., 2014; Steig et al., 2009); and a new generation of scientists trained with the critical skills needed to study the ice sheets as part of a complex coupled system, and to integrate remote sensing with field measurements;
- Has a strong base of infrastructure support at McMurdo Station (which will be further strengthened with the currently planned modernization program), and has a strong track record of support for deep-field research in West Antarctica—thanks in part to unique airlift access to the ice sheet interior via LC-130, Basler/DC-3, and DHC-6 Twin Otter aircraft;
- Has developed the capacity to efficiently drill through the ice shelves and to install complex sensors and instrumentation on, in, and beneath the ice, and in the surrounding oceans;
- Has significant research support infrastructure in the region, including proven runways, summer research camp installations, and a partial array of ocean moorings and automatic weather stations, and established overland traverse capability (aided by advances in crevasse detection techniques and discovery of crevasse-free routes);
- Has conducted numerous research cruises around West Antarctica that have yielded much of the detailed bathymetry, ocean measurements, and marine sediment cores acquired in the region (Jacobs et al., 2012).

To build on these past successes, the Committee suggests that the NSF launch an ambitious new integrated, interdisciplinary, international research program referred to here as the *Changing Antarctic Ice Sheets Initiative* (*Changing Ice Initiative* for short). This initiative will improve understanding of how the marine ice sheets of Antarctica have changed in the past, how they are changing now, and how they will change in the future; and it will advance knowledge of how ice sheets work as part of the global ice–ocean–atmosphere system. The ultimate goal of this work is to improve quantitative projections of how much and how fast sea level will rise in the future.

The initiative will involve two distinct but linked components that address different aspects of the same underlying challenge. One component aims to better understand the drivers, mechanisms, and projections for the changes currently taking place in Antarctica's ice sheets. The other component aims to better understand the rates and processes of future ice sheet change by examining the past behavior of the ice sheets in response to natural forcings. Together this work will comprise a large, decadal-scale initiative, involving a broad cross section of the Antarctic and Southern Ocean research community and will be more extensive in scope and duration than West Antarctic research campaigns to date. As discussed later, expanded cooperative efforts—within NSF, among the USAP agencies, and at the international level—will be needed to advance this "grand challenge" of Antarctic and Southern Ocean science.

The proposed effort, component i: **A multidisciplinary initiative to understand why the Antarctic ice sheets are changing now and how they will change in the future**

Ice sheets are part of a complex atmosphere–ocean–climate system, and changes in both atmospheric and oceanic forcing can trigger faster flow and melt of Antarctic ice. Increases in circumpolar winds observed over the Southern Ocean (thought to be due to both polar and tropical influences) are driving warm deep ocean water closer to the areas where ice contacts the ocean. Particular concern centers on the warm water reaching into the deepest troughs where the largest glaciers enter the ocean, and into the "grounding line" where the ice sheet begins to float on the ocean as an ice shelf. As noted earlier, these are the sites where the key processes of MISI can occur, if there is landward-sloping bedrock (i.e., sloping toward the interior of the ice sheet). This warm ocean water drives increased melt at the flotation point and on the underside of the ice shelf. (See Figure 3.2.) Questions remain about the factors controlling rates of change, but the underlying causes of retreat of the grounding line, ice shelf thinning, and increased ice flow are nonetheless clear (e.g., Dutrieux et al., 2014; Rignot, 2008; Shepherd et al., 2004).

Major gaps remain in understanding these processes, because of a lack of observations in the critical areas in the ocean and beneath the ice shelves and limited understanding of the causes of the changing Antarctic atmospheric and ocean circulation. As most of the fundamental processes driving Antarctic ice sheet change are hidden beneath the surface of the ocean and the ice sheet, they cannot be imaged from space. Understanding them requires a coordinated research effort on-site in Antarctica and the Southern Ocean, with measurements taking place over an extended time in the critical regions affecting change. In addition, numerical modeling efforts and studies to elucidate past ice sheet dynamics are needed to place these observations in a broader context.

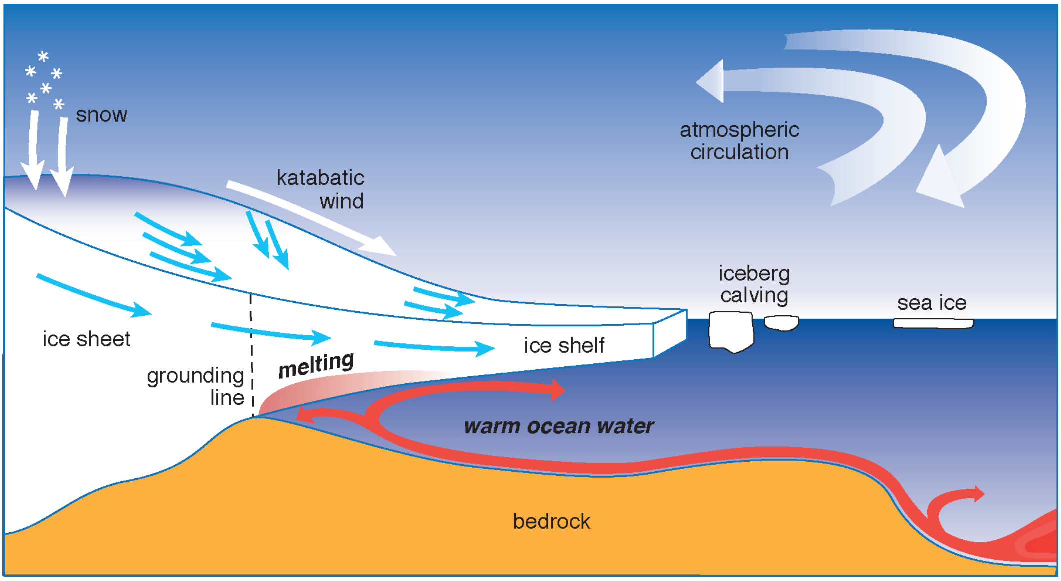


FIGURE 3.2 A simplified schematic of the forces that affect growth and loss of an ice shelf, including ice that flows from the ice sheet, warm ocean water that melts the underside of the ice shelf, and wind patterns (e.g., coastal easterlies, sub-antarctic westerlies) that affect ocean and sea ice dynamics. The marine ice sheet instability (MISI) process occurs where the bedrock behind the grounding line slopes inward toward the interior of the ice sheet.

Historically, ice sheets have been studied in isolation from atmospheric and oceanic drivers. Proposed here is a more integrated effort involving both ocean- and ice sheet-based investigations. This effort will require investment in new instrumentation for detailed mapping of the seabed and subglacial bedrock, for long-term on-site observations, and for exploration of the regions where key processes occur—including explorations of the ocean cavities beneath the ice shelves and the edges of the continental shelf.

The main elements of this initiative include interdisciplinary studies of key processes, systematic measurements of the atmospheric and oceanic drivers of change, mapping of unknown submarine and subglacial terrains that modulate rates of change, and use of these new data streams in coupled models. Each of these elements is discussed further below:

(i) Advancing our understanding of the complex ice, oceanic, and atmospheric processes driving the observed Antarctic ice sheet changes, through **interdis-**

BOX 3.4
East Antarctic Ice Sheet Research

A large East Antarctic marine-based ice sheet project is not suggested as part of the *Changing Ice Initiative*, but it is important to note that there are compelling research needs and opportunities in that part of the continent. Parts of the EAIS are grounded below sea level and exhibit inland-sloping bed topography, and this marine-based ice contains the equivalent of ~19 m of global sea level rise (Fretwell et al., 2013), much more than the marine ice of West Antarctica. Yet relatively little is known about the potential of East Antarctic ice to contribute to rapid sea level rise. Mengel and Levermann (2014) constructed a model of the Wilkes Basin in East Antarctica wherein a coastal "ice plug" of moderate size is all that prevents a self-sustaining discharge of ice that would produce 3 to 4 m of global sea level rise. These model results, together with recent observations of deep passages permitting relatively warm ocean waters to reach the Totten Glacier of East Antarctica (S. Rintoul, personal communication, July 9, 2015; Greenbaum et al., 2015; Khazendar et al., 2013), suggest that the relative stability of East Antarctic ice may have been significantly overestimated.

A wide variety of field studies and modeling efforts are needed for better understanding the sea level rise risks posed by East Antarctica. Although not the recommended primary focus of major NSF-sponsored field campaigns, U.S. field work in this area should still be advanced through PI-driven research efforts, particularly those involving collaborations with Australia and other countries with an active presence in key regions of East Antarctica.

ciplinary studies of key processes such as grounding-line dynamics, ice shelf collapse, and atmospheric drivers of ocean waters.

(ii) Providing the first **systematic measurements and understanding of atmospheric and ocean drivers of change** in West Antarctica. This requires a continuous data collection presence in the region and closer integration of observations and process models. In situ observations related to atmospheric and ocean circulation, formation and transformation of ocean water masses, sea ice changes and influences, ice sheet flow and accumulation, the sub-ice-shelf and grounding-line environment, and near-coastal ocean hydrography and biogeochemistry are needed. Retrospective investigations based on targeted sediment cores, shallow ice cores, and ice borehole logging are needed to understand the century-scale context for today's climate changes. The relative contributions of tropical and high-latitude forcings to atmospheric and oceanic behavior that affects West Antarctica need to be better understood.

(iii) **Mapping the unknown terrains beneath the major ice shelves and the critical regions beneath the ice sheet**. Technologies such as airborne imaging, active seismic surveys, gliders and autonomous vehicles (AUVs), as well as traditional coastal and on-ice surveys, will be essential to determine the boundary conditions that control the fluxes and processes determining ice sheet change.

(iv) **Advancing coupled atmosphere–ocean–sea ice–ice sheet models**. These models should be optimized for the Antarctic environment and designed to build closer connections between observations, processes, and ice and ocean physics. They should be run at spatial resolutions that can resolve critical physical processes. This will help inform and improve lower-resolution global-scale coupled models being developed elsewhere in NSF, NOAA, DOE, and NASA.

These interdisciplinary studies of critical processes that control the rates of ice sheet change will require improved access to logistically challenging coastal regions of Antarctica. Some key locations for this work are Thwaites Glacier, Pine Island, and ice shelves along the northern WAIS coast. There are currently no coastal stations in the critical zone between McMurdo and the Antarctic Peninsula, a distance of roughly 4,000 km. As a result of local meteorological dynamics, the automatic weather stations

BOX 3.5
Recommendations from *Abrupt Impacts of Climate Change* (NRC, 2013)

These suggested activities directly echo recommendations in the recent NRC report *Abrupt Impacts of Climate Change* (NRC, 2013), which identified destabilization of the WAIS as one of the possible "abrupt changes" in the climate system of highest concern. As recommended there:

> Improved understanding of the retreat rates of WAIS and other marine-based ice drainage zones is necessary to narrow the currently broad uncertainties and better quantify the potential worst-case scenarios. Much process-based research coupling field work, remote sensing, and modeling is required to advance assessment of the likelihood of a threshold-crossing leading to abrupt sea level rise from the ice sheets, as well as to improve projections of more-gradual sea level rise that could lead to threshold-crossing events in other systems. . . . Key environmental information includes air temperatures and ocean temperatures in the upper kilometer of the ocean, sea ice, and related oceanic properties. . . . More fixed monitoring sites as well as UAV-based observations are needed in the remote areas of both poles. Ocean temperatures are not well monitored, particularly in polar regions and particularly near the grounding lines and along the ice–ocean interface for marine-based ice. A concerted effort is needed to collect better data for constraining ocean conditions.

in this area of the continent are not representative of conditions over the critical ocean and sea ice zones—thus there is a need for drifting oceanic and sea ice buoys to obtain the needed measurements. Studies based around the Ross Ice Shelf and Siple Coast would also be valuable for assessing current structure and establishing a baseline for evaluation of future changes. The Ronne Filchner Ice Shelf that bounds the WAIS is an excellent target for international programs advanced by nations with strong logistics hubs in the region, including the United Kingdom, Chile, and Germany.

Working in any of these areas requires research vessel, airlift, aerogeophysical, and over-snow traverse capabilities; these infrastructure and logistical needs are discussed further in Chapter 4. New sampling approaches and technologies will also be needed, to extend the temporal and spatial reach of observations into unique environments. The needed remote sampling strategies are within reach due to recent advances in ocean and ice sheet instrumentation, including use of autonomous instrumented submarines, and advanced moorings, buoys, and gliders developed by the NSF Ocean Observatories Initiative. Attention is needed for widespread deployment of existing technologies that enable sub-ice AUV location and navigation, for instance, using acoustic transponders because, currently, AUVs cannot communicate their position to satellites from underneath the ice, and thus they have limited scientific use. A recent German program in the Weddell Sea demonstrates the success of this approach.

To help address these needs, the initiative could include supporting calls for proposals for targeted engineering development of specialized moorings, AUVs and gliders, unmanned airborne vehicles (drones or UAVs), and autonomous surface sensor stations. Emphasis for this engineering should be placed on reliability and low maintenance, small environmental footprint, and ease of removal.

The proposed effort, component ii: **Using multiple records of past ice sheet change to understand rates and processes**

As the second major component of the *Changing Ice Initiative*, the Committee proposes an integrated program of sediment and ice core observations that can directly inform and test the models used to predict future WAIS melting. This includes studies aimed at the question *"How fast did WAIS collapse in the past*?" and studies aimed at the question "*How much sea level rise was caused by past WAIS collapse?*" Both of these are discussed in turn below.

How Fast Did WAIS Collapse in the Past?

Today's rate of climate forcing is thought to be higher than the forcing rates that triggered WAIS collapse in the past; yet the timescale over which past collapse events occurred may be similar to what one could expect in the future. That is, the MISI process described above may have a standard characteristic timescale—and this timescale may be recorded in a variety of paleoclimatic and paleoceanographic records.

The most recent warm interval in which WAIS collapse is thought to have happened is the last interglacial period about 125,000 years ago, a time when sea level was 5-9 m higher than present and global mean surface temperature was 2-3°C higher (Kopp et al., 2009). In Northern Hemisphere records, this time interval is often referred to as the Eemian. Although it is not certain that the WAIS collapsed at this time, circumstantial evidence suggests that it did (Alley et al., 2015; Pollard et al., 2015). Availability of high-resolution ice cores that can provide the needed chronological accuracy diminishes rapidly if one looks further back in time, and so, ice core studies targeting the last interglacial are the most likely to be successful in answering the question of how fast sea level might rise. For this reason, the last interglacial has been targeted as a priority for future research by the International Partnerships in Ice Core Sciences.[1]

In recent years, a wide array of paleorecords have been recovered from the last interglacial period; but in many cases, the low temporal resolution and poor dating of these samples has frustrated attempts to further constrain questions about the rate of ice sheet collapse. The WAIS Divide ice core showed it is possible to count annual layers of fine dust concentration in the ice back more than 60,000 years (McConnell et al., 2007). During interglacials when high snow accumulation rates compensate for age-driven thinning, it should be possible (in places where the ice survived) to count annual layers back to 130,000 years. High snow accumulation rates would also be expected at coastal sites that are proximal to the collapse region, which increases the chances of successfully identifying annual layers during a collapse interval. Thus pursuing these types of annually resolved ice core samples may yield particularly valuable evidence for establishing how fast Antarctic ice has melted.

Annually or near-annually resolved intervals from past ice sheet collapse phases can also plausibly be recovered in carefully selected marine sediment records. Rapidly accumulating marine sediments have been recovered from shelf basins from nearly all sectors of the Antarctic margin (Boldt et al., 2013; Escutia et al., 2011; Michalchuk et al., 2009; Milliken et al., 2009), and many of these samples are sufficiently finely layered to provide annual-scale resolution (Leventer et al., 2006; Maddison et al., 2012; Swann et al., 2013). Such records can document the timing and location of rapid ice margin retreat during intervals of warming (Mackintosh et al., 2011, 2014). New targeted collections of marine sediments from key time periods can provide new insights on how

[1] See http://www.pages-igbp.org/workinggroups/endorsed-and-affiliated/ipics/.

fast and how much Antarctic ice melted during previous episodes of warmer temperatures, high sea level, and rapid deglaciation, each with different solar and oceanic forcing characteristics.

Targeted coring and drilling efforts can provide samples with chemical indicators that also allow us to infer whether collapse has occurred or not over time. These indicators can also provide estimates of environmental conditions associated with periods of rapid ice loss—such as sea ice/open-water feedbacks or the penetration of relatively warm seawater onto the Antarctic continental shelf. For instance, to detect marine ice sheet presence or absence and amount of collapse recorded in ice cores, the presence of nearby open water can be inferred from high concentrations of sulfur-containing compounds (diagnostic of nearby marine biological productivity) and high-precision seawater isotope indicators (deuterium excess, ^{17}O excess) (Steig et al., 2015). Marine sedimentary strata typically record depositional events during periods of ice margin retreat, and thus provide insights into the timing and rates of Antarctic ice sheet advance and retreat (e.g., Anderson, 1999; Anderson et al., 2002; Gohl et al., 2013). Marine sediment cores also contain a variety of indicators of open water and geochemical recorders of seawater temperature, which provide insights on the timing and rate of ice margin retreat in specific regions and the role of ocean thermal forcing.

This initiative should include drilling one or more new ice cores from sites on the margin of the suspected WAIS collapse region. These sites should be downwind of where open marine water would have replaced portions of the WAIS, so that the ice core would contain airborne chemical and isotopic indicators of WAIS status. During our community outreach sessions, an often-mentioned sampling site is Hercules Dome, located at the boundary between East and West Antarctica (86°S/105°W; Jacobel et al., 2005). At this site, ice from the last interglacial (120-130 ka) appears to be present in the bottom 200 m of the ice sheet, based on interpretation of radar layering combined with ice flow modeling. The relatively high snow accumulation rate at Hercules Dome, combined with low mean annual surface temperatures, implies that downward advection of cold ice may have precluded loss of the target ice by basal melting. A recent modeling study suggests that the diagnostic chemical fingerprint of WAIS collapse should be detectable in a Hercules Dome ice core (Steig et al., 2015), allowing a precise estimate of the rate of collapse. Other possible candidate sites should not be excluded, however (e.g., the Whitmore Mountains), and thus an appropriate survey of suitable sites is suggested.

This initiative should also include high-resolution sediment cores from marine basins within and adjacent to the suspected WAIS collapse region, in carefully chosen locations where erosion of soft young sediment by ice flow is unlikely. Sites should be chosen based on seismic surveys and the identification of seabed features that provide accommodation space for rapidly accumulating deposits and also limit subsequent glacial erosion.

Determining the speed of past ice sheet collapse at a level of accuracy that is directly useful for informing society's adaptation planning decisions may require paleorecords dated accurately enough to determine the duration of the collapse with an uncertainty of half a century or less—which is very roughly the timescale for turnover/replacement of much common coastal infrastructure. Therefore, we suggest pursuing sediment and ice cores with this scale of chronological accuracy or better. This can, however, be pursued together with other research approaches, described below, that make use of different types of indicators and thus provide independent, complementary information for constraining ice sheet models.

How Much Sea Level Rise Was Caused by Past WAIS Collapse?

To determine how much sea level rise was caused by past WAIS collapse, one must determine the geographical footprint (and thus the total volume of ice lost) during past marine ice sheet collapse. This requires mapping the areal extent of the past collapse region, and use of ice flow models to predict the thickness of the adjacent remaining ice sheet. One promising approach for gaining such information is to employ cosmogenic isotope exposure dating techniques on short bedrock cores taken from beneath the WAIS. In concept, if the ice sheet was removed during the Eemian, some areas of above-sea-level bedrock would have been exposed to cosmic radiation, and as a result, cosmogenic nuclides (e.g., ^{10}Be and ^{26}Al) would have been produced in the top few meters of rock. It is challenging to detect cosmogenic isotopes stemming from an irradiation of only several thousand years' duration happening 125,000 years ago, but it should be feasible (J. Stone, personal communication, 2014).

The combination of these sub-ice datasets, along with cosmogenic data from nearby moraines and related glacial deposits that record ice margin positions, will provide a rich opportunity to assess changes in WAIS ice volume over time. Access to these bedrock archives would be facilitated by rapid, agile drilling systems. The Ice Drilling Program Office is constructing an agile sub-ice rock drill for this purpose, which will reach ice depths of 700 m and take rock cores 10 m long, as well as a deep-ice rock coring system (Rapid Access Ice Drill) designed to reach 3,300-m depth with 25-m rock cores.[2]

[2] http://icedrill.org/equipment/raid.shtml.

Another valuable line of evidence for evaluating how WAIS could contribute to sea level rise is to improve understanding of the "style" of past ice sheet retreat—for instance, the details of regional variation in ice retreat and interaction with outlet glaciers. Glacial geomorphologic studies that highlight changes in ice elevation and marginal position can shed light on these details, and thus may be another important contributor in guiding the modeling of the present-day ice sheet retreat. Terrestrial deposits that document WAIS recession, especially after the Last Glacial Maximum and throughout the Holocene, may provide context for evaluating WAIS collapse during the preceding (Eemian) interglacial period, as well as into the future. Likewise, reconstructed ice-surface profiles from trimlines and erratics on nunataks in West Antarctica and from moraines alongside outlet glaciers may help document changes in ice thickness as a function of both the timing and spatial pattern of grounding-line retreat, all of which provide critical test points that help refine glaciological models for rapid ice sheet retreat (e.g., Anderson et al., 2014; Conway et al., 1999; Hall et al., 2013).

A well-integrated program of sediment and ice observations yielding multiple archives and datasets can directly inform and help constrain models that are used to predict future melting of the West Antarctic Ice Sheet. Models are crucial for assimilating these datasets with other relevant observations, and making the best possible

BOX 3.6
Rapid Sea Level Rise 14,500 Years Ago:
Can the Source Be from Retreating Glaciers in Antarctica?

The most recent significant sea level rise occurred from the melting of massive ice sheets following the Last Glacial Maximum, which reached its peak ~19,000 years ago. As the ice sheets melted, sea level began a steady rise. But superimposed on this steady rise are two periods of accelerated sea level rise, termed meltwater pulse (MWP) 1A and 1B. Evidence for MWP-1A comes from several places, including data from Tahiti, Hawaii, Barbados, and Southeast Asia.

The rate of sea level rise during MWP-1A is estimated to be at least 3.5 to 5 m per century, but it is not known where the meltwater came from. Geologists and oceanographers have focused on two regions—a Northern Hemisphere source from the Laurentide Ice Sheet that covered much of North America (and at its maximum stored as much as 70 m of potential sea level rise), and a Southern Hemisphere source from Antarctica. Although data from studies of sea level rise across the globe point to an Antarctic source, geologists working in Antarctica have yet to find evidence for ice sheet retreat of the magnitude required for MWP-1A. The debate continues, and meanwhile, this work illustrates that understanding past sea level rise requires ongoing collaboration between Antarctic-based studies and far-field studies of indicators at key locations around the globe.

estimates of the amount of sea level rise caused by WAIS collapse. These models can be driven by the forcing factors thought to be most critical during periods of past WAIS collapse—in particular, by local ocean temperatures, which can be validated by comparison with the proposed paleorecords (i.e., with existing ocean temperature records that are augmented by the marine sediment coring efforts proposed here). The models could then be used with modern climate-forcing estimates to project future sea level rise rates.

This research goal aligns well with priorities that have been identified by the broader scientific community—for instance, in the SCAR Horizon Scan, in the U.S. Ice Drilling Program's Long Range Science Plan (IDPO, 2015), and in the recommendations of a 2014 conference on Paleoclimate Records from the Antarctic Margin and Southern Ocean attended by many U.S. scientists.

Programmatic Considerations

NSF/PLR has supported a tremendous amount of highly successful research on the changing ice sheets over the past few decades. The support for this work has generally been divided between four research sections: Integrated Systems, Geology and Geophysics, Oceans and Atmosphere, and Glaciology. Coordination within the research community for the WAIS activities was chaired for over two decades by Dr. Robert Bindschadler and is now chaired by four scientists on a rotating basis. These past efforts have led to many important advances in scientific understanding, but the increased urgency of the issue necessitates a greatly expanded coordination effort among the U.S. research community and at the international level, with strong leadership and support from NSF.

Within NSF/PLR, a new dedicated section or science office may need to be established to oversee such planning efforts, and to manage the ongoing fieldwork and modeling activities, the development of essential technologies, and the expansion of collaborative activities with other federal agencies and other countries. Some of the major research components outlined above could each be supported as university-based centers, perhaps modeled after the NSF's Centers of Excellence funding platform. Beyond traditional collaborations, programs should be set up to support graduate student and postdoctoral researcher exchanges between disciplines, and cross-training in field and modeling methods.

The questions raised here span multiple science disciplines, which in many cases have traditionally had little direct interaction. Component i represents a new generation of multidisciplinary studies that bring together those studying Antarctica's ice, ocean, atmosphere, and climate—in a common quest to better understand the processes that currently control rates of melting and ice sheet flow. Component ii will link ice core, marine, and terrestrial research on the speed, mechanisms and extent of past WAIS collapse events. It will bring together Antarctic ice core, glacial modeling, earth science, and marine communities in order to develop integrated insights and the greatest scientific return on investment.

While there are real distinctions in the research strategies and geographical focus of the two components of this initiative, they cannot be isolated efforts. Ongoing interaction and integration among these different research communities will yield the innovations that can elevate the *Changing Ice Initiative* above and beyond the USAP West Antarctic research that has been carried out to date. For instance, this initiative would encourage those studying current atmospheric and oceanic dynamics to seek new insights by working closely with those collecting paleoclimate records; and it would foster the evaluation of modern observational data in the context of climate records extending back over decades, centuries, and millennia.

The initiative outlined here is a large and complex effort that will stretch the current planning and management capabilities of both NSF and the research community at large. Detailed science and implementation plans should be further developed through broad community workshops with international participation. Thereafter, the annual WAIS community meetings that have taken place in recent years should continue, but should entrain a wider array of disciplines than have historically participated in such gatherings.

Strategic Priority II
How Do Antarctic Biota Evolve and Adapt to the Changing Environment? Decoding the Genomic and Transcriptomic Bases of Biological Adaptation and Response Across Antarctic Organisms and Ecosystems

Background Context and Motivation

Antarctica and the immense encircling Southern Ocean encompass uniquely isolated ecosystems of chronically frigid, extreme conditions. This isolation and cooling began over 30 million years ago (DeConto and Pollard, 2003; Zachos et al., 2001), punctuated with periodic climatic transitions up to the present day (Naish et al., 2009; Naish et al., 2001). For many Antarctic species, especially macrofauna, the remoteness of the continent and the insulating Antarctic Circumpolar Current effectively impeded dispersal in north-south directions. Species confined within the Antarctic region have had to evolve continually to adapt to changing environmental challenges. This continual evolution has led to the distinctive Antarctic biota of today.

Unlike other landmasses, Antarctica has no terrestrial vertebrates, and land invertebrates and plants are rare. In the Southern Ocean, some key taxonomic groups are low in diversity while other groups have proliferated. Plants, invertebrates, fishes, marine birds, and mammals that have succeeded in colonizing the harsh Antarctic environments are endemic, and microbial "extremophiles" dwell in ice, soil, rocks, frozen mountain lakes, and subglacial environments under thick ice sheets. Antarctica provides an invaluable vast natural laboratory for understanding species evolution and functional specializations driven by extreme and changing environments through its geological history.

The tempo of Antarctic environmental changes is being hastened in modern human times by global climate change and increasing commercial fisheries in the Southern Ocean. There remains much to understand about how cold-adapted and specialized Antarctic species will respond and keep pace with these changes, and how Antarctic ecosystems may be altered. Warming ocean temperatures, which in turn affect oxygen availability, and increasing ocean acidification both present major challenges to cold-adapted marine species (Somero, 2010). The same warming ocean that threatens to collapse Antarctic ice sheets (see Strategic Priority I) could also bring about radical ecological changes for marine biota in sea ice and coastal ecosystems. In the western Antarctic Peninsula, for instance, some regions are experiencing ecosystem changes associated with declines in sea ice, changing precipitation, and melting glaciers (Schofield et al., 2010). This includes a large decline in Adélie penguins, concomitant with declining biomass of their major prey, Antarctic krill— attributable to climate-related loss of sea ice that supports krill proliferation (Fraser et al., 2013; Trivelpiece et al., 2011).

Climate change could also open up the continent and Southern Ocean to invasive species. For instance, because of warming water temperatures, cold-intolerant crab species long thought to be excluded from cold Antarctic continental shelf waters (Aronson and Blake, 2001; Thatje et al., 2005), have recently been found in the Palmer Deep basin of the western Antarctic Peninsula shelf (Smith et al., 2012). Continued invasion of these top benthic predators into shallower shelf waters may significantly alter biodiversity and ecosystem structure in the coming decade.

These clear signs of an environment in flux, with cascading effects on Antarctic biota, point to a compelling urgency to understand how vulnerable or resilient Antarctic species and ecosystems might be, both to natural and anthropogenic selection pressures. There is likewise an urgent need to establish baseline references for Antarctic species and ecosystems, as this provides the foundation for detecting and understanding future impacts of climate change and human activities. To help gauge the fate of these ecosystems requires ascertaining the diversity of life forms that have succeeded in the harsh Antarctic environment and better understanding of both adaptation over evolutionary timescales and adaptive potential (i.e., phenotypic plasticity and adaptability) to contemporary environmental change (Nicotra et al., 2015).

The question of how life has adapted to survive and exploit extreme Antarctic and Southern Ocean environments has been widely studied at different levels of biological organization, ranging from the molecular level to physiology and ecology for microbial species (e.g., Bakermans et al., 2014; Deming, 2002; Dolhi et al., 2013; Grzymski et al., 2006; Smith et al., 1994) and more complex organisms (e.g., Bakermans et al., 2014; Devries, 1971; Dolhi et al., 2013; Fields and Somero, 1998; Hill et al., 2011; Kawarasaki et al., 2014; Magalhães et al., 2012; Thatje et al., 2008). For example, it was discovered that the microbial ecosystem in the dark, freezing subglacial Lake Whillans is sustained by autotrophic bacteria that can derive energy from oxidizing inorganic compounds; and these autotrophs and their products serve as food that sustains heteotrophic bacteria (Christner et al., 2014). And research revealed that cold-blooded fishes that abundantly colonized the Southern Ocean have survived through evolutionary innovation of antifreeze proteins and adaptive changes in various functional proteins (Cheng and Detrich, 2007; Pörtner et al., 2007).

In contrast, a frontier that remains little explored in the studies of Antarctic life and evolution is the fundamental and comprehensive core of genomic information encoded within species. Decoding this genomic information across Antarctic ecosystems will richly inform us about the breadth of biological diversity that evolved in this extreme environment, and about the evolutionary capacity governing species ability to continue to evolve. In addition, decoding transcriptomes and metatranscriptomes can provide information about the functional capability and plasticity of these cold-specialized species to deal with continued environmental challenges.

Numerous recent technological innovations now make it possible to rapidly advance investigations of the genetic and functional bases of Antarctic life, evolution, and adaptive potential. For instance, massively parallel sequencing has made genome and transcriptome sequencing highly feasible, and the supporting infrastructure is now commonplace across research institutions and universities. Decoding small microbial genomes can be accomplished rapidly. Sequencing and analyses of larger, more complex invertebrate and vertebrate genomes requires progressively greater effort, but is still within reasonable timescales of a few years.

New methods such as reduced-representation genome sequencing can be used to assess genetic variations among individuals of populations of the same species, which helps elucidate species resiliency to habitat change. Species biodiversity and interactions among species can now be assessed using high-throughput sequencing methods, as an alternative to the traditional, logistically demanding "catch and identify" biodiversity surveys. Environmental DNA (eDNA),comprising metagenomes and/or fragmented genomic DNA from microorganisms and higher taxonomic groups (in the form of genetic material within bits of metabolic wastes or tissues shed to the environment), can be recovered from sediments, ice, or water samples. They can then be sequenced and analyzed to reveal past and present species diversity (Kelley et al., 2014; Thomsen and Willerslev, 2015; Thomsen et al., 2012). One can even deduce predator-prey relationships for higher taxonomic organisms by sequencing DNA recovered from animal gut contents or scats (Boyer et al., 2013; Murray et al., 2011).

Given these tremendous advancements in technologies and methodologies, the field is poised to make countless new discoveries. Three particular areas where great progress could be made are described below.

(i) Antarctic Biodiversity Across Time and Ecosystems as an Indication of Evolutionary Success and Potential.

DNA sequence in a genome specifies the unique identity of an organism. Genome and metagenome sequencing of extant and fossilized macrofaunal organisms, viral and microbiota (bacteria, archaea, protists) species and communities (in seawater, ice, subglacial lakes, soil or rock, and in ancient pollens or other forms of ancient DNA), will greatly expand understanding of the species and biodiversity that uniquely succeeded in colonizing Antarctica through geological timescales.

Environmental microbes often cannot be grown in the laboratory, but information about the genetic diversity of microbes in the environment can be gained through direct metagenome sequencing of samples of seawater, ice, and soil, etc. Information from metagenome sequencing of entire species assemblages of microbial communities can be analyzed using bioinformatics and molecular phylogenetics, to reveal community genetic and taxonomic diversity. Currently advancing technologies to sequence single-cell genomes will enable the capture of microbial genomes that are truly representative of the Antarctic microbiome (Rinke et al., 2013). Genomic characteristics that allow one to assess taxonomic identity or affinity will help resolve enduring questions about the origin and extent of endemism of Antarctic microbiota.

Decoding the genomes of taxonomic groups that have undergone adaptive radiation and proliferated in the harsh Antarctic environment will help us understand the genetic and genomic factors that have shaped Antarctica's distinctive faunal composition (see, e.g., Figure 3.3). Whole-genome assessments of the genetic diversity within geographically distinct populations of a species can provide important information about how resilient or vulnerable these species may be to drastic environmental change.

(ii) Species Functional Response to the Changing Antarctic Environment as an Indication of Their Phenotypic Plasticity

Combining genomic sequence information with transcriptomic (and metagenomic/metatranscriptomic) sequences can provide a powerful foundation for understanding the diversity of Antarctic species and species assemblages. To understand how organisms might respond to rapid environmental changes, one must elucidate the cellular and metabolic pathways that govern a species' or community's ability to cope with changes, through their functional response to contemporary and/or future conditions. A species' cellular and metabolic functions are encoded in the protein-coding genes and DNA and RNA regulatory elements in the genome. Systemwide transcriptome

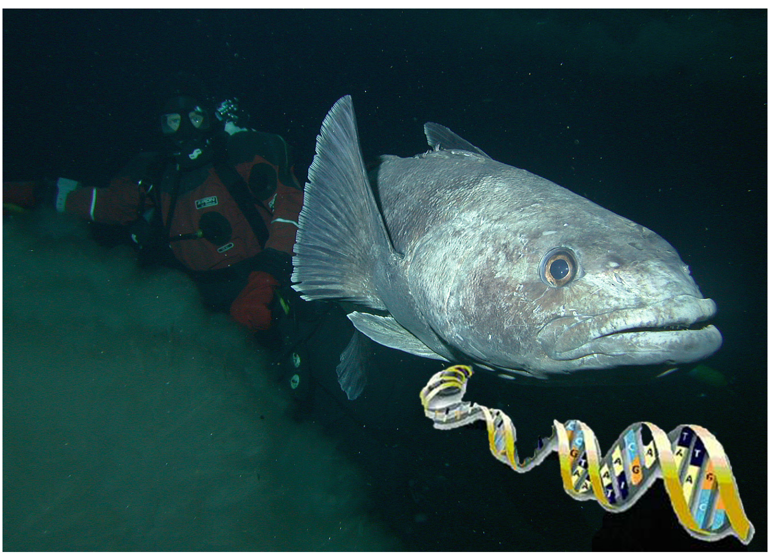


FIGURE 3.3 A giant Antarctic toothfish being released by a research diver back into McMurdo Sound. The toothfish and the family of Antarctic notothenioid fishes to which it belongs are "swimming libraries" of cold-adapted and cold-specialized genes. SOURCE: Paul Cziko and Chi-Hing Christina Cheng.

and metatranscriptome sequences provide global profiles of gene transcripts, from which encoded functions can be inferred. Sequencing native transcriptomes can help us understand the functional phenotypes forged by the selection pressures of extreme polar conditions (Bilyk and Cheng, 2013; Dilly et al., 2015; Huth and Place, 2013). Sequencing native metatranscriptomes can elucidate functional ecology, which is particularly useful for microbial assemblages (Chan et al., 2013).

The extent to which these functional capacities limit or allow species to deal with environmental stressors can be tested under experimental conditions and assessed via transcript sequencing and analyses. But designing well-formulated experiments requires better knowledge of the environmental conditions and variability that Antarctic life faces in its natural setting. One gains this knowledge by monitoring basic environmental parameters such as temperature, soil moisture, ocean salinity, and pH. The collection and sharing of such data can be aided by existing LTER programs, and perhaps by a Ross Sea "Research Coordination Network" (as suggested earlier in this chapter).

There is increasing use of high-throughput sequencing of transcriptomes to understand Antarctic species response to changing environments (Bilyk and Cheng, 2014; Enzor and Place, 2014; Teets et al., 2012). But the value of these transcriptomes is limited by the lack of whole-genome sequences of Antarctic species. These whole-genome data (from which one derives transcript sequences) are needed in order to identify and quantify responding gene transcripts and spliced variants, and to determine how genetic variations between related species affect response capability.

For microbiotic systems, metagenome and metatranscriptome sequencing and analyses are at incipient stages and yet have already provided insights into soil and rock microbial diversity and community functional ecology in McMurdo Dry Valleys (Chan et al., 2013). Microorganisms play important roles in elemental cycling within polar ecosystems, including in the Southern Ocean, which is estimated to account for up to half of the annual oceanic uptake of anthropogenic CO_2 from the atmosphere (Arrigo et al., 2008; Gruber et al., 2009), and which (through vertical mixing) is thought to supply enough nutrients to fertilize three-quarters of the biological production in the global ocean north of 30°S (Sarmiento et al., 2004). Robust estimates of microbial abundance and diversity are critical to understanding elemental cycling in the Southern Ocean, and genomic tools are the only means to map this microbial diversity and to identify the microbial species (phytoplankton, bacteria, viruses) that play key roles in mediating elemental fluxes. Many insights can be gained by using genomic profiles to generate microbial community inventories, and by combining this with studies of the functional analysis of gene expression, to characterize microbial responses over a range of environmental conditions.

(iii) Evolutionary Cold Adaptation/Specialization and Future Evolutionary and Adaptive Potential

DNA sequence in the genome and genome structure both provide historical records of a species' genetic and genome structural changes over time. Decoding the genome sequences and structures of Antarctic species whose evolution was shaped by extreme polar conditions and comparing them with decoded sequences and structures of related non-Antarctic temperate species provide a powerful basis to assess how Antarctic species evolved and adapted over geological timescales, and to assess their evolutionary potential to adapt to future environmental changes. Coupling this assessment of evolutionary potential with assessment of phenotypic plasticity (through comparisons of functional response, as informed by transcriptomes and experimental testing) allows detection of Antarctic-specific genetic, genomic, and functional innovations and gains and losses that underlie cold adaptation and specialization. These comparisons may also elucidate how much genomic and functional "reengineering" might be necessary and possible for a particular Antarctic species, in order to attain more temperate characteristics that would allow it to survive in a changing climate.

Even more definitive assessments of the adaptive potential of Antarctic species to survive a warmer world can be achieved by studying species that were of Antarctic origin but later colonized temperate non-Antarctic regions during the lineage's evolutionary history. Comparative genomic analyses of these related Antarctic/non-Antarctic species allow one to see the genomic and functional retooling required for adapting to the more temperate environments. Estimating the rate of evolutionary genetic change can indicate whether Antarctic species can evolve at a sufficient pace to remain viable in the face of future environmental change. These comparative analyses can yield powerful insights into past and present cold-adaptive/specialized processes as well as future adaptive potential.

The Proposed Effort

The value of decoding genomes of key Antarctic organisms in order to understand evolutionary adaptations and ecological success was recognized over a decade ago (NRC, 2003b). More recently, both international and U.S. community-scale assessments (Kennicutt et al., 2014b; NRC, 2011a) have reiterated these same research themes as a priority for Antarctic science. Our community engagement discussions likewise revealed widespread interest to advance the understanding of past adaptation and future adaptive capacity by leveraging powerful molecular and genomic approaches and technologies.

An *Antarctic Genomics Initiative*, inclusive of genomes and transcriptomes of individual species and species assemblages, will involve biologists working on diverse species in a coordinated pulse of activity—with a shared goal of decoding the genomic and functional bases of organismal adaptation in a changing environment. Genomic sequencing could encompass ancient DNA, viruses, bacteria, and complex eukaryote species from major Antarctic habitats, including ice sheets, soils, outcropping rocks, surface and subglacial lakes and streams, the ocean, and sea ice. A priority focus can be given to keystone species and organisms/communities that are fundamentally important for addressing questions about Antarctic adaptation in the past and in the future. As a necessary adjunct to the genomic analysis in different Antarctic habitats, this initiative should also advance understanding of the environmental properties and variability driving species responses.

High-throughput sequencing can be performed on various platforms appropriate for the complexity of the specific samples. This effort could lend itself well to collaboration across universities and research institutes, as well as cooperation and shared funding support between NSF and other federal agencies (e.g., DOE's Joint Genome Institute, Los Alamos National Laboratory, and National Institutes of Health Sequencing Centers).

We suggest that NSF could implement this initiative in a set of calls for proposals designed to encourage interplay among lab-based genomic analyses, field-based environmental investigations, and collection of biological samples and environmental physical data. These calls can be concomitant or phased, and could be broken out roughly as follows:

- *Sequencing of existing samples.* Many investigators already have substantial collections of materials from key taxa or biological samples in frozen storage from prior Antarctic field research programs. These could be readily used for genome sequencing. Thus an initial component of this initiative could center on sequencing genomes or metagenomes of the existing species/samples that are well suited for providing answers to the types of genome-enabled inquiries described above.
- *Acquisition of new samples.* The second component, which could begin in parallel, is the acquisition of additional species or samples for sequencing, to allow genomics-enabled inquiries that existing samples do not cover. New field acquisitions such as a series of seasonal environmental DNA samples can address dynamic microbial or planktonic fauna changes that affect the food web. Genetic materials also can be retrieved from archival materials such as ice, sediment, or rock cores. Surveys of environmental properties and

processes would accompany these collections, to characterize the conditions that contribute to genomic diversity and functional ecology.

- *Field experimentation*. The third component supports new field experimentation, and testing of hypotheses that are developed through the genomic data analyses carried out in the first two components of sequencing and analyses work.

Critical to the success of this initiative is concurrent support for bioinformatics advancements, to aid in assembling and annotating the genomes to be analyzed. It will be particularly useful to support collaboration among bioinformaticists and biologists mutually interested in certain taxonomic groups or environmental metagenomes, to continually add to and refine draft genomes/metagenomes for accuracy and completeness. This will help avoid the pitfall suffered by many genome sequencing projects, where the draft genome remains fragmented and unimproved, thus undermining the utility of the genomic data for the community.

This initiative should include NSF-sponsored workshops targeted at fostering communication among different disciplines, engaging early-career researchers, and training community members in new bioinformatics tools. Community-wide discussions will ensure that the most relevant candidate species and ecosystems are selected for analysis, that appropriate sequencing approaches are used, and that data analysis and sharing standards are developed.

As noted above, this initiative could be based in part on sequencing genomes from suitable biological samples already available. There could also be opportunities to leverage existing terrestrial and marine research projects to collect new biological samples and related metadata (as long as careful attention is paid to sampling protocols). At a time of budgetary constraints and ever more costly field deployments, this initiative can be an effective way to advance Antarctic biological research without taxing already overstretched budgets and field logistics.

Despite the United States being the global leader in the invention and continued innovation of high-throughput sequencing technologies, U.S. Antarctic biology still remains at the cusp of the genomic revolution. Thus far, only one Antarctic metazoan genome (the small genome of the Antarctic midge) has been decoded by a U.S. team (see Box 3.7). Meanwhile, significant efforts have been and are being led by other countries. Advancing U.S. leadership in this field requires a concerted and well-executed initiative, which will generate a trove of high-quality genome sequence data from a range of Antarctic species and samples of important scientific value.

Well-assembled and annotated genomic and transcriptomic sequences of strategically chosen species and samples will catapult the abilities of biologists now and for gener-

BOX 3.7
Antarctic Midge Genome Sequencing

The midge (*Belgica antarctica*) is a small wingless fly and the only land insect endemic to Antarctica. During its 2-year life cycle it endures an array of extreme conditions (e.g., seasonal temperature extremes, extremely dry to extremely wet transitions, osmotic and pH changes). The larvae are remarkably freeze-tolerant; they overwinter encased in icy substrate for many months during development (Baust and Lee, 1987). They can also become freeze-avoidant, via cryoprotective dehydration, if their overwinter microhabitat is dry (Kawarasaki et al., 2014). The adults can encounter high temperatures on rock surfaces during mating; and they have developed a heat-shock response system that seems tailored to meet these environmental conditions.

The genome of the Antarctic midge was sequenced (Kelley et al., 2014) to understand organismal-wide adaptations in surviving these extreme polar conditions. The genome was found to be the smallest reported for an insect. Some genes that may play roles in coping with the harsh environment are enriched, while other genes are reduced (like those for odorant binding, likely a specialization in response to limited food and other sensory cues). The diminished genome size suggests Antarctic environmental extremes may constrain genome architecture. And yet in the case of Antarctic notothenioid fishes, it has been found that genome sizes steadily increase as lineages became more derived (Detrich et al., 2010). Such examples illustrate that decoding genomes of diverse Antarctic organisms promises to reveal diverse processes of evolution associated with polar adaptation and specialization.

ations to come to understand the genomewide basis of evolutionary adaptation and specialization that allowed some species to flourish in the harsh Antarctic and Southern Ocean environment. It will also provide the genomic framework for assessing the ability of Antarctic organisms to evolve and adapt to continuing environmental change. Studying the cold-adapted proteins and molecular adaptations of these organisms may even offer promising opportunities for discovering low-temperature industrial and medical applications.

Antarctica and the Southern Ocean encompass some of the most extreme and pristine regions on Earth. The biome in this vast region has been shaped by over 30 million years of isolation and chronic cold. Scientists have only begun to understand the impacts of climate change and human activities in the region on cold-attuned Antarctic biota and ecosystems. Such impacts will continue in unforeseeable ways in the coming years, and thus urgently need careful investigation. This initiative would advance fundamental understanding of how Antarctic life has succeeded in the changing Antarctic environment through time, of how extant biota and ecosystems continue to respond to current changing conditions, and of how their viability may change in the future.

Strategic Priority III
How Did the Universe Begin, and What Are the Underlying Physical Laws That Govern Its Evolution and Ultimate Fate?
A Next-Generation Cosmic Microwave Background Program

Background Context and Motivation

The cosmic microwave background (CMB) is the fossil light from the early universe of nearly 14 billion years ago. Measurements of the CMB have revealed the seeds of all structure existing today in the universe. But, how were the seeds produced? Data indicate that the seeds resulted from quantum fluctuations on the smallest scales being stretched to astronomical scales during the first moments of the universe, in a process of accelerated expansion known as inflation. If the universe did indeed start with inflation, what can one learn about the physics of this process, and how can one use that information to constrain physics at high energies?

The theory of inflation provides a compelling framework to understand CMB measurements; it led to predictions of several properties of the CMB which were subsequently confirmed by observations. A key test remains, however—detection of the imprint on the CMB of gravitational waves generated during inflation, when the universe was less than 10^{-34} seconds old and only about 10^{-29} m in size (many orders of magnitude smaller than a single proton). Such a detection would provide a spectacular confirmation of the inflationary origin of our universe. In addition, it would open a window on physics at energy scales many orders of magnitude greater than could ever be probed with particle accelerator laboratory research. It would provide evidence of the long-sought, but so far elusive, quantum nature of gravity.

Measurements of the CMB have already provided remarkable insights into the makeup of the universe, determining the relative fractions of ordinary matter, dark matter, and dark energy, as well as the presence of the cosmic neutrino background. Neutrinos are the second most abundant particles in the universe (second only to photons—particles of light), and a cosmic neutrino background was released in the first second of the universe. Trillions of these neutrinos pass through your body each second. Their nonzero masses indicate the existence of new physics beyond our current standard model of particle physics. Fully understanding the physics of neutrinos will extend our knowledge of the basic workings of nature and may offer important insights into a process known as baryogenesis, which produced the asymmetry (imbalance) between baryons and antibaryons in the very early universe and therefore the origin of all the ordinary matter in existence (including us).

A next-generation ground-based CMB experimental program, referred to as CMB Stage IV (CMB-S4), is being developed to provide definitive measurements of the early universe, detecting inflationary gravitational waves or at least setting limits that rigorously rule out classes of models (e.g., so-called large-field inflationary models). The next generation of CMB measurements would also offer enough sensitivity to make precise determinations of the number and type of neutrino species, as well as the sum of their masses. The CMB-S4 program builds on the successful CMB programs using telescopes at the South Pole and the high Atacama Plateau in Chile, and possibly will add a new site in the Northern Hemisphere to allow observations of the full sky. The program will be designed to be highly complementary to the continuation of the successful Long Duration Balloon CMB programs, or even a future satellite mission. Future balloon and satellite measurements can provide broader-frequency coverage for constraining foregrounds as well as wide-sky coverage for pursuing the largest angular scales.

The precision and accuracy envisioned for the next-generation measurements will help unlock the story of the universe's evolution that as of yet remains hidden in the CMB. During its 14-billion-year journey across the universe, the electromagnetic and gravitational interactions of the CMB photons with intervening structures impart subtle spectral distortions and spatial correlations in the CMB. Untangling these signals will provide insights into compelling questions such as: How and when did the first stars and galaxies in the universe form? What are the properties of the mysterious dark energy that is causing the present-day expansion of the universe to accelerate? What is the ultimate fate of the universe? These experiments address fundamental questions about our origins and the workings of the natural world, questions that have been asked for millennia. In striving to answer these questions, scientists have discovered phenomena that cannot be explained with current understanding of physics and that thus demand further investigation.

CMB science has been highlighted in several reports, including astronomy and astrophysics decadal surveys (NRC, 2010) and most recently in the report of the Particle Physics Project Prioritization Panel (P5), *Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context* (Particle Physics Project Prioritization Panel, 2014). The P5 report included the CMB-S4 project under all funding scenarios considered and recommended to "support CMB experiments as part of the core particle physics program," stating that "the multidisciplinary nature of the science warrants continued multiagency support."

Despite its highly technical nature, this research has generated a great deal of popular interest, as people are naturally curious about questions relating to the origin, makeup, evolution, and ultimate fate of the universe. Tremendous excitement was generated by the apparent BICEP2 detection of B-mode polarization induced by inflationary gravitational waves. Unfortunately, that result has now been shown to be just an upper limit rather than a confirmed detection, but the hunt continues with more enthusiasm and interest than ever.

One cannot predict the societal benefits that could eventually result from the pursuit of new physics. The last time there was such clear evidence for new physics was roughly 100 years ago, and the result was the quantum revolution leading to lasers and electronics that have transformed human society. It has been said that there are two types of science—applied and not yet applied. It is critical to invest in both. The investment in applied science for CMB research is the development of new detector technology that could have applications as diverse as x-ray and optical astronomy, sensors for advanced light sources, medical imaging, and homeland security.

In this rapidly progressing field of research, the CMB-S4 project is the next logical step, and possibly the last major step for the ground-based CMB observational program. The U.S. research community is ready to move ahead and the technology development is in place. Taking the next step now will ensure U.S. leadership and continued return on NSF's investment in CMB research.

The Proposed Effort

The entire CMB-S4 program will likely be on the order of 10 telescopes of two types, small apertures similar in size to BICEP and larger apertures, possibly 5 to 8 m in diameter. The family of telescopes will be located at the South Pole, Chile, and possibly a new northern site to optimize the science return. The 10-m South Pole Telescope would likely remain. (See Figure 3.4.) The deployment will likely stretch over 3 to 4 years, and operations will continue for roughly 5 years after deployment is complete. Of all these sites, the atmospheric observing conditions at the South Pole are superior and would allow the most sensitive observations; while the other sites allow more sky coverage.

An infrastructure upgrade will be required for CMB-S4 at the South Pole. The scope of the upgrade will be equivalent to the renovation or replacement of the current Martin A Pomerantz Observatory—which may soon become unavailable because it is being buried by snow. The power requirements for CMB-S4 at the South Pole, driven primarily by the helium cryocoolers, are similar to those of the current program.

For efficient operation of the CMB-S4 telescopes at the South Pole, it is highly desirable to improve the 24/7 Internet/voice access and increase the data transmission. The current transmission of CMB data from the South Pole is around 120 GB/day. It

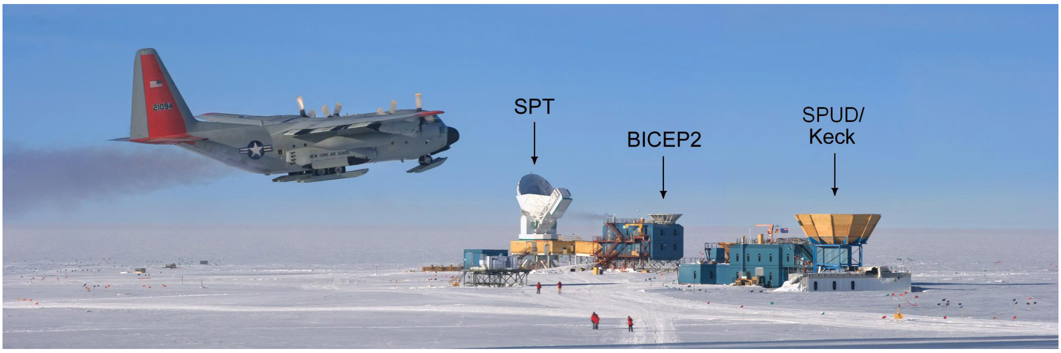


FIGURE 3.4 A view of the BICEP telescope and the 10-m South Pole Telescope located at the Amundsen Scott South Pole research station. SOURCE: Steffen Richter.

would be desirable to increase the transmission to roughly 1 TB/day. Lower transmission rates would require considerably more on-site analysis, with physical transport of the backed-up data media during the austral summer seasons. Although possible, this would severely diminish the science output by not allowing the full power of the CMB-S4 science team to work on real-time data inspection and data analysis.

This next-generation CMB initiative will be an interagency effort. In addition to three NSF divisions involved (PLR, Physics, and Astronomical Sciences, with PLR leading management of South Pole activities), the DOE Office of Science has also expressed interest in being involved, particularly in the scaling-up of detector arrays and in handling the computation required for the large datasets. NASA leads the ballooning and space-based CMB studies and there are nascent community discussions of planning a possible future NASA satellite designed to complement the ground-based effort. The project is expected to include international partners. The current international partners of the ongoing CMB projects would naturally be expected to participate in CMB-S4, including the United Kingdom, Canada, Germany, Japan, Chile, and others.

Regarding the anticipated management needs, a Joint Oversight Office with members from all participating agencies and NSF divisions will be necessary. It will be highly beneficial to have a dedicated NSF program officer to work with the CMB-S4 project and interface with other agencies.

SELECTING AND SUPPORTING THE RECOMMENDED PRIORITIES

The Committee's task was to help NSF make some hard choices, which means that many compelling research topics raised in the community engagement discussions are not listed among the recommended priorities. We did not feel it would be constructive to list the merits and limitations of all the various, wide-ranging research ideas suggested. Rather we simply note that the ideas that were not selected did not fare as well in meeting some or all of the evaluation criteria, as compared to the recommended priorities. And emphasis was placed on activities for which NSF/PLR in particular is best suited to lead.

One unique example to note is the IceCube-Gen2/PINGU proposal (discussed in Box 2.4). Although the Committee acknowledges that this project has the potential to lead to exciting new scientific advances, we were cognizant of the fact that construction of the original IceCube facilities had major impacts on the USAP logistical system, and we had concerns that high demands on USAP logistical support likely required for the IceCube-Gen2 construction would be incompatible with our recommendations to expand logistical support for activities for West Antarctic research.

This report outlines only general-level guidance for what the recommended initiatives should look like, with expectations that the more fine-grained implementation details will be shaped by NSF and by the relevant research communities. These planning processes will also allow robust cost estimates to be determined for each of the initiatives. On a very general level, we surmise that the *Antarctic Genomics Initiative* and the *Cosmic Microwave Background Initiative* can be supported within the existing PLR core program budgets (for Antarctic Organisms and Ecosystems, and Antarctic Astrophysics and Geospace Sciences, respectively), without significantly impeding the ability of those programs to continue support for traditional PI-driven proposals. And for both initiatives, NSF and the research community should consider whether establishment of a science and/or technology center could be an appropriate vehicle for supporting and advancing the work.

The scale is significantly larger for the proposed *Changing Ice Initiative.* If carried out at the scope and duration envisioned, this effort may require resources equivalent to much of the research budget of the following PLR Antarctic Science core programs—Earth Sciences, Glaciology, Ocean and Atmospheric Sciences, and Integrated System Science. And yet we would not want to see the proposed initiative overwhelm the capacity of these programs to provide ongoing support for traditional PI-driven proposals—an outcome that runs contrary to the overall strategic vision proposed at the start of this chapter.

This apparent conflict may be ameliorated in part by leveraging new and expanded partnerships between PLR and other divisions of NSF, other federal agency programs, and other countries' Antarctic research programs. But more importantly, the Committee fully believes that because of the urgency and potential magnitude of the threats that ice sheet collapse poses for human society, this issue must be looked at through a different lens—beyond the constraints of what current budgets dictate is feasible. This research will ultimately provide critical guidance on when, where, and how sea level may occur, and it will thus help society make the needed adaptation investments in a reasonably informed matter. Although the cost of this research is large relative to current PLR/ANT program budgets, it is tiny relative to the projected costs of adaptation to and damage from sea level rise (see Box 3.3). We thus suggest there is strong rationale for NSF to seek to significantly augment the funding available to support this research.

Moreover, it is worth noting the potential co-benefits to USAP science that could result from the recommendations to bolster support for deep-field work offshore and near, under, and on the ice shelves. This enhanced logistical capacity could yield a wealth of new opportunities for other types of smaller (PI-driven) investigations that would otherwise lack the critical mass to justify logistical support. This may even include opportunities for disciplines that are not directly related to the initiative itself—for instance, opportunities for ecology researchers to join research cruises and coastal expeditions to collect samples that would otherwise be impossible to obtain.

There are inevitably difficult trade-offs that must be made in any effort to truly set priorities among research needs. However, the Committee has tried to provide a framework that balances the desire to make major leaps forward on a few critical research topics with the need to preserve flexibility for NSF to continue responding to new creative ideas arising from across the research community.

CHAPTER FOUR

Foundations for a Robust Antarctic and Southern Ocean Research Program

The preceding chapter discussed the Committee's strategic vision of priorities for Antarctic and Southern Ocean science in the coming decade. This chapter discusses the "foundational elements" that the Committee feels are critical for a healthy, effective research program—elements that directly support the implementation of the priority research topics, and can add lasting value to the outcomes of these research efforts.

CRITICAL INFRASTRUCTURE AND LOGISTICAL SUPPORT

The infrastructure and logistical support needs that the Committee identified as particularly critical for advancing the priority research topics, and for supporting investigator-driven research across PLR's core programs, are discussed below in the following general categories:

- Access to remote field sites especially in West Antarctica,
- Data transfer, communication, and information technology needs,
- Icebreaker support to ensure access to McMurdo Station and deep-field research,
- Support of sustained observations.

All of these needs must be considered in the context of the proposed Antarctic Infrastructure Modernization for Science (AIMS) program to modernize McMurdo and Palmer bases (See Box 4.1).

Access to Remote Field Sites

The USAP has long been a leader in supporting deep-field research campaigns, due largely to the availability of ski-equipped LC-130s and the U.S. Air Force C-17, which have enabled the delivery of fuel to some of the most inaccessible sites on the planet. Increasingly, this heavy-lift airborne support has been complemented by surface

BOX 4.1
The Antarctic Infrastructure Modernization for Science (AIMS) Project

An important development during the course of our study was the announcement that the U.S. Antarctic Program (USAP) is developing a Major Research Equipment and Facilities Construction (MREFC) proposal for a project to modernize McMurdo and Palmer stations. The project, called Antarctic Infrastructure Modernization for Science (AIMS) Project, is aimed at continuing progress on NSF's commitment to more efficient and cost-effective science support as recommended by the Blue Ribbon Panel report (BRP, 2012).

The project is currently in the conceptual design phase and, as of this writing, still needs to go through numerous levels of review and approval before being granted MREFC funding. Because many of the specific details of this effort are yet to be determined, the Committee did not attempt to evaluate directly, or make explicit recommendations to, the AIMS planning effort. But we note that AIMS does have great potential to advance the efficiency and quality of science support at McMurdo and Palmer stations, and to help enable the science programs recommended here.

Those working on the AIMS planning will need to take into account the logistical support implications of the science priorities recommended in this study. For example, the science priorities point to the importance of McMurdo as not only a research station, but also as a launching point for studies in the deep interior of Antarctica. And in light of lessons learned from the South Pole Station modernization experience, we urge that all possible efforts be made to ensure that the AIMS project does not cause any serious interruption to scientific research during the construction period.

NSF representatives noted that as part of the efforts to minimize such interruptions, they are hoping to arrange for year-round flights into McMurdo, thus allowing much of the construction work to take place during the "off-season" beyond austral summer. While the priority for this extended access must of course go to the construction support personnel, it is worth noting that many scientists would be excited to take advantage of any opportunity to join these additional flights and explore research questions that cannot be addressed within the confines of the standard research season—for instance, to study the year-round life cycle and migration patterns of certain animal species. A special NSF workshop held more than a decade ago identified a wide array of science opportunities that could result from year-round access to McMurdo (Priscu, 2001). The new AIMS developments may provide a strong motivation to reexamine this analysis and explore opportunities to act on those recommendations.

traverses, which are being used to deliver large volumes of fuel to the South Pole and to move major field infrastructure, as in recent support of the Whillans Ice Stream Subglacial Access Research (WISSARD) project. This all provides a valuable foundation for supporting much of the priority research identified here—research that requires access to deep-field sites on the continent and in the ocean. In particular, the *Changing Ice Initiative* will require expanded access to critical regions of the West Antarctic

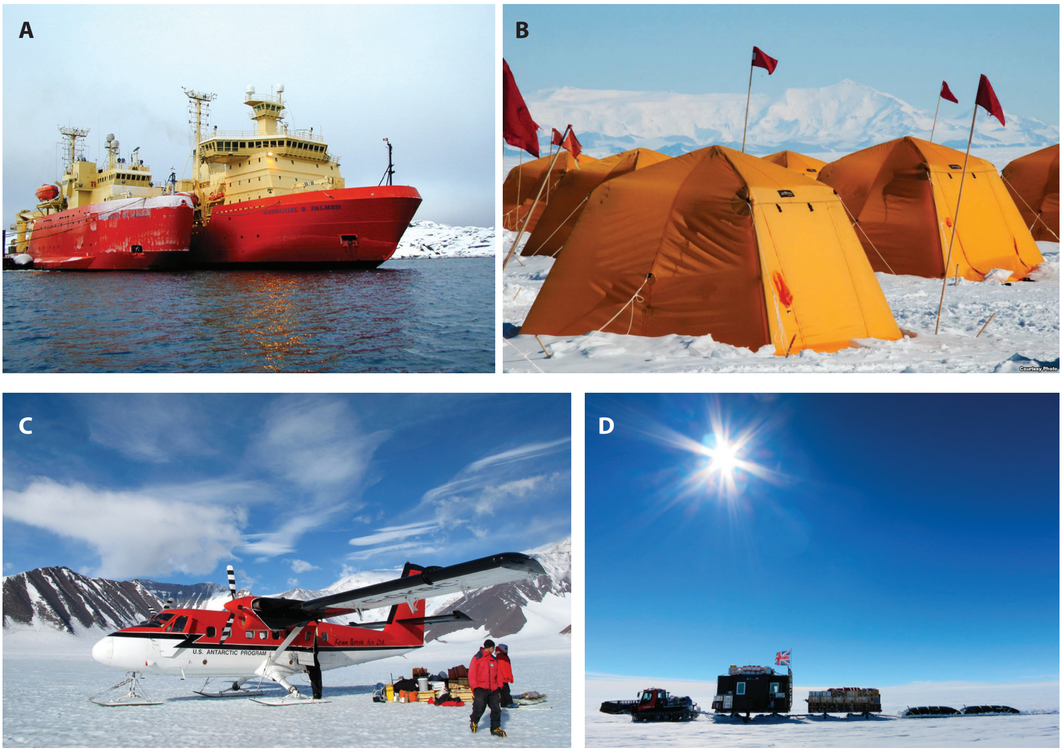


FIGURE 4.1 Examples of deep-field research access needs. **A:** The research vessels *Lawrence M. Gould* and *Nathaniel B. Palmer*. SOURCE: Christine Hush, NSF. **B:** A science field camp, with Mount Erebus in the background. SOURCE: Alberto Behar. **C:** A Twin Otter airplane transports scientists and cargo to remote field sites. SOURCE: Peter Rejcek, NSF. **D:** A British Antarctic Survey science traverse. SOURCE: Damon Davies, University of Edinburgh.

Ice Sheet (WAIS) by aircraft and traverse from McMurdo, and improved access to the adjacent ice shelves and the Southern Ocean with a next-generation research vessel. These key needs are discussed further below.

Crucial regions that the *Changing Ice Initiative* must target are, in priority order, the Amundsen Sea sector (including Thwaites and Pine Island glaciers and the surrounding active regions), the Ross Ice Shelf, and the grounding lines of the Siple Coast. The related ice-coring and geoscience sampling efforts likewise require access to a variety of remote areas around West Antarctica. Research in these regions will require surface and airborne studies based from a deep-field camp in West Antarctica, geophysical and oceanographic surveys on the continental shelf, and installation of observatories/

moorings beneath the ice shelves and in the adjacent ocean. A location such as the WAIS Divide Camp (or possibly Byrd Station) could serve as a central field camp and logistics hub for the surface and airborne programs. The exact location would be selected in consideration of weather conditions and access to the Amundsen Coast—a notoriously challenging area to work in, with difficult weather conditions often limiting flight operations. The surface program will include Bassler- and Twin Otter–supported field parties, and will require the development of an effective over-snow

BOX 4.2
Improved Weather Forecasting—A Critical Infrastructure

Antarctica and the Southern Ocean are parts of the Earth where the weather can change suddenly, and scientists and support personnel can be abruptly confronted with extreme and dangerous conditions. Knowledge of the weather and its changes are key factors for safety, efficiency, and cost-effectiveness of Antarctic operations by air, sea, and land. Year-round flights into McMurdo Station, for example, are only possible when accurate weather forecasts are available. Remote field camps in West Antarctica and elsewhere depend on accurate weather forecasts for their success. The types of meteorological observations needed for generating accurate forecasts can also provide valuable contributions to research efforts.

Weather forecasters face many challenges in these areas. Available forecast models are designed for lower latitudes, and they have problems representing polar-specific processes. Direct atmospheric observations are very limited, making it difficult to know precisely what atmospheric events are happening. Satellite observations are difficult to use over snow and ice surfaces. Advancing forecasting capabilities requires more and better information about the vertical structure of the atmosphere, which must come from high-temporal-resolution observations collected from surface-based sounders, radars, or instrumented towers. The most important forecast model deficiency is the prediction of low clouds and fog, information that is critical for aircraft landings. Another persistent problem occurs in characterizing the cold, stable atmosphere near the surface, which determines the generation of strong winds and blowing snow. Analysis of the atmospheric structure (a starting point for forecast models) needs significant improvement, and more effective use of satellite data promises the greatest return.

Forecasts longer than 1-2 days out require prediction of ocean and sea ice conditions; developing this prediction capability requires coupling capable sea ice and ocean models with weather prediction models. In addition, the generation of multiple numerical weather forecasts from an array of slightly different starting points (known as ensemble prediction) is very useful for assigning confidence to longer-duration forecasts. The World Meteorological Organization's Polar Prediction Project (running from 2013 to 2022) aims to address many of these issues; and its flagship activity, the Year of Polar Prediction (2017-2019), is an important opportunity for coordinated international advancement of Antarctic weather forecasting.

science traverse capability (one or more traverse trains expressly for science support). The British Antarctic Survey has demonstrated that a modern traverse can produce remarkably high-resolution data and insights into the base of the ice sheet and can operate under moderately poor weather conditions. This deep interior field camp and logistics hub will facilitate aerogeophysics support and the installation of important new weather observatories (see Box 4.2).

FIGURE Automatic Weather Station on Mulock Glacier. SOURCE: Jonathan Thom, Space Science and Engineering Center, University of Wisconsin-Madison.

Concerns about ship support for Antarctic and Southern Ocean research were raised repeatedly in our community outreach discussions, and this is a critical need for supporting the *Changing Ice Initiative*. The United States has very limited heavy icebreaker support for research in Antarctic waters. As discussed later in this chapter, the USCGC *Polar Sea* is over 40 years old and is tasked primarily with breaking a channel into McMurdo Station. The *Nathaniel B. Palmer* is approaching the end of its design service life, and in any event, is designed for only limited icebreaking (with a specified capability of breaking through 3 feet of level ice at 3 knots). The NSF recognized the urgency of advance planning for a *Palmer* replacement more than 12 years ago and has since supported a series of associated science workshops, icebreaker design contracts (with the U.S. Maritime Administration), and mission requirement refresh activities. Yet no significant progress has thus far been made toward the acquisition of a new polar research icebreaker on the funding side.

The potential gap in ship capacity presents a fundamental challenge to U.S. leadership. The only solution at present for U.S. scientists to pursue key research in heavy-ice areas, or along most of the coast during winter, is to work on research icebreakers of other nations. To adequately support the science priorities recommended by this Committee, and to retain a leadership-level role in both Antarctic and Arctic research, NSF will need to prioritize the acquisition of a next-generation research icebreaker. A new MREFC proposal is one possible vehicle that could be explored for advancing this goal. Given the long time horizon for funding, building, and deploying such assets, NSF will meanwhile need to establish stronger ties with foreign research vessel operators to provide critically needed field opportunities for U.S. scientists.

Data Transfer, Communication, and Information Technology Needs

As noted in the Blue Ribbon Panel report (BRP, 2012), there are four USAP communications and information technology enterprise lines of function—Technical Services, Communications, Information Systems, and Governance—each of which has many subsidiary components. The most relevant concerns for researchers are assurance of safety in the field, operational support and management of manned and autonomous instrumentation, and daily bulk transmission capacity for scientific data.

To address these issues, NSF commissioned the Aerospace Corporation to analyze alternatives for USAP communications architectures and mission support capabilities for the planning horizon of 2015-2030. This study built upon a May 2011 workshop that addressed three main elements of communications needs: (i) South Pole users, which currently have the largest bulk data requirements; (ii) distributed users, which are largely serviced by low Earth orbit systems such as ARGOS and Iridium; and (iii) maritime users, which may impose new needs such as acoustic communications to manage under-ice operations and data transmission. Developments stemming from that analysis will likely be helpful for supporting the research recommended here, but a few outstanding needs are worth highlighting.

At the South Pole, to accommodate the proposed next-generation Cosmic Microwave Background program, an increase in the total transmission rate by roughly a factor of five to around 1 TB/day in 6 to 8 years would be required. Although a modest increase by some standards (compared to Moore's law), it represents a challenge for USAP. It is expected that the GOES-3 satellite will not be operational much past 2017, and NASA will have gaps in the Tracking and Data Relay Satellite (TDRS) coverage during the same time frame. NSF is coordinating with the U.S. Air Force to obtain access to the Defense Satellite Communications System's DSCS III satellite for high-bandwidth communications from the South Pole to compensate for the loss of the other capabilities. DSCS will provide significant operational and cost advantages (for Southern Ocean and McMurdo as well as the South Pole) once appropriate ground stations are installed, and at the South Pole it should provide 4- to 6-hour blocks of connectivity, equivalent to TDRS. In addition, there is a need to investigate other access options from the South Pole, such as fiber optics and/or repeater stations to reach more favorable latitudes. It is possible that there will need to be significant physical transport of backed-up data media from the CMB telescopes (needs that may be even greater if data transmission requirements of other South Pole experiments significantly increase).

Increased bandwidth requirements associated with some elements of the *Changing Ice Initiative* are also anticipated, including for autonomous sensors and for research vessels, and assured 24/7 communications from the ships, field camps, and deployed systems. Addition of a new satellite ground station on Ross Island (as proposed for the AIMS MREFC) should add significant flexibility and assurance, as well as cost savings over the current exclusive reliance on Black Island. Availability of DSCS may open an opportunity for tactical ground stations such as used by the military for some field camp communications—similar in nature to the portable GOES-3 station that was employed at WAIS Divide. One important requirement will be for data transmission and operational communications (including technologies that enable location and navigation) for autonomous underwater vehicles operating around and under the ice shelf. Depending upon the details of the observing strategy, this may well require installation of an extensive acoustic communications and navigation network in the Amundsen Sea region, as well as ship-based acoustic communications enhancements.

Icebreaker Support to Ensure Access to McMurdo and Deep-Field Research Opportunities

Much of the research highlighted in this report will require robust support of McMurdo Station as a logistics and research hub. Everything from movement of scientists and telescopes to the South Pole to drilling new ice and sediment cores, to studying the changing grounding line of the West Antarctic Ice Sheet, to collection of biological samples for genomic analysis, will require access to the continent through McMurdo and the western Antarctic Peninsula.

Operation of McMurdo requires opening a channel through the sea ice (break-in) by an icebreaker each austral summer. In accordance with U.S. policy regarding Antarctic operations, break-in to McMurdo is supported by U.S. Coast Guard icebreakers when requested and funded by NSF. This service has traditionally been performed either by USCGC *Polar Star* or *Polar Sea*. Starting in 2004-2005, reliability concerns and other operational considerations led the USAP to charter icebreakers from Russia and Sweden. Initially these vessels were backups to deployed USCG vessels, but subsequently were used in the primary role, and in the 2009-2010 through 2012-2013 seasons, only foreign icebreakers were used to support McMurdo break-in. In recognition of the dangers inherent in relying upon foreign support to sustain American research commitments to Antarctica, the *Polar Star* was overhauled and reactivated in December 2012 with an expected additional 7-10 years of service life. *Polar Star* supported the 2013-2014 McMurdo break-in and is expected to continue to provide such support while in service. *Polar Sea* has been in inactive status since October 2011.

While the Coast Guard has initiated a project for design and construction of a new polar class icebreaker, there remain numerous concerns in the research community about (i) the national commitment to acquire one or more new U.S. polar class icebreakers; (ii) the time line for funding and constructing such vessels; (iii) the disposition of *Polar Sea*, and the *Polar Star* when she again has operational problems; and (iv) whether a new icebreaker would be able to support science operations to any reasonable degree in the absence of a dedicated new polar research vessel. Our Committee shares all of these community concerns and urges NSF to place a high priority on providing adequate ship-based support, both for maintaining operations at the three U.S. Antarctic research stations and for advancing the priority research identified in this report.

Support of Sustained Observations

Many previous reports from the NRC and elsewhere have discussed why understanding the natural environment, and human influences on that environment, often requires that key physical and biological observations be sustained over long periods of time—months, years, even many decades in some cases. This is an ongoing need for almost all areas of environmental science; but for polar-based research in particular, maintaining robust observing systems can present major challenges due to the harsh and remote setting in which these systems are implemented.

There has been longstanding debate about NSF's role in collecting long-term observations, based on the argument that routine monitoring activities fall outside the scope of the agency's mandate to advance fundamental scientific understanding, and that such activities are best covered by other, mission-driven agencies. While agencies such as NASA and NOAA certainly have important roles to play in this regard, some sustained observational efforts are in fact critical to discovery-based, fundamental research. The scope of the work envisioned for the *Changing Ice Initiative* includes observations aimed primarily at understanding processes, particularly the underlying drivers, mechanisms, and impacts of change. This is clearly within the purview of NSF—as opposed to observations aimed primarily at documenting changes and trends in key environmental systems, which fall more clearly under the purview of NASA and NOAA.

The following discussion from the report *The Arctic in the Anthropocene: Emerging Research Questions* (NRC, 2014) further articulates this idea, with arguments that apply just as well to Antarctic as to Arctic science:

> When suitably constructed, long-term observing systems serve a variety of purposes for a variety of stakeholders. On one hand, they enable quantification of the natural variability, over a range of temporal and spatial scales, of complex "noisy" systems. Once the noise is defined and quantified, long-term observations enable detection of gradual, systematic changes. On the other hand, because of the nonlinear character of many systems, a carefully developed monitoring scheme may detect abrupt and/or unanticipated changes. In this capacity, long-term observations serve as part of an early warning system . . . , which then allows for a choice of responses. These responses will vary depending upon the nature of the change, but they could include collecting focused measurements designed to better understand the emerging phenomenon; development or initiation of mitigating procedures, if deemed feasible; or, in the event of a potential catastrophe, appropriate emergency responses. Long-term observations also provide the temporal-spatial context in which shorter-duration, hypothesis-driven process studies can be undertaken. In this context it allows researchers to determine

> whether the processes under consideration occurred under typical or atypical conditions. . . .
>
> Monitoring is a synergistic component in modeling and hypothesis development. It provides datasets necessary for the evaluation and development of models and/or suggests investigations needed to improve model parameterizations and/or processes. Models provide an integrated approach to understanding system behavior and can be used to modify the monitoring program as necessary. Models also augment monitoring efforts by suggesting how unsampled system components may be evolving. Monitoring and model results both contribute to the construction of hypotheses on how the system or parts of it operate. (pp. 118-119)

Future Science Opportunities in Antarctica and the Southern Ocean (NRC, 2011a) advocated establishing "a broad-based observing system, including remote sensing as well as in situ instrumentation, that can collect data which will record ongoing changes in the Antarctic atmosphere, ice sheets, surrounding oceans, and ecosystems." While there have been some encouraging developments in recent years with respect to oceanic observing systems (e.g., the Southern Ocean Observing System [SOOS]) planning efforts, support for the Southern Ocean Carbon and Climate Observations and Modeling [SOCCOM] project), pursuing a comprehensive coastal/terrestrial observing system across the Antarctic may not be a feasible goal in today's constrained budget environment. Yet the sustained observational efforts that are at the heart of the proposed *Changing Ice Initiative* could serve as valuable building blocks for the broader goal of a more comprehensive pan-Antarctic observing system. More generally, there are many relatively low-cost steps that can be taken toward this broader goal by better coordinating, integrating, and strategically augmenting existing observational and data management efforts being carried out by different research groups, different federal agencies, and different countries. NSF's responsibility to manage the logistical support for Antarctic-based research means that their leadership in this coordinating work is indispensable.

This need was emphasized in the report *Autonomous Polar Observing Systems* (NSF, 2011), which resulted from an NSF-sponsored workshop. This report identified several strategies for maximizing the scientific value and minimizing the costs and logistical burdens of deploying arrays of autonomous sensors. For instance, they recommended better coordination of existing disciplinary observing systems to fully exploit their synergies, and establishing "supersites" where researchers with diverse interests could share logistics and on-site capabilities, and where support personnel would have the training to meet the needs of multiple science groups. For Southern Ocean studies, mooring-based observatories and underwater autonomous vehicles are opening up new opportunities to better characterize undersampled regions of the ocean, and to extend and integrate existing, isolated observational efforts. (See examples in Boxes 4.3 and 4.4).

A common theme in the input from the community was the call for expanded NSF support of sustained observational efforts, including the need for mechanisms to ensure continuity of support for efforts that span beyond the length of a typical research grant. Similar concerns and needs were expressed by researchers in widely varying disciplines. Some examples of sustained observing system needs that were frequently highlighted include:

- Expanding the Automatic Weather Station network, both to aid fundamental research efforts and to aid operational weather forecasting;
- Continuing the seismic and geodetic (GPS) monitoring around the continent to constrain ice sheet models;
- Expanding use of key ocean observing platforms such as surface and sub-surface moorings, profiling floats, and gliders;
- Characterizing long-term changes in solar variability and its impacts, for instance, with neutron monitoring stations, magnetic measurements at key sites, auroral observatories, and lower, middle, and upper atmospheric weather stations.

BOX 4.3
Southern Ocean Observatories

Two Southern Hemisphere observatories have been implemented under the NSF's Ocean Observatories Initiative (OOI). A National Research Council report (NRC, 2003a) and community workshops led to establishment of sampling sites in the South Pacific at 55°S, 90°W (called the Southern Ocean site) and in the South Atlantic at 42°S, 42°W (called the Argentine Basin site). These sites were designed to observe from the sea surface to the sea floor, to collect up to 20 years of data, to provide high temporal vertical resolution over the full water column, to carry multidisciplinary instrumentation, and to sample horizontal variability on the mesoscale and smaller scales.

In the data-sparse Southern Hemisphere, these and any additional new sites can make exceptionally valuable contributions to better quantifying and modeling surface meteorology and air–sea fluxes of heat, freshwater, momentum, and chemical constituents such as CO_2. The OOI arrays add a unique new capability to understand the role of the ocean mesoscale in upper-ocean dynamics and vertical exchanges and mixing. Studies indicate that increased model resolution shows greater mesoscale structure, and eddy-permitting models yield different upper-ocean stratification and ventilation than coarse, non-eddy-resolving models (Hallberg and Gnanadesikan, 2006; Lachkar et al., 2007).

BOX 4.4
Linking Remote Distributed Field Stations Via Autonomous Sampling Systems

The West Antarctic Peninsula is experiencing the largest winter warming trend of any region on Earth (Vaughan et al., 2003), with over 80 percent of the region's glaciers in retreat (Cook et al., 2005; Vaughan, 2006) and the annual sea ice season shortened by 90 days (Stammerjohn et al., 2012). These changes in the physical system have been mirrored in alterations in phytoplankton, zooplankton, and penguin communities (Fraser et al., 2013; Schofield et al., 2010; Steinberg et al., 2015). There is an intensive presence of the international research community in this region, with 16 countries maintaining land-based field stations. Because few of these stations have airfield capabilities, the majority rely on small-boat operations for their research. Safety considerations significantly limit the range of these boats, which ultimately limits the research capabilities of the field stations.

Rapidly maturing autonomous technologies now offer the opportunity to safely expand the research footprint of these field stations. For instance, autonomous gliders can collect physical, chemical, and biological data over thousands of kilometers, in missions that may last up to several months (Schofield et al., 2007). The close proximity of many field stations along the Peninsula means they could be linked by a fleet of gliders—with field stations launching gliders to other stations, which then receive, rebattery, and redeploy the gliders to return to their home base. These surveys could be conducted periodically and provide the foundation for an integrated sampling network, at a fraction of the cost compared to a similar-scale sampling network using ships. Discussions have already commenced on developing this community of glider operators, as a way to maintain a sustained presence in the coastal waters of the shelf region, to better understand the changing environment.

One area in which NSF has made great strides in supporting sustained observational-based research is the LTER network. The two Antarctic-based LTER stations collect a wide array of observations that provide highly valuable information for supporting a range of scientific investigations. At the McMurdo Dry Valleys LTER this includes, for instance, continued observations of atmospheric temperature, lake levels, soil temperature and moisture, timing and amount of glacial melt–generated stream flow, as well as biomass primary production and biodiversity measurements. And at the Palmer LTER, examples of key observations include sea ice coverage, coastal ocean properties (temperature, salinity, optical depth, circulation patterns, biological productivity), and surveys of the abundance and distribution of marine mammals, seabirds, zooplankton. In some cases, advancing critical observing systems requires expansion of interagency cooperation—as highlighted in the examples in Boxes 4.5 and 4.6.

BOX 4.5
Research and Monitoring for Sustainable Southern Ocean Fisheries

Commercial fishing in the Southern Ocean has raised longstanding concerns about overfishing of key target species, and cascading impacts on other species through unintentional by-catch and alteration of regional food-web dynamics. These concerns are exacerbated by climate-related stressors on fish populations such as acidification and warming of Southern Ocean waters. The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) came into force in 1982, chiefly as a result of concerns about increasing catches of krill—a vital foundation of the Antarctic marine food web. More recently, there have been growing concerns about the Antarctic toothfish (commonly marketed as Chilean Sea Bass), which faces growing illegal, unregulated, and unreported fishing. As a top predator in the Southern Ocean, the toothfish is critical to overall ecosystem functioning.

For several years now, CCAMLR has overseen intense debates and negotiations about Marine Protected Areas aimed at managing Southern Ocean fishery resources on a sustainable basis. But the scientific information needed to establish appropriate guidelines and goals, and to eventually establish formal regulatory programs, is almost entirely lacking. For instance, the life cycle of the Antarctic toothfish is virtually unknown. There are pressing needs for intensive monitoring efforts to better establish the current state of key fish stocks, including information on how these populations vary over time and space (life history, population structure, reproductive cycle) and details on their life cycle (breeding grounds, migration patterns, etc.).

While scientific needs are clear, the question of who has the mandate and resources to lead such work is much less clear. In most fishing areas where the United States has economic interests, NOAA has the mandate to lead research and monitoring efforts. For instance, NOAA conducts an annual survey for key economic marine species such as pollock, snow crab, king crabs in the Alaskan Arctic. And in the Southern Ocean, the NOAA Antarctic Marine Living Resources program conducts research on krill, finfishes, krill-dependent predators, and other components of the Antarctic ecosystem—including annual surveys of key species around the South Shetland Islands. It is logical that NOAA should continue to lead in this work—given the primary focus on ongoing monitoring and applied ecosystem management goals. But the resources allocated to this NOAA program do not appear to be nearly sufficient to carry out this work on a scale that is needed. And given NSF's unique role in overseeing the USAP, a strong partnership between NSF and NOAA is critical. This should include fully exploiting possibilities for collaborative work with the Palmer LTER and other NSF-supported activities in the western Antarctic Peninsula.

Ideally, such issues are examined in the context of comprehensive, ecosystem-wide studies—including not only fish species but also (for the Southern Ocean) whales, seals, seabirds, and plankton. But if NSF does not consider efforts of this scale to be currently feasible, there are a few key life history traits that may be amenable to study with relatively limited, small-scale studies. For instance, if NOAA is able to expand operational monitoring and data-sharing efforts, this may provide a useful platform for NSF-supported biologists to address basic research questions about the toothfish life history. This could be one of the topics to examine in the context of the Ross Sea Research Coordination Network proposed earlier in this report.

BOX 4.6
Observations for Understanding the Coupling and Transport of Energy, Momentum, and Mass in a Dynamic Solar Wind–Magnetosphere–Ionosphere–Upper Atmosphere System

Advancing understanding of the dynamics of the Earth's upper atmosphere and how this region is affected by short-term and long-term changes in solar forcing requires coordinated observations of critical parameters in space and on the ground. This includes optical techniques to measure the location and energy of charged-particle precipitation into the atmosphere, magnetometers to measure the effects of electrical currents and hydrodynamic waves produced by various plasma processes, GPS receivers to measure the ionospheric electron content and also investigate the plasma instabilities, and various radio techniques that provide the means to remotely sense a variety of magnetospheric parameters. There is increasing need for greater spatial coverage and resolution in these sorts of observations, in order to inform and validate numerical models of the geospace system.

NASA is undertaking ambitious satellite missions to advance understanding of the physics that governs space weather. Instrumentation that can be deployed and operated autonomously in remote polar regions is vital to the analysis of the data being obtained by these satellite missions. This is particularly important for the Antarctic, which until recently has been extremely data sparse, and which provides the best stable land mass to support instrumentation at high polar latitudes. For example, the South Pole and surrounding regions provide several months of darkness that allow optical auroral measurements at the dayside ionospheric intersection of the magnetic field lines that first encounter the solar wind.

In the coming decade, ground coordination with the existing Time History of Events and Macroscale Interactions During Substorms satellite mission, the Magnetosphere Multiscale Mission scheduled for launch in March 2015, along with other future missions, will maximize the science being accomplished by either the ground-based science or satellite missions alone. Coordination with other ground-based and satellite experiments will provide additional synergy to advance the scientific return from these investments. Such a coordinated approach forms a "heliophysics observatory." While NSF has indispensable roles to play in coordinating the ground-based components of this observatory (i.e., distributed arrays of remote autonomous observations), NASA could play a leading role in supporting this network—just as (in other parts of the world) NASA supports ground-based observational arrays that are critical for validation and interpretation of their remote sensing observations.

Recommendation: NSF should prioritize the following actions to advance infrastructure and logistical support for the priority research initiatives recommended here—actions that will likewise benefit many other research activities supported under NSF/PLR's core programs.

- **Develop plans to expand deep-field access in key regions of the West Antarctic and Southern Ocean, including the following key elements: deep-field camp and logistics hub, over-snow science traverse capabilities, ship support for research in ice-covered Southern Ocean coastal areas (see below), all-weather aircraft access to McMurdo, and improved aircraft access to remote field locations.**
- **Support the efforts of the Coast Guard to design and acquire a new polar-class icebreaker; and with the assistance of other research partners, design and acquire a next-generation polar research vessel. In the near term, work with international partners to provide ocean-based research and sampling opportunities through other countries' ice-capable research ships.**
- **Actively pursue opportunities for better coordinating and strategically augmenting existing terrestrial observation networks and better coordinating of national vessels to increase sampling of the Southern Ocean.**
- **Continue advancing efforts to improve USAP communication and data transmission capacity, including location/navigation for autonomous underwater instrumentation.**

COORDINATION AND COLLABORATION OPPORTUNITIES

As discussed in Chapter 2, research supported by NSF/PLR is inherently intertwined with research supported in other parts of NSF, in other U.S. federal agencies, and in other countries' Antarctic and Southern Ocean research programs. The Committee's recommended scientific priorities bear this out because they all require some degree of collaborative efforts on all of these different fronts. Some of these needs are discussed below.

Intra-NSF Coordination

Some examples of opportunities for expanding intra-NSF partnerships were discussed Chapter 3— for instance, the cosmic microwave background efforts would involve collaboration with the NSF Divisions of Physics and of Astronomical Sciences, and the Antarctic genomics research could involve collaboration with the NSF Directorate for Biological Sciences. Here we highlight in particular the many opportunities that the proposed *Changing Ice Initiative* presents for joint efforts between PLR and other divisions in NSF's Directorate for Geosciences.

A prime example is the **Division of Atmospheric and Geospace Sciences' (AGS)** support for the global *Community Earth System Model*, the *Whole Atmosphere Community Climate Model*, and a variety of regional earth system modeling efforts (in particular, efforts to advance sea ice and ice sheet components of these models). These AGS-supported efforts can both contribute to and benefit from PLR-supported research that improves understanding of key ice–ocean–atmosphere interactions, understanding of the teleconnections that link Antarctic-region changes to climate variations in subtropical and tropical latitudes, and understanding of how aerosols and clouds affect radiative balance over the Southern Ocean and Antarctica. Although AGS may be best suited to lead the support for much of this work, it should be developed in close cooperation with PLR, especially in developing the plans for the *Changing Ice Initiative*.

The **Division of Earth Sciences (EAR)** supports efforts to improve models of ice sheet retreat through the collection and interpretation of field data (e.g., the mapping and dating of raised shorelines across the globe during periods of recent global warmth) and to develop and improve novel geochronological tools for higher-precision dating of relevant glacial landforms. The Division's core strengths of geology, geochemistry, and geophysics are well suited for addressing the complex response between ice sheet retreat and sea level rise, which varies geographically and is dependent on factors such as mantle rheology, crustal processes, and detailed understanding of ice sheet melt geometries.

The **Division of Ocean Sciences (OCE)** overlaps substantially with PLR research, as highlighted by the recent *Decadal Survey of Ocean Sciences* (NRC, 2015), which recommended that a top-priority science question for OCE is *"What are the rates, mechanisms, impacts, and geographic variability of sea level change?"* Addressing this question hinges in large part on the research recommended in our *Changing Ice Initiative*. Thus cooperative efforts are critical—in terms of both direct research support and infrastructure/logistics support. The ocean does not respect the 60°S line between PLR and OCE "territory," so this artificial boundary should not impede efforts to advance research on the ocean as one integrated system. Likewise, the fact that NSF operates two separate fleets of research ships (one funded principally by OCE and operated under UNOLS [University-National Oceanographic Laboratory System], another funded by PLR and operated under Edison Chouest Offshore, Inc. [ECO]) , should not impede efforts to prioritize investments on the basis of overall significance to scientific priorities. OCE-funded investigators most often use UNOLS vessels for research north of the 60°S boundary line, but better use of PLR vessels for this research is increasingly important, given growing constraints in the availability of global-class UNOLS vessels, and the efficiency gains of avoiding long transits. For instance, the *Nathaniel B. Palmer* was recently used for a hydrographic cruise (part of GO-SHIP), and it is expected to be used for annual servicing of OCE's Southern Ocean OOI arrays. Future planning efforts to acquire and manage NSF research vessels would greatly benefit from adopting an integrated usage strategy.

Interagency Cooperation

NSF is charged with responsibility for budgeting and managing the entire U.S. national program in Antarctica, including logistic support activities. This responsibility mandates close coordination with all other federal agencies involved in Antarctic and Southern Ocean research, as well as with the Department of State's involvement in the Antarctic Treaty Consultative Meetings. Thus there are existing mechanisms for interagency cooperation, and indeed there are many good examples of where this is done effectively (see Chapter 2). All three of the recommended priority initiatives present new opportunities for interagency cooperation, and our community engagement participants repeatedly raised calls for improving and expanding such cooperative efforts. Some particular research areas frequently emphasized include:

- Collaboration with NASA in Antarctic radar mapping exercises, and in the Long Duration Balloon Program;
- Collaboration with NOAA in expanding meteorological observations and atmospheric studies and in fisheries-related Southern Ocean monitoring.
- Collaboration with DOE and other agencies, as well as interagency programs such as U.S. CLIVAR, to improve representation of Antarctic and Southern Ocean processes in earth system models, and to advance understanding of how polar processes can affect mid-latitude/tropical variability and global climate change.

It is beyond the scope of this study to recommend new mechanisms for interagency engagement, but it is worth noting the model used in Arctic research, with the Interagency Arctic Research Policy Committee (IARPC). Consisting of principals from 16 agencies, departments, and offices across the federal government, and operating under the auspices of the White House National Science and Technology Council, IARPC provides a platform for sharing information and developing interagency research plans, which has helped to ensure better coordination and effective leveraging of resources among the agencies. While recognizing the very different political context of the U.S. Antarctic Program, it may be worth considering the possible strategic benefits of having an IARPC-like forum for Antarctic and Southern Ocean research.

International Cooperation

Our community engagement participants also frequently stressed the need for expanding international collaboration, to help alleviate the difficulties and costs of Antarctic research, and to expand opportunities for research well beyond the confines of any one nation's facilities and logistic reach. These opportunities cut across a wide array of research areas, encompassing, for instance, model intercomparison studies; joint research cruises; terrestrial and marine biological sampling efforts; ice core, marine sediment, and geological drilling; astronomy and astrophysics projects; subglacial lakes explorations; and aerogeophysical, bathymetric, and seismic mapping exercises. Collaborative opportunities also extend to aircraft, weather observing networks, and other aspects of deep-field support infrastructure. SCAR and COMNAP will continue to provide critically important platforms for NSF for building and sustaining this international cooperation.

In light of the concerns expressed earlier about ensuring adequate support from polar research vessels and icebreakers, it is worth stressing in particular the need to improve cooperation across research vessels working in the Southern Ocean. This could greatly advance critical data collection such as routine collection of underway meteorological and oceanographic data; seafloor mapping; deployments of floats, gliders, and drifters, and deployment/recovery of moorings installed along regular transit routes. The proposed *Changing Ice Initiative* provides a valuable opportunity for NSF to both benefit from and contribute to observations planned by international programs such as SOOS and CLIVAR.

DATA MANAGEMENT

Formalized, coordinated, professional data stewardship is necessary to achieve the integrative goals of the USAP and to address the specific recommendations of this report. It was clear from the community input received that researchers demand finer-scale and more-real-time data as well as more open and coordinated data collection and sharing, more consistent time series, and better use of existing data. The community is also taking an increasingly systems-oriented view to research problems, which requires more integration of data across nations, disciplines, and data types. NSF/PLR has already made significant strides in this area and is well positioned to help the community sustain and develop necessary data services for integrative science.

Several recent reports have provided solid advice on NSF's role in supporting data stewardship. The report on *Critical Infrastructure for Ocean Research and Societal Needs* *in 2030* (NRC, 2011b) provides an excellent summary of sound data management practices; Baker and Chandler (2008) also describe a useful information management strategy. A workshop report on *Cyberinfrastructure for Polar Science* (Pundsack et al., 2013) provides a compelling vision of "Data as a Service," including on-demand data sharing, discovery, access, and delivery through standard protocols. The 2013 NSF/PLR Committee of Visitors report emphasizes the need to proactively address long-term archiving and ensuring active data management planning.

The International Polar Year provided valuable experience with interdisciplinary and international data policy, coordination, and stewardship; lessons and recommendations are highlighted in numerous reports and are summarized by Parsons et al. (2011a,b) and Mokrane and Parsons (2014). All of these reports emphasize the need to involve data scientists directly in the science early and throughout the process at all levels (senior planning to field and lab support). This means funding data science as an integral part of the scientific effort, training data scientists, training researchers in data science, and supporting an underlying international data stewardship infrastructure.

The Blue Ribbon Panel report (BRP, 2012) discussed communication and information technology needs of Antarctic research, highlighting the lack of a capital budget for USAP as a root of many inefficiencies in supporting these and other research infrastructure needs. Data should be viewed similarly—as a valuable capital asset that requires initial investment and ongoing maintenance. Failure to do so results in large inefficiencies because each investigator must spend undue time and effort finding and preparing data for their application.

Research infrastructure is more than physical assets and technologies; rather it encompasses a complex body of relationships connecting people, machines, and institutions (Edwards et al., 2007). NSF needs to foster these relationships by encouraging interdisciplinary and international collaboration and by linking scientific research with modern e-science tools and methods (cf. Assante et al., 2015; Mattmann, 2013). Data are often at the boundary of these relationships—be it a collaboration between scientists from different disciplines, integration of an algorithm with a scientific instrument, or assimilation of an observation into a model. As such, it is vital not only to support data as a valuable asset, but also to support the people—the curators and data scientists who act as mediators and add value to the data.

This emphasis on data curation is especially critical in Antarctic and Southern Ocean research because so much of the data are what the National Science Board (NSB, 2005) describes as "research collections," that is, custom datasets collected by individual investigators and research teams. As opposed to community or reference collections, research collections are the most diverse, least standardized, and least accessible type of data; and they are generally at the greatest risk of loss (Heidorn, 2008). These issues can be substantially mitigated by including curators or "data wranglers" in the planning and collection of the data from the outset (Parsons et al., 2004).

Antarctic and Southern Ocean research is increasingly interdisciplinary: improving the interoperability among disciplinary datasets requires bringing researchers and data scientists together to address specific research problems (Benedict et al., 2007). There is a need for increased standardization of data formats, descriptions, and collection protocols, along with a need for communities to better use the standards that currently exist. Disciplinary communities need to work together to create or use standards that are best for them (see, e.g., work done by the in situ sea ice observation community in Fetterer [2009]), while also working with international organizations such as SCAR to ensure that their work is broadly relevant and not duplicative or contradictory to other efforts.

There is a long history of international collaboration within the Antarctic research community, for instance, under the Antarctic Treaty and through mechanisms such as SCAR and its Standing Committee on Antarctic Data Management. But data scientists within Antarctic research must also engage in broader-based data-sharing efforts such as the Research Data Alliance and the World Data System, as well as disciplinary-specific efforts such as the International Oceanographic Data Exchange and the Global Biodiversity Information Facility. Although challenging, it is essential for data scientists to operate at local, regional, and international scales simultaneously (Khondker, 2004). Pundsack et al. (2013) suggest some specific mechanisms to advance these efforts.

The Antarctic and Arctic Data Consortium[1] is an encouraging development, but financial incentives and long-term strategies are needed to overcome the current competitive atmosphere across U.S. polar data management institutions. It is also important to build on the community-led Polar Data Coordination Network effort (Pulsifer et al., 2014). The Antarctic data landscape is evolving quickly and requires innovative, adaptive solutions to accommodate and achieve flexible collaboration among domain-specific data communities. Southern Ocean observing systems are in a more nascent state, with SOOS providing a plan, but with the OOI Southern Ocean and Argentine Basin observatories and the SOCCOM program now collecting substantial new datasets. It would thus be timely for NSF to formulate plans for Southern Ocean as well as Antarctic data management.

These are data stewardship challenges facing almost all fields of research. NSF/PLR cannot address all of these challenges alone or immediately, but there are several key

[1] http://www.a2dc.org.

steps such as those listed below that could improve NSF/PLR's efforts to realize its scientific objectives:

- ***Plan for and archive what is collected.*** None of the priority science recommended in this report can be done well or efficiently if the underlying data are not preserved and accessible. Ensuring the preservation and accessibility of valuable data collected thus needs to be a top priority of NSF's Antarctic research program. This means that not only do individual proposals need a data management plan, but PLR overall needs a data management plan, including a long-term (7+ years) archive funding strategy. An effective strategy would be for every PLR/ANT program to identify (and, if necessary, fund) relevant archives to manage and preserve the data collected as part of that program, and for all proposal data management plans to identify a funded archive willing to accept the data generated as part of the project (with demonstration of safe archiving of past data as a prerequisite for continued funding).

  This may include specific NSF-funded Antarctic data archives such as the Antarctic Glaciological Data Center, the Polar Rock Repository, and others in A2DC, or disciplinary archives that reach beyond the poles (e.g., the Biological and Chemical Oceanography Data Management Office). They need not be NSF-funded archives, but financial support for handling the data must be explicit, and ideally would be funded through cooperative agreements with periodic community review (with memoranda of understanding drafted as needed to formally clarify expectations).

  The EarthCube Council on Data Facilities could coordinate some of this activity. The USAP Data Center at Columbia University currently provides a valuable service in helping the community identify appropriate archives, but likely cannot steward all data from all disciplines currently without an archive. NSF/PLR needs a long-term archiving strategy developed in conjunction with other agencies. All data need not be archived or managed with the same level of service, but all must be considered in the strategy. Funders have an important role in the development of evolving archive certification criteria (see, e.g., Callaghan et al., 2014).

- ***Support data science and curation as an integral component of research.*** Having every funded project identify and support professional data scientists or curators (not necessarily full time) to ensure data are preserved and reusable should not be seen simply as an additional cost, but as an investment in efficiency. Data management must be embedded in the planning and execution of any research project, as an ongoing effort, not only in a one-off data management plan. It is best if projects include data professionals in the field and in the actual collection of data, and have someone charged with continually thinking of how the data may be reused beyond their original application.

- ***Support targeted data/cyberinfrastructure initiatives that explicitly advance polar science in a global context.*** NSF/PLR's cyberinfrastructure (CI) program needs to develop those elements of CI that uniquely benefit Antarctic research, while also working within larger NSF initiatives such as EarthCube and the Research Data Alliance. CI programs can support projects that address concrete Antarctic science needs while also advancing data access, interoperability, or reuse in a broader context (avoiding "one-size-fits-all" solutions).
- ***Require and support collaboration at all levels, but do not define the nature of collaboration.*** We encourage projects that collaborate across disciplinary and national boundaries, and that demonstrate collaboration with relevant national, regional, and international data initiatives such as EarthCube and the Research Data Alliance. But rather than requiring projects to collaborate in particular ways or with particular initiatives, it is better to pursue a grassroots-style approach that helps ensure that collaboration occurs in areas where the community actually sees a need. Small amounts of seed funding (e.g., to support the salary and travel necessary to facilitate collaboration) can do much to motivate enthusiastic volunteers. The key is to focus on supporting initiatives that have strong community commitment and leadership, rather than top-down mandates.

Recommendation: NSF should pursue the following steps to ensure preservation and accessibility of the valuable data collected under the U.S. Antarctic Program: Identify specific archives to manage and preserve data collected in all the core programs; encourage all funded projects to include personnel specifically trained to address data management needs throughout a project's planning and execution; and work to both advance Antarctic-specific data management activities and advance cooperation with broader NSF-wide, national, and international data management initiatives.

EDUCATION AND PUBLIC OUTREACH

The integration of scientific research and education is essential to NSF's central mission. In 2012, the President's Council of Advisors on Science and Technology projected a shortfall of 1 million students over the next decade who will graduate in science, technology, engineering, and mathematics (STEM) fields. Fewer than 40 percent of all college students who intend to major in a STEM field complete a STEM degree. One of the major reasons cited by students who leave STEM fields is uninspiring introductory courses, in which the culmination of repetitive, standard problems and routine laboratory sessions have left little room for discovery. On the other hand, retention in STEM fields improves when standard laboratory courses are replaced with discovery-based research courses (PCAST, 2012).

Given the broad allure of Antarctica and the Southern Ocean in providing opportunities for discovery and delivering a one-of-a-kind platform for interdisciplinary research, this science represents an enticing but underutilized element in the K-12 and undergraduate curricula. It remains largely untapped as a resource for attracting students to STEM disciplines in higher education and career pathways. Just as the space program sparked national interest in STEM fields in the last century, well-placed studies of Antarctic science in K-12 and undergraduate curricula could help attract and retain future generations of STEM students. NSF/PLR thus has a unique opportunity to cultivate the next generation of Antarctic specialists and to help the nation build a strong STEM workforce more generally.

A considerable barrier to broad incorporation of Antarctic and Southern Ocean science in STEM courses however, is that most faculty (beyond polar researchers themselves) lack sufficient experience and familiarity with datasets and research findings that make the Polar sciences relevant to standard K-12 and undergraduate courses of study. NSF could have a major impact in overcoming this shortcoming through targeted support that encourages incorporation of Antarctic topics in curricular development across the disciplines.

The development of the next generation of researchers does not end with undergraduate education. There must be defined pathways that could lead to further research and educational opportunities for graduate students and postdoctoral researchers, as well as developmental opportunities in teaching and research for early-career Antarctic scholars. Given the swift pace at which Antarctic and Southern Ocean research develops, and the rapid advancements required in technological innovations, the next generation of Antarctic scholars will need to be especially competent in integrating new technologies with interdisciplinary research. This will require an ongoing effort to engage a wide range of talented students in Antarctic science. The priority research initiatives recommended in this report may offer excellent opportunities for entraining and mentoring early-career scientists across a large array of disciplines.

In times of flat budgets and rising costs for logistical support of field work, there are always temptations to pursue immediate cost-saving measures such as reductions in the number of graduate and undergraduate participants in field programs, and decreases in funding opportunities for postdoctoral researchers and early-career scholars. NSF must remain wary of the pitfalls such measures can present, in terms of potentially decreasing the number and quality of next-generation Antarctic and Southern Ocean scientists.

In addition to these important opportunities for expanding Antarctic science and training in formal K-12, undergraduate, and graduate education, NSF has a unique role to play in supporting the development and dissemination of high-quality education and public outreach materials to a wide array of "informal" educational institutions, including libraries, museums, zoos, aquariums, youth organizations, educational radio programs, parks, nongovernmental organizations and private corporations—all of which help advance the goals of creating an informed, scientifically literate public, and informed decision makers and policy makers at all levels of government. (see Box 4.7).

BOX 4.7
IceCube Education and Public Outreach Efforts

The IceCube Neutrino Observatory offers a good example of a project that developed a wide array of education and outreach efforts, for instance:

- **Reaching motivated high school students and teachers through IceCube "Masterclasses."** The 2014 pilot IceCube Masterclass had 100 participating students at five institutions. Students met researchers, learned about IceCube hardware, software, and science, and reproduced the analysis that led to the discovery of the first high-energy astrophysical neutrinos. Ten institutions are participating in the 2015 Masterclass.
- **Providing intensive research experiences for teachers and undergraduate students.** PolarTREC teacher Armando Caussade, who deployed to the South Pole with IceCube in January 2015, kept journals and did webcasts in English and Spanish. Support from the NSF *International Research Experiences for Students* program enabled 18 U.S. undergraduates to have a 10-week research experience working with European IceCube collaborators. Support from the NSF *Research Experiences for Undergraduates* program is allowing 18 more students to do astrophysics research over the next three summers. At least one-third of the participants for both programs are from 2-year colleges and/or from underrepresented groups.
- **Supporting IceCube communication through social media, science news, web resources, webcasts, print materials, and museum programs and displays (Figure 4.2).**

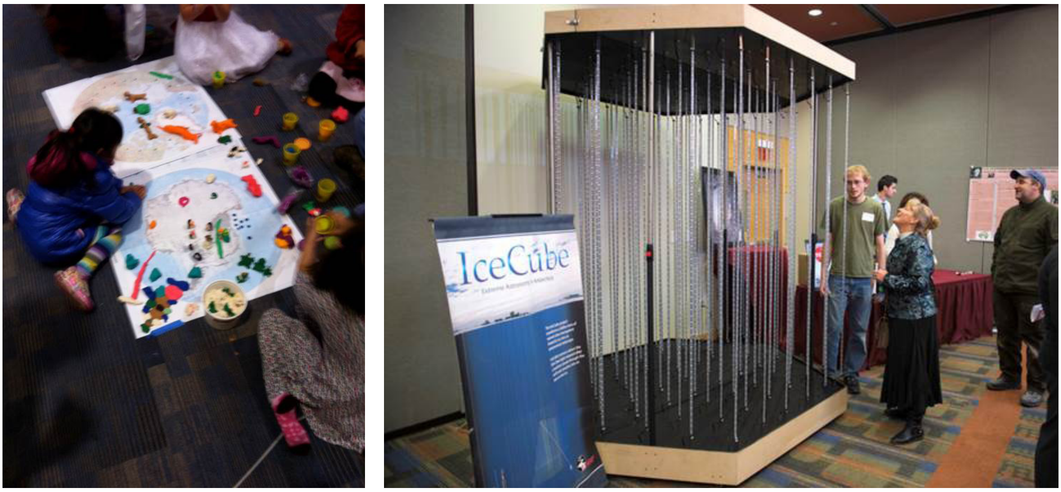


FIGURE 4.2 Left: AGU 2013 exploration station.SOURCE: Polar Educators International, http://polareducator.org/. Right: IceCube education display. SOURCE: James Madsen.

Misconceptions about Antarctica abound in the public, for instance, regarding the belief that polar bears co-exist with penguins, regarding the ways in which Antarctica affects and is affected by climate change, and even regarding the location of the continent itself. The protection and preservation of Antarctica will depend on how people value and revere this continent as a "place." Societies work hard to protect places they feel connected to, but given its remoteness and inaccessibility, it is difficult for much of the general public to feel a sense of connection to Antarctica.

Education and public outreach efforts can provide powerful, engaging experiences that help people feel this sense of connection—a critical foundation for making the public aware of the essential need for continuing research in Antarctica and its role in broader Earth systems that ultimately affect everyone's lives. Making these connections is also critical for ensuring that wise and thoughtful decisions will be made about Antarctica's future. Emphasizing the mystery and uniqueness of Antarctica (for instance, through stories about new discoveries) is a powerful tool to engage people in learning activities and experiences, and ultimately to increase the public's support for protection and continued support of research in Antarctica.

In the community outreach efforts for this study, and in discussions among the Committee members themselves, numerous suggestions were raised for how NSF/PLR can best contribute to these formal and informal educational goals, working with other parts of NSF, and other federal agency and nongovernmental organization partners. For instance, for meeting the education and public outreach goals discussed above, potential steps include:

- Developing a "council" of scientists and educators at the forefront of research and teaching, who could provide guidance in leveraging and implementing Antarctic and Southern Ocean science into STEM curricula and education and public outreach materials;
- Developing programs that leverage NSF funding with other governmental, private, and philanthropic foundations whose shared goal is also to increase STEM education and public literacy;
- Continuing support for "Antarctic Clearinghouse" websites where education providers and the public can find curriculum, resources, media releases, researcher webpages, journal articles, videos, photos, and more (e.g., the Polar Hub[2] and PolarTREC[3] websites);
- Promoting and disseminating Antarctic research by engaging educators in new data and findings and stories that convey the excitement of new learning as it develops;
- Developing materials for K-12 classrooms (especially material that can contribute to Next Generation Science Standards related to earth science and global climate change[4]), and ensuring that these materials are easily accessible to learners, in terms of practical access and appropriate readability of diagrams, charts, graphs, pictures, and text;
- Encouraging and supporting Antarctic and Southern Ocean research teams to include efforts and personnel to develop quality educational materials that connect the public to their research (including the successful PolarTREC model of involvement); and
- Prioritizing the widespread dissemination and coordination of education and public outreach efforts by Antarctic research teams.

For meeting the career development goals discussed above, potential steps include:

- Promoting international collaboration and institutional exchange for graduate students and postdoctoral scholars in Antarctic science, especially for field research at other countries' national bases;

[2] http://thepolarhub.org/.
[3] http://www.polartrec.org.
[4] http://www.nextgenscience.org.

- Encouraging further development of NSF's research experiences for undergraduates, graduates, postdocs, and educators through targeted funding opportunities;
- Developing and highlighting career pathways in Antarctic science though workshops and events designed for undergraduate and graduate students, postdoctoral scholars, early-career scientists, and educators. (Such efforts could be led by the Association of Polar Early Career Scientists and Polar Educators International.)
- Increasing effort to expand diversity in polar research by outreach to minority-serving institutions that are currently not well integrated into the mix of academic institutions in polar research, and organizations such as the Society for Advancement of Hispanics/Chicanos and Native Americans in Science, Society of Black Engineers, Society of Hispanic Engineers, and Society of Women Engineers.
- Expanded development of CAREER grants to early polar scientists (e.g., assistant professor level), which can help fill a gap between postdoctoral fellowships and award of full proposals to more-established mid-career scientists.

CONCLUDING THOUGHTS

As the discussions throughout this report illustrate, NSF support for Antarctic and Southern Ocean research is vital for advancing the frontiers of human knowledge across many disciplines, for developing new insights about the workings of the planet, and for informing critical choices about how society might respond to major environmental changes over time. Although there is an endless reservoir of exciting questions that Antarctic and Southern Ocean research could potentially address, in the face of limited budgets for research and logistical support, the need for prioritization in allocating resources is real.

Here we have recommended a strategic vision for NSF's Antarctic and Southern Ocean research program for the coming decade. It includes continued support for a wide array of basic, curiosity-inspired research across the existing core programs. And it includes three major areas of research that, in the Committee's view, should rank as high priorities for investment over the coming decade. These are research directions that we believe will offer a large payoff of new fundamental understanding about the past, present, and possible future evolution of three very different systems—of the massive West Antarctic Ice Sheet that may drive global sea level rise, of the unique biota that survive in Antarctica's extreme environment, and of the very universe that envelops us all. And finally, this strategic vision includes a set of foundational elements that enable and provide lasting value to the entire spectrum of scientific research (see Figure 4.3).

We hope the ideas raised here, which were richly informed and inspired by the input of researchers across the country, will provide a useful basis for helping NSF leadership and staff make wise planning choices for the coming years.

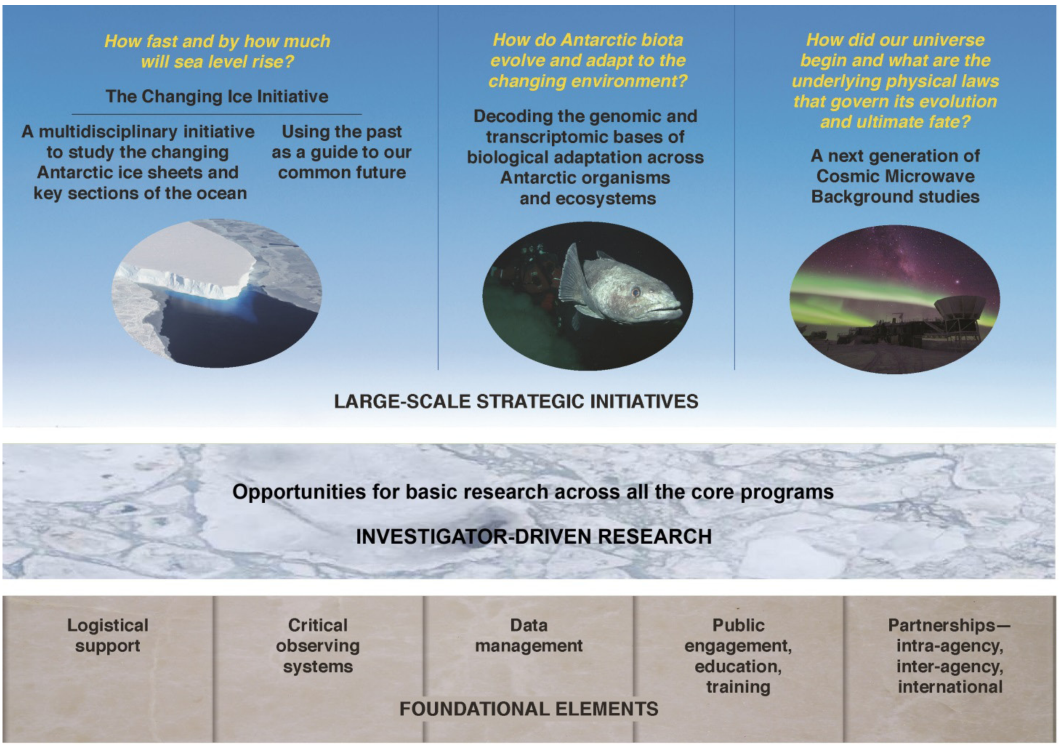


FIGURE 4.3 A schematic illustration of the main components of the Committee's overall strategic vision for NSF's investments in Antarctic and Southern Ocean research.

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APPENDIX A

Committee Member Biosketches

Robin Bell (Co-chair) is Palisades Geophysical Institute/Lamont Research Professor at Columbia University's Lamont-Doherty Earth Observatory. For 20 years, Dr. Bell has worked alongside a team of Lamont-Doherty Earth Observatory scientists and engineers to coordinate nine major aerogeophysical expeditions to Antarctica and Greenland in order to study ice sheet collapse. Her discoveries have included a volcano beneath the West Antarctic Ice Sheet, several large lakes locked beneath 2 miles of ice, and most recently, evidence that the ice sheet can thicken from below. Dr. Bell was a leading proponent of the 2007-2008 International Polar Year and has chaired the National Academy of Sciences Polar Research Board. Her work examines the implications of climate change on the poles and involves adapting scientific instruments to produce imaginative new insights into the Polar regions. Dr. Bell received her Ph.D. in geophysics from Columbia University in 1989. She has been part of the research staff at Columbia University's Lamont-Doherty Earth Observatory since 1989 and is a member of the Earth Institute faculty. Dr. Bell has published over 90 peer-reviewed articles and more than 30 other publications, and continues to pursue new directions in her field to meet the challenges presented by climate change in the polar regions.

Robert Weller (Co-chair) is a senior scientist with the Woods Hole Oceanographic Institution, where he formerly served as director of the National Oceanic and Atmospheric Administration (NOAA) Cooperative Institute for Climate and Ocean Research and past chair of the Physical Oceanography Department. His research focuses on atmospheric forcing, surface waves on the upper ocean, prediction of upper-ocean variability, and the ocean's role in climate. Dr. Weller has been a pioneer in developing tools and technologies that enable scientists to investigate upper-ocean processes on scales from meters to tens of kilometers and with accuracy never before available. Dr. Weller has been on multiple mooring deployment cruises and has practical experience with ocean observation instruments. He served as co-chair of the U.S. Climate Variability and Change (CLIVAR) Scientific Steering Group and as a member of the international CLIVAR Scientific Steering Group. He serves on the World Meteorological Organization/Intergovernmental Oceanographic Commission international Ocean Observing Panel for Climate and the NOAA Climate Observing System Council and Climate Working Group. He co-chairs OceanSITES, an action group under the international Joint Commission on Oceanography and Marine Meteorology that works to advocate and coordinate sustained time-series observations in the global ocean. He has served on several NRC committees, including the Committee to Review the U.S. Climate Change Science Program Strategic Plan, the Committee on Implementation of a Seafloor Observatory Network for Oceanographic Research, the Committee on Utilization of Environmental Satellite Data, and the Board on Atmospheric Sciences and Climate; and he chaired the NRC committee on the Assessment of Intraseasonal to Interannual Climate Prediction and Predictability. Weller received his Ph.D. in physical oceanography from Scripps Institution of Oceanography.

David Bromwich is a senior research scientist and director of the Polar Meteorology Group at the Byrd Polar & Climate 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 role of the Antarctic and Arctic in the global climate system using observations and modeling, and the contribution of Antarctic and Greenland ice sheets to global sea level change. 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 (SCAR); currently he is chief officer of the SCAR Standing Scientific Group on Physical Sciences. 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 also recently served on the NRC Polar Research Board and on the Committee for Future Science Opportunities in Antarctica and the Southern Ocean. 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.

John Carlstrom (NAS) is the Subrahmanyan Chandrasekhar Distinguished Service Professor at the University of Chicago with the Kavli Institute for Cosmological Physics, 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 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 that advises NSF, NASA, and 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. He recently served on the NRC Committee for Future Science Opportunities in Antarctica and the Southern Ocean.

Chi-Hing Christina Cheng is a professor in the Department of Animal Biology/School of Integrative Biology at the University of Illinois at Urbana-Champaign. She is an animal physiologist and molecular evolutionary biologist who studies the unique ability of polar teleost fish to survive and thrive in extreme icy cold. To fully address the linkage between environmental selection and evolutionary response and adaptation, her work integrates past and present polar thermal histories, species evolutionary history, organismal physiology, protein structure-function, molecular evolution, and transcriptomic and whole-genome sequence analyses. Through the NSF Division of Polar Programs, Dr. Cheng and her team have conducted studies on Antarctic fishes at McMurdo Station and Palmer Station for over two decades. She served on the NSF Polar Programs Advisory Committee from 2012 to 2014. In 2012, Dr. Cheng was selected as an American Association for the Advancement of Science fellow for her distinguished contributions to the field of molecular evolution, focusing on molecular mechanisms that lead to the creation of novel genes and adaptive protein functions under environmental extremes. Dr. Cheng received her Ph.D. from the University of Illinois at Urbana-Champaign.

C. Robert Clauer is a professor in the Department of Electrical and Computer Engineering and director of the Magnetospheric Ionospheric Science Team at Virginia Tech. Previously, he was a research professor at the University of Michigan Department of Atmospheric, Oceanic, and Space Sciences, where he led the development of a new generation of high-performance, three-dimensional magnetohydrodynamics codes to perform simulations of the space environment from the solar surface to the Earth's upper atmosphere. His research interests include experimental and theoretical investigations of the electrodynamic coupling between the solar wind, magnetosphere, and ionosphere using global arrays of ground-based and satellite-based instruments, utilization of computer networks to form knowledge networks in the support of scientific and educational activities, and experimental and theoretical investigations of the geomagnetic storm time ring current. Dr. Clauer has over two decades of research activity in the areas of solar–terrestrial relationships, solar wind–magnetosphere–ionosphere coupling, storm and substorm phenomenology, and magnetospheric electrodynamics. He pioneered the development and operation of autonomous environmental monitoring platforms in remote regions of the Arctic and Antarctic. He served on the National Research Council's Polar Research Board from 2005 to 2008. Dr. Clauer received his Ph.D. in geophysics and space physics from the University of California, Los Angeles.

Craig Dorman attended Dartmouth College on a Navy scholarship and remained in naval service until he retired as Rear Admiral in 1989. His naval career was equally divided between operational tours and command in Naval Special Warfare (UDT/SEAL teams) and management of oceanographic and antisubmarine warfare research and development programs from Washington, DC. After leaving the Navy, he served as director of the Woods Hole Oceanographic Institution (WHOI) until 1993. He then became deputy director, Defense Research and Engineering for Laboratory Management, and then moved to London as chief scientist and technical director of the Office of Naval Research's International Field Office from 1995 to 1997. While in London, he held an appointment as visiting professor at Imperial College. He returned to Washington to serve as special assistant and then chief scientist at the Office of Naval Research from 1998 through 2001. In 2002, he began service as vice president for research for the University of Alaska Statewide System, and in 2003 added responsibility for academic affairs. Dr. Dorman retired from the University of Alaska in 2007. He has served on boards of both industry and academic institutions and directed studies and reviews for the National Research Council, the National Oceanic and Atmospheric Administration, the National Science Foundation, and the Smithsonian Institution. He recently served as a member of the Blue Ribbon Panel that produced the report *More and Better Science in Antarctica Through Increased Logistical Effectiveness*. He received a Ph.D. in physical oceanography from the Massachusetts Institute of Technology-WHOI joint program in 1972.

Robert Dunbar is the William M. Keck Professor of Earth Sciences at Stanford University. Dr. Dunbar was the founding director of the Interdisciplinary Graduate Program in Environment and Resources. He directed the Stanford Earth Systems program for 9 years. He is also the first J. Frederick and Elisabeth B. Weintz University Fellow in Undergraduate Education and a senior fellow of Stanford Woods Institute for the Environment. He serves on the Board of Trustees of the U.S. Consortium for Ocean Leadership, where he is now chairman of the board. Dr. Dunbar's research interests link climate dynamics, marine science, and environmental policy and solutions. His research group works on topics related to global environmental change, with a focus on the hydrological cycle, air–sea interactions, tropical ecosystems and polar biogeochemistry, and glacial history. His lab participated in the ANDRILL program as shore-based and field-based scientists exploring the history of Antarctic climate at Windless Bight (McMurdo Ice Shelf Drilling) and Southern McMurdo Sound. He was also a participant on the recently completed International Ocean Discovery Program Expedition 318 to Wilkes Land, Antarctica. Dr. Dunbar received his Ph.D. in oceanography from the Scripps Institution of Oceanography, University of California, San Diego.

David Marchant is a professor at Boston University and chair of the Department of Earth and Environment. In 2014, was appointed a Howard Hughes Medical Institute Professorship for his Antarctic research and novel teaching program. Professor Marchant's research focuses on long-term landscape evolution and process geomorphology, specifically on Antarctic glaciation and climate change, and by extension climate change and ice ages on Mars. He has led 25 expeditions to the Transantarctic Mountains and combines results of field mapping with cosmogenic-nuclide analyses, argon–argon dating, and numerical process modeling. Several discoveries by Marchant and his team include the development of one of the longest terrestrial records for East Antarctic Ice Sheet glaciation in the Transantarctic Mountains; the elucidation of long-term climate change and extinction of tundra ecosystems from the central Transantarctic Mountains; and the discovery and analysis of ancient buried ice. Dr. Marchant has authored more than 90 peer-reviewed publications, is a member of the Geological Society of America and the American Geophysical Union, and serves as chair of the Science Operations Committee for the U.S. Polar Geospatial Center. For his research and teaching efforts he received Boston University's highest teaching award, the Metcalf Award, and from the Royal Geographical Society the prestigious W. S. Bruce Medal for outstanding contributions to the field of earth science, especially in relation to the East Antarctic Ice Sheet. He earned his Ph.D. in geomorphology from the University of Edinburgh, Scotland.

Mark Parsons is the managing director of the U.S. component of the Research Data Alliance and the Rensselaer Center for the Digital Society. He focuses on stewarding research data and making them more accessible and useful across different ways of knowing. He has been leading major data stewardship efforts for more than 20 years, and received the American Geophysical Union Charles S. Falkenberg Award as an advocate of robust data stewardship as a vital component of earth system science and as an important profession in its own right. Prior to joining Rensselaer, Parsons was a senior associate scientist and the lead project manager at the National Snow and Ice Data Center (NSIDC). While at NSIDC, he defined and implemented their overall data management process and led the data management effort for the International Council for Science/World Meteorological Organization International Polar Year 2007-2008. He is currently active on several international committees while helping lead the Research Data Alliance in its goal of accelerating innovation through data exchange. His research interests include the role of scientific social interaction in the success, development, and extension of data-sharing networks.

Jean Pennycook is an educator and researcher who studies Adélie penguins in Antarctica and educates others about what her science team is learning about the penguins. She has 12 seasons of science research and education outreach experience with Antarctic projects and has worked hard to engage the public and K-12 community with the science, wonder, and stewardship of this region, as well as promoting career and educational opportunities in the science, technology, engineering, and math (STEM) pathways. She recently completed a 2-year appointment with the NSF on an Albert Einstein Distinguished Educator Fellowship. She has spent over 20 years in a multicultural, multilingual urban school district in Fresno, California, as a secondary school science teacher providing curriculum and classroom experiences in biology, earth science, physical science, chemistry, and environmental studies. Her many awards and accomplishments as an educator include: NASA teacher grants, Sierra Club Environmental Educator of the Year, NSF Teachers Experiencing Antarctica award, and district- and state-level committees and boards. She has been nationally recognized as she translates and repackages the science research of Antarctica for classrooms around the world. Her focus on Adélie penguins makes the excitement of discovery available to all through an interactive website. She holds a B.S. in wildlife fisheries biology from the University of California, Davis, and an M.S. in science education and curriculum from California State University.

A. R. Ravishankara (NAS) is a professor in the Department of Chemistry and Atmospheric Science at Colorado State University. Previously he served as director of the Chemical Sciences Division of the NOAA Earth System Research Laboratory, and assistant professor of chemistry at the University of Colorado, Boulder. Dr. Ravishankara's research has contributed fundamental studies of the gas-phase and surface chemistry of Earth's atmosphere, and has advanced the understanding of basic chemical processes and reaction rates related to ozone-layer depletion, climate change, and air pollution. For example, his results have led to a better understanding of the chemistry that causes the Antarctic ozone hole, identified new processes that affect ozone pollution in the lower atmosphere, and elucidated the role of aerosols and clouds in climate. Dr. Ravishankara has played leading roles in national and international reports assessing the state-of-the-science understanding of ozone-layer depletion and other issues. He is a co-chair of the Scientific Assessment Panel of the U.N. Montreal Protocol that protects the stratospheric ozone layer. He is a member of the U.S. National Academy of Sciences. His awards include his election as a fellow of the American Geophysical Union, fellow of the American Association for the Advancement of Science, fellow of the United Kingdom Royal Society of Chemistry, recipient of the Polanyi Medal and Centenary lectureship of the Royal Society of Chemistry, the U.S. Environmental Protection Agency's Stratospheric Ozone Protection Award, the Department of Commerce Silver Medal, and the U.S. Presidential Rank Award. He has authored or coauthored over 300 scientific publications. Dr. Ravishankara received his Ph.D. in physical chemistry from the University of Florida.

Ted Scambos is lead scientist, senior research scientist at University of Colorado's National Snow and Ice Data Center. His main area of research is in using remote sensing and field work to understand climate change effects and glaciological processes at the Earth's poles, particularly in Antarctica. He has conducted field research in the Antarctic Peninsula, Siple Coast, Dry Valleys, and the East Antarctic Plateau on 16 separate deployments to Antarctica. Dr. Scambos' field expeditions have been focused on a number of geophysical measurements, such as ice-penetrating-radar profiles; site surveys for ice coring; GPS installations for ice motion, isostatic rebound, and ice-shelf changes; gravimetry; and recently, the installation of automated multisensor systems in key ice–ocean–climate change sites. His field work collaborations have included the Australian, British, Norwegian, Korean, and Argentine Antarctic research programs. He has made extensive use of satellite data as well, for example, from the ICESat altimeter and the Landsat satellite series as a member of the Landsat Science Team. These satellite-based methods, along with the field data, have been applied to key cryospheric problems in NSF- and NASA-funded research grants spanning 20 years. Dr. Scambos received his Ph.D. in geoscience from the University of Colorado, Boulder in 1991.

Oscar M. E. Schofield is a professor of biological oceanography and chair of the Department of Marine Sciences at Rutgers, The State University of New Jersey. He is interested in how plankton dynamics structure marine food webs and feed back on the ocean's biogeochemistry. His research focus has combined genetics and biochemistry with the development of new ocean observing technologies (satellites, radars, and autonomous underwater vehicles). He is co-director and co-founder of the Center of Ocean Observing Leadership (COOL), which has become a technology and research group of 5 faculty and a team of over 20 technicians and students. The COOL group has been awarded and has managed over 50 million dollars in competitive awards from NOAA, the Office of Naval Research, the Department of Homeland Security, NASA, and the National Science Foundation over the last 20 years. Dr. Schofield's research efforts have focused on polar and temperate waters with extensive efforts in the Southern Ocean, with ongoing research along the West Antarctic Peninsula and the Ross and Amundsen seas. The group has also focused on integrating the research into innovative education and outreach efforts spanning K-12 to undergraduate students and the general public. He currently serves as the co-chair for the international Southern Ocean Observing System (SOOS) initiative.

Jeffrey Severinghaus (NAS) is professor of geosciences at the Scripps Institution of Oceanography, University of California, San Diego. He received his Ph.D. from Columbia University's Lamont-Doherty Earth Observatory in 1995, in isotope geochemistry. He also received a master's degree in geological sciences from the University of California, Santa Barbara. He is an environmental geochemist working on gases trapped in ice cores, to reconstruct past variations in atmospheric composition and climate. His research often takes him to Antarctica and Greenland, where he has participated in the West Antarctic Ice Sheet Divide (WAIS Divide) and North Eem (NEEM) ice core projects. He is a member of the WAIS Divide Executive Committee, the NEEM Steering Committee, and the International Partnerships in Ice Core Sciences Steering Committee, and is co-chair of the Oldest Ice project. Dr. Severinghaus is the author of 72 refereed publications, and is the 2011 Claire C. Patterson Medalist for environmental geochemistry. In 2012, he was elected a fellow of the American Association for the Advancement of Science (AAAS), and in 2013 a fellow of the American Geophysical Union. He is a member of the American Geophysical Union, the Geochemical Society, the European Geosciences Union, Sigma Xi, and the AAAS.

William Schlesinger (NAS) is president of the Cary Institute of Ecosystem Studies. Before coming to the institute, he served in a dual capacity at Duke University, as both the James B. Duke Professor of Biogeochemistry and dean of the Nicholas School of the Environment and Earth Sciences. He has been investigating the link between environmental chemistry and global climate change for over 30 years. His recent work focuses on understanding how trees and soil influence atmospheric carbon dioxide levels. He is the author or coauthor of over 200 scientific papers on subjects of environmental chemistry and global change and the widely adopted textbook *Biogeochemistry: An Analysis of Global Change.* Dr. Schlesinger was among the first to quantify the amount of carbon held in soil organic matter globally, providing subsequent estimates of the role of soils and human impacts on forests and soils in global climate change. He was elected a member of the National Academy of Sciences in 2003, and was president of the Ecological Society of America for 2003-2004. He is also a fellow in the American Academy of Arts and Sciences, the American Geophysical Union, the Soil Science Society of America, and the American Association for the Advancement of Science. His past work has taken him to diverse habitats, including three times as a Duke alumni tour guide to Antarctica. His research has been featured on NOVA, CNN, NPR, and on the pages of *Discover, National Geographic,* the *New York Times,* and *Scientific American.*

Cristina Takacs-Vesbach is an associate professor in the Department of Biology at the University of New Mexico. Dr. Takacs-Vesbach conducted her graduate work in microbial ecology and performed research on the factors affecting bacterioplankton distribution and productivity in the lakes of the McMurdo Dry Valleys, Antarctica. Her postdoctoral work focused on the microbial phylogenetic and physiological diversity of hydrothermal springs. Her current research focuses on microbial diversity and productivity in the McMurdo Dry Valleys ecosystem. Her National Research Council experience includes service on the Committee on Preventing the Forward Contamination of Mars, the Planning Committee for the International Polar Year, and the Committee on the Origins and Evolution of Life. She received her Ph.D. in microbial ecology from Montana State University.

APPENDIX B

Statement of Task

The Committee will identify priorities and strategic steps forward for Antarctic research and observations for the next decade, in the context of the current state of knowledge, ongoing research activities, and resource availability. The Committee's report will present a compelling research strategy for increased understanding of Antarctica and the Southern Ocean. The report will include the following elements:

1. Building upon the high-level scientific questions identified in NRC (2011a), identify areas of strategic investment in compelling scientific activities that may yield the highest potential reward for Antarctic research over the coming decade. Suggestions will be prioritized based on factors such as: recent or anticipated scientific and technological breakthroughs; opportunities to make progress on vital, yet underdeveloped topics; and foundational research with potential for both short- and long-term benefits.
2. Analyze the research infrastructure needed to address the priority research topics identified in #1.
3. Analyze the current research portfolio of USAP investments with recommendations to achieve the priorities established in #1 and #2.

The final report will articulate a strategic vision commensurate with U.S. national interests in Antarctica and identify a prioritized suite of science questions or topical areas that the USAP should consider. The report will also outline a roadmap through which the vision and these priorities can be met. Recommendations should include guidance on the most effective portfolio of investments to support the research infrastructure and programmatic science necessary to address the most significant priorities, including: assessing trade-offs among options; assessing the impact of new initiatives and/or modification of existing programs on the overall portfolio; and identifying activities that should be considered for phase-out.

APPENDIX C

Overview of Outcomes from the Report: Future Science Opportunities in Antarctica and the Southern Ocean *(NRC, 2011a)*

At the request of the National Science Foundation Office of Polar Programs, in coordination with the Office of Science and Technology Policy and the Office of Management and Budget, the National Research Council convened a committee of experts to identify the major science questions that will drive research in Antarctica and the Southern Ocean over the next 10 to 20 years. The committee suggested eight questions that fall into two broad themes: those related to global change, and those related to fundamental discoveries, described below.

Global change. Over the past century, temperatures on land and in the ocean have started to increase. Sea level is rising, global weather patterns are shifting, and the chemical and biological processes of the planet are changing. The climate and geography of Antarctica are both an important influence on these processes and a unique environment from which to monitor change. The Committee highlighted several areas of science that will be important in future research on how Antarctica and the Southern Ocean affect and are affected by broader global changes.

1. How will Antarctica contribute to changes in global sea level?
2. What is the role of Antarctica and the Southern Ocean in the global climate system?
3. What is the response of Antarctic biota and ecosystems to change?
4. What role has Antarctica played in changing the planet in the past?

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.

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

In addition, the Committee identified several opportunities that could be leveraged to sustain and improve the science program in Antarctica and the Southern Ocean in the coming two decades.

Collaboration. Over the past half-century, collaborations between nations, across disciplinary boundaries, and between public- and private-sector entities, and between scientific and logistics personnel have helped research in Antarctica become a large and successful international scientific enterprise. The International Polar Year, held from 2007 to 2008, demonstrated how successful international collaboration can facilitate research that no nation could complete alone. 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 in energy-supply technology can make scientific research in Antarctica more cost-effective, allowing a greater proportion of funds to be used to support research rather than to establish and maintain infrastructure. For example, most of the energy required to power research stations and field camps and to 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 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.

Education. Antarctica and the Southern Ocean offer great opportunities for inspiring popular interest in science in much the same way as space exploration did in the latter half of the 20th century. The National Science Foundation 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 will not only increase public awareness and understanding of the research taking place in Antarctica, but will help to inspire the future generations of polar scientists. 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 life-long learners, would help engage the next generation of scientists and engineers required to support an economically competitive nation and foster a scientifically literate U.S. public.

Observing network with data integration and scientific modeling. To better predict future conditions, scientists need networks of observing systems that can collect and record data on the ongoing changes in the Antarctic region's atmosphere, ice sheets, oceans, and ecosystems. This network should be able to measure and record ongoing changes to develop an advanced understanding of the drivers of change and to provide inputs for models that will enable the United States to better project and adapt to the global impacts of a changing Antarctic environment. The envisioned observing network shares many characteristics of previous initiatives, such as the Arctic Observing Network or the proposed Pan-Antarctic Observing System. There is also an inherent need for improved sharing of data and information. Improvements in the collection, management, archiving, and exchange of information will allow data to be used for multiple purposes by a variety of stakeholders.

In addition, improvements in scientific models of the Antarctic region are urgently needed to strengthen the simulation and prediction of future 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 the research program and support infrastructure in the Antarctic region, the United States has the opportunity to play a leading role in efforts to develop a large-scale, interdisciplinary observing network and robust earth system models that can accurately simulate the conditions of the Antarctic region.

APPENDIX D

Overview of Outcomes from the Report: More and Better Science in Antarctica Through Increased Logistical Effectiveness *(BRP, 2012)*

This review was co-commissioned by the Directors of the Office of Science and Technology Policy and the National Science Foundation, who called for examination of the logistical capabilities needed to support the science drivers identified in a National Research Council report, *Future Science Opportunities in Antarctica and the Southern Ocean* (NRC, 2011a), and ways to improve the logistical efficiency of U.S. Antarctic Program (USAP) operations. The Blue Ribbon Panel (BRP) that addressed the charge was chaired by Norman Augustine who previously headed the panel that led to the reconstruction of South Pole Station, comprising military and civilian experts in logistics and research management, as well as two scientists from the NRC (2011a) study.[1]

Based on its analysis of the NRC (2011a) report, the BRP considered major logistical drivers for the coming decades to include:

- Extensive at-sea research with a need for near- and under-ice operations,
- Year-round research and likely expansion of major instrumentation and data transmission at the South Pole,
- Focus on climate-related measurements and analysis (including continuity of the LTERs),
- Construction and year-round operation of a comprehensive and automated continent-wide and Southern Ocean observing system, and
- Intensive and widespread deep-field research projects.

[1] NSF's response to the Blue Ribbon Panel report, issued in March 2013, can be found here: http://www.nsf.gov/geo/ plr/usap_special_review/usap_brp/rpt/nsf_brp_response.pdf.

The BRP panel concluded that "substantial cost savings can be realized and more science therefore accomplished, some through rather straightforward operating changes and others requiring initial investment. The latter offer long-term gains that are justified on a discounted cash-flow basis, from safety considerations, or from science returns. The essence of our findings is that the lack of capital budgeting has placed operations at McMurdo, and to a somewhat lesser extent at Palmer Station, in unnecessary jeopardy. . . ."

Given the need for and cost of extensive facility modernization, the BRP closely examined the logistical and scientific factors influencing the choice of McMurdo Station on Ross Island as the primary point of resupply and support for USAP continental operations. As its first of 10 principal recommendations, the panel validated the continued use of McMurdo, Palmer, and South Pole stations as the primary U.S. science and logistics hubs on the continent.

The BRP's other major recommendations called for:

- The need for major facility upgrades at Palmer and McMurdo,
- The establishment of a long-term facilities capital plan and budget,
- Restoration of the U.S. polar ocean fleet to ensure reliable resupply and to support research and national security,
- Adoption of state-of-the-art logistics and transportation support,
- Modernized and expanded communications capabilities,
- Improved energy efficiency,
- Emphasis on fully burdened cost and technological readiness in review of science projects,
- Pursuit of additional opportunities for international cooperation in logistics support as well as science, and
- Review and revision of the documents governing U.S. Antarctic policy and implementing mechanisms.

These 10 principal recommendations were complemented by some 84 "implementing and ancillary actions", the most significant of which can be categorized as follows:

Essential for safety and health and considered mandatory**:**

- At Palmer Station modify or replace the pier, reconstruct the boat ramp, add fire suppression in the workshop, move power generators out of housing and dormitory spaces away from kitchens, and consolidate hazardous materials.
- Modernize the McMurdo clinic and replace compromised warehouse flooring.
- Manage populations (especially at McMurdo) so that currently crowded conditions do not remain a health hazard and morale issue.

- Provide backup power or gravity feed for all fire suppression systems.
- Implement a more comprehensive system of safety inspections and ensure follow-through, and increase emphasis on workplace health and safety through greater use of signage, near-miss reporting, and widespread use of antibacterial liquids.
- Continue to provide basic clothing for safety and health, replace obsolete gear, and reinforce guidance regarding gear required for field and flying.
- Improve planning for complex field operations to ensure adequate contingency, defined risk analysis, and mitigation measures.

Readily implementable without significant financial expenditure, and yielding disproportionately great benefits:

- Establish within the Division of Polar Programs/Division of Antarctic Infrastructure and Logistics a small independent systems engineering/cost analysis group to seek continued opportunities for safety and efficiency.
- Improve workforce professionalism and stability, seek to reduce McMurdo contractor personnel by ~20 percent, and streamline field-camp support force.
- Establish a DARPA-like program to develop enabling technologies for polar research to include automation and robotics for traverse, robotic field stations, and advanced remote sensing systems for use on, under, and above the ice; and expand current deployed automated networks to lead the development of a comprehensive international terrestrial and Southern Ocean observing and prediction network.
- Provide rigid-hulled inflatable boats at Palmer to enhance safety and expand the local research perimeter.
- With the Department of Defense and Air National Guard (ANG), maximize use of C-17s to refocus LC-130 operations on deep-field support, reduce the LC-130 fleet and flying-hour program by 40 percent, and modify an ANG aircraft as a science platform.
- Work with Christchurch International Airport and Lyttleton Port to ensure USAP needs are met as New Zealand develops its new master plans.
- Explore logistic support collaborations with Chile and the UK in the Antarctic Peninsula, and with New Zealand, Italy, and South Korea in the Ross Sea region; and review the U.S./international support balance sheet for equity.
- Utilize the merit review system to ensure justification for continued support of ongoing programs as new science opportunities emerge, and more stringently and formally enforce test, evaluation, and assessment of technological readiness of new equipment and processes.

Significant investment/large payoff, requiring more detailed analysis by NSF:

- Increase the number of traverses for South Pole resupply and field support and incorporate automation, thus releasing the LC-130 fleet for deep-field support.
- At South Pole Station construct a runway capable of supporting wheeled aircraft to enable C-17 operations, and construct a solar-heated vehicle storage building.
- Designate Pegasus Field as a permanent site with appropriate facilities, retain Williams Field for an alternate and LC-130 operations, and discontinue the annual ice runway.
- At McMurdo, consolidate warehousing and storage into a single inside facility, implement a vehicle modernization plan and expand the vehicle maintenance facility, build a single consolidated facilities maintenance building, streamline on-site product flow, consider converting waste that must otherwise be retrograded into heat and electricity, centralize recreation facilities, and deploy an optimum number of wind turbines.
- Develop a multifactor supply-chain planning and implementation process, and utilize a modern commercially available inventory management system.

APPENDIX E

Schedule of Outreach Sessions Held to Gather Community Input for This Study

Some of the Committee's outreach sessions were stand-alone events and others were held as part of existing conferences and meetings. For each of these sessions, the NSF grantee databases and subsequent personal recommendations were used in efforts to identify and invite all Antarctic and Southern Ocean researchers based within a roughly 2-hour driving radius of the event (i.e., people located close enough that it would be feasible to travel to/from the event within that day). The exact format varied from one event to the next, depending on the time available and number of participants, but the same basic questions were discussed with each group (also the same as the questions posed on our virtual townhall website). All events were held in 2014.

May 7	Ohio State University, Columbus, OH
May 22	National Research Council, Washington, DC
June 9	Antarctic Meteorology Conference, Charleston, SC
June 16	Geospace Environment Modeling Workshop, Portsmouth, VA
July 30	Woods Hole Oceanographic Institute, Woods Hole, MA
August 28	SCAR Open Science Conference, Auckland, NZ
September 18	POLENET Workshop, Washington, DC
September 25	WAIS Ice Core Workshop, La Jolla, CA
September 25	Southern Ocean Carbon Cycle Workshop, La Jolla, CA
September 26	WAIS Ice Sheet Meeting, Camp Julien, CA
October 8	University of Colorado, Boulder
October 15	Lamont-Doherty Earth Observatory, Palisades, NY

October 21	University of Wisconsin, Madison
November 12	Stanford University, Stanford, CA
November 13	Virtual (Webinar) Session
November 14	University of Washington, Seattle

APPENDIX F

Speakers at the Committee Meetings

During their open meeting sessions, the Committee spoke with a variety of people to gain additional perspectives about recent developments, current needs, and future opportunities in Antarctic and Southern Ocean research. This included representatives of the following federal agencies involved in the U.S. Antarctic Program:

- NSF Division of Polar Programs: ***Kelly Falkner, Scott Borg, Lisa Clough, Alex Isern, Brian Stone, Charles Amsler, Vladimir Papitashvili, Nature McGinn, Marco Tedesco***
- White House Office of Science and Technology Policy: ***Brendan Kelly,*** Director (former) of the OSTP Interagency Arctic Policy Committee
- State Department: ***Alfred Schandlbauer, Ray Arnaoudo*** (American Association for the Advancement of Science, former State Department)
- U.S. Coast Guard: ***Gary Rasicot,*** Director of Marine Transportation
- Department of Energy: ***Renu Joseph,*** Manager, Regional & Global Climate Modeling Program; ***Phil Jones,*** LANL Project Leader for Climate, Ocean, Sea Ice Modeling
- NASA: ***Thomas Wagner,*** Cryosphere Program Manager
- NOAA: ***James Butler*** and ***Brian Vasel,*** Earth System Research Laboratory (with input from other NOAA divisions)

Briefings were also given by representatives of several relevant organizations and research efforts, including representatives of:

- The National Academies of Sciences, Engineering, and Medicine's Space Studies Board, Ocean Studies Board, Board on Atmospheric Sciences and Climate, Polar Research Board
- Participants in the *Future Opportunities* (NRC, 2011a) and Blue Ribbon Panel reports: ***Hugh Ducklow, Diana Wall***
- Scientific Committee for Antarctic Research and the SCAR Horizon Scan effort: ***Chuck Kennicutt***
- NRC study *Arctic in the Anthropocene: Emerging Research Questions*, ***Stephanie Pfirman***

- Cold Regions Research and Engineering Laboratory's Antarctic Program: ***Janet Hardy, James Lever, Zoe Courville***
- Woods Hole Oceanographic Institute Unmanned Underwater Vehicles Program: ***Andy Bowen***
- Committee of Visitors 2013 Review of NSF's Polar Program Division: ***John Cassano***

APPENDIX G

Acronyms

ACC	Antarctic Circumpolar Current
AFP	antifreeze protein
AGS	NSF Division of Atmospheric and Geospace Sciences
AIL	NSF Division of Antarctic Infrastructure and Logistics
AIMS	Antarctic Infrastructure Modernization for Science
ANDRILL	ANtarctic geological DRILLing
ARM	DOE Atmospheric Radiation and Monitoring program
AST	NSF Division of Astronomical Sciences
AUV	autonomous underwater vehicle
BICEP	Background Imaging of Cosmic Extragalactic Polarization
BRP	Blue Ribbon Panel
CCAMLR	Convention on the Conservation of Antarctic Marine Living Resources
CI	cyberinfrastructure
CLIVAR	WCRP Climate Variability Program
CMB	cosmic microwave background
COMNAP	Council of Managers of National Antarctic Programs
DARPA	Defense Advanced Research Projects Agency
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DSCS	Defense Satellite Communications System
EAIS	East Antarctic Ice Sheet
EAR	NSF Division of Earth Sciences

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ENSO	El Niño–Southern Oscillation
EPICA	European Project for Ice Coring in Antarctica
GOES	Geostationary Operational Environmental Satellite
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
IARPC	Interagency Arctic Research Policy Committee
IODP	International Ocean Discovery Program
LTER	Long Term Ecological Research
MAPO	Martin A. Pomerantz Observatory
MARAD	U.S. Maritime Administration
MISI	marine ice sheet instability
MREFC	Major Research Equipment and Facilities Construction
MWP	meltwater pulse
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OCE	NSF Division of Ocean Sciences
OOI	Ocean Observatories Initiative
OSTP	White House Office of Science and Technology Policy
PHY	NSF Division of Physics
PI	principal investigator
PINGU	Precision IceCube Next Generation Upgrade
PLR	NSF Division of Polar Programs
POLENET	Polar Earth Observing Network

SAM	Southern Annular Mode
SCAR	Scientific Committee for Antarctic Research
SOCCOM	Southern Ocean Carbon and Climate Observations and Modeling project
SOOS	Southern Ocean Observing System
SPT	South Pole Telescope
STEM	science, technology, engineering, and mathematics
TDRS	Tracking and Data Relay Satellite
UNOLS	University-National Oceanographic Laboratory System
USAP	U.S. Antarctic Program
USCG	U.S. Coast Guard
UAV	unmanned airborne vehicle (drone)
VLF	very low frequency
WAIS	West Antarctic Ice Sheet
WISSARD	Whillans Ice Stream Subglacial Access Research Project