New Frontiers and Future Directions in Antarctic Science

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ABSTRACT. The study of Antarctica and the Southern Ocean, and their role in the Earth system, has never been more important as the region experiences change that has global implications. The Antarctic region is a "natural laboratory" for scientific research of importance in its own right and impossible to achieve elsewhere on the planet. Understanding the Earth system, its components, connections and feedbacks is a major endeavour of contemporary Antarctic science. The following on-going and emerging research activities will be a continued focus of Antarctic research in the coming years: past, current and future climate change; the systematic response of Antarctica to change; understanding Antarctic biodiversity, evolution and ecology; exploration and modelling of ice dynamics and sub-ice environments; ocean, ice, atmospheric and cryospheric observing and modelling; linkages and teleconnections between polar regions and the Earth system; and the poles as a vantage point to observe Earth, near-Earth space, the Solar System and beyond. The Scientific Committee on Antarctic Research (SCAR) is a leader in facilitating international, interdisciplinary science in Antarctica, and through its portfolio of scientific projects, committees, and programs provides a venue for partnerships and exchange of the latest findings. The SCAR accomplishes its scientific mission in close partnership with a wide range of organizations, including the Council of Managers of National Antarctic Programs, the Convention for the Conservation of Antarctic Marine Living Resources, the Scientific Committee on Oceanic Research, the Association of Polar Early Career Scientists, and the International Arctic Science Committee. The SCAR works to ensure that maximum value is derived from the Antarctic research. Emerging frontiers and new directions in Antarctic science continue the historical recognition of the value of the Antarctic as a reserve for science and peace.

INTRODUCTION

As we celebrate on the 50th anniversary of the signing of the Antarctic Treaty and the successes of the International Polar Year, it is an opportune time to reflect on emerging themes in Antarctic science. This is one of the most, if not the most, exciting times for Antarctic science in history. The study of Antarctica and the Southern Ocean, and their role in the Earth system, has never been more important as the region experiences change that has global implications. The Antarctic region is a "natural laboratory" for scientific research of importance in its own right and impossible to achieve elsewhere on the planet. In addition, sound science and knowledge-based advice have never been more critical

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to the policy community to inform decision making and to support complex environmental stewardship and conservation efforts in Antarctica. The Scientific Committee on Antarctic Research (SCAR), as an interdisciplinary, international scientific body of the International Council of Science (ICSU), has been a facilitator and champion of Antarctic science for more than 50 years, dating back to the beginnings of the Antarctic Treaty (Walton, this volume).

PREDICTING FUTURE TRENDS IN ANTARCTIC SCIENCES

Predicting future directions in Antarctic science is difficult as investments in science are decided individually by each nation in different ways:

- investments in science are national enterprises,
- processes for setting scientific priorities are highly variable among nations,
- future directions are dependent on the outcome of "in progress" research,
- trajectories can be non-linear or discontinuous, and
- technology and science can be decoupled.

Indeed, science can drive technology and technology can drive science.

Looking at the broad sweep of Antarctic science, several trends are discernable. Antarctica, as a geographic focus for science, is unique in that the community of scientists that conduct research in the region come from almost all scientific disciplines. In the twenty-first century, Antarctic science will be increasingly called upon to address complex questions that require sophisticated and diverse technologies. In the twenty-first century, an Earth system science approach is fundamental to understanding Antarctica's past, present, and future, and in most instances, Antarctic science will be pursued within an interdisciplinary framework. Understanding the Earth system, its components, connections and feedbacks is a major endeavor of contemporary Antarctic science and research. Antarctic research will generate large and complex volumes of diverse data and information, require transcontinental or at least region-wide investigations to address scientific questions, and entail greater access to all areas of the continent.

On the basis of a review of the International Polar Year (IPY) project database, a wide range of planning documents, and conferring with leaders in Antarctic science, several major scientific themes are apparent:

- Antarctica and global climate;
- deciphering paleoclimate;
- organisms, ecosystems, and biodiversity;
- subglacial aquatic environments;
- exploration beneath the ice;
- cryospheric observing and modeling;
- ice sheet dynamics and sea level;
- Southern Ocean observing and modeling; and
- the poles as a vantage point.

Life Sciences. Although thought of as a cold and isolated environment, Antarctica is undergoing significant change due to regional climate warming, ozone depletion, non-native species introductions, global transport of contaminants, increased scientific and tourist visits, and natural resource exploitation and extraction. Biologically, Antarctica and the Southern Ocean are centers of evolutionary divergence and adaptation to environmental extremes. Antarctic life sciences research focuses on understanding the effect of past, current, and predicted environmental change on biodiversity, adaptation, organism functioning, ecosystem structure/function and the effects of cold, darkness, and isolation on organisms and ecosystems, both on the continent and in the Southern Ocean.

Geosciences. The Antarctic continent and surrounding oceans have been key elements of the Earth system throughout the history of the planet. The basement of Antarctica is built of a suite of crustal blocks that were parts of various supercontinents and the continent contains outcrops that provide insight into Earth processes in the distant past. Sedimentary records on and around Antarctica provide glimpses of paleohistory and variations in the Earth's environment over the eons, harboring clues to the evolution of Antarctica. Geodetic and geophysical observatories document the geodynamics of the continent. Antarctic geosciences research focuses on continental crustal structure and composition, geodynamical processes, the record of life in a warmer Antarctica, the effects of geological processes on Antarctic biota and understanding the controls on ice sheet evolution and stability.

Physical Sciences. Processes at the interfaces between ice, ocean, land and atmosphere are key to understanding climate dynamics and predicting future climate. The nearly pole centered continent of Antarctica gives it a unique place in the global climate system. The role of, and the impact upon, the polar regions in climate processes are a focus of Antarctic physical sciences research. This research aims to understand ice sheet dynamics, climate records from ice cores, changes in sea ice distribution and ocean circulation, atmospheric dynamics and chemistry, oceanic upwelling and melting ice shelves and the impact of the ozone hole on Antarctic climate. The Antarctic continent is also a unique place for astronomical and solar-terrestrial observations of phenomena such as interactions between the Sun and the Earth.

This chapter reviews these major themes and highlights some of the ongoing programs and projects illustrative of future directions. Reflective of the truly integrated nature of modern Antarctic science, many scientific programs crosscut interdisciplinary scientific themes. This chapter can only provide a partial glimpse of the complex web of science programs that link thousands of scientists in more than 30 countries collectively forming modern Antarctic science.

ANTARCTICA AND GLOBAL CLIMATE

By far the most pervasive theme in Antarctic science is climate change. The study of climate change in the region and linkages with the global climate system will occupy Antarctic scientists for many years to come.

The Antarctic is a critically important part of the Earth system. The climate, physical, and biological properties of the continent and the surrounding ocean are closely coupled to other parts of the global environment by the ocean and the atmosphere. Antarctica contains approximately 90% of the world's ice and approximately 70% of the world's freshwater, which is enough to raise sea level by 63 m. It also holds high-resolution records of past climate change and sensitive biological indicators of contemporary change. For example, the Antarctic ozone hole was one of the most significant scientific discoveries of the last century and resulted in major changes in environmental management throughout the world (Benedick, 1998). For the last 30 years the ozone hole has shielded the Antarctic from the effects of "global warming." The western coast of the Antarctic Peninsula is experiencing one of the most rapid rises in mean temperature anywhere on Earth. The Southern Ocean warming causes change in both terrestrial and marine ecosystems. There has been a rapid expansion of the area covered by the two flowering plants on the Antarctic Peninsula. Parts of the Antarctic are losing ice at a rapid rate. Paleoclimate studies in Antarctica show the current changes in global climate are unusual. Assuming a doubling of greenhouse gas concentrations over the next century, Antarctica is predicted to warm significantly, with the largest increases experienced by West Antarctica.

The instrumental records from the research stations and automatic weather stations are valuable but are generally too short to provide enough data for climate trend analyses where changes need to be looked at over decades, centuries, or even longer. When these records are integrated with proxy records of change from ice and sediment cores, they offer a powerful tool for climate analyses. The SCAR has released a comprehensive synthesis of current understanding of Antarctic climate science, *Antarctic Climate Change and the Environment* (Turner et al., 2009; this report has been widely distributed and is available from the SCAR Web site, http://www.scar.org). The report concludes that a key objective for future Antarctic climate studies is to improve representations of polar processes in models so that more-accurate predictions are produced. Higher-resolution global models, regional climate models, and ecosystem and ice sheet models are required. Climate models require better simulations of polar-specific processes, such as sea ice and the atmospheric boundary layer.

Climate variability in the polar regions is greater than in other parts of the world, and improved monitoring and more detailed understanding of past climate are needed in order to discriminate natural variability from anthropogenic influences. There is an urgent need to establish marine and terrestrial biological baseline monitoring programs in order to understand past change and to establish the links between physical and biological variability. There is a requirement for greater cross- and interdisciplinary observational efforts linked to modeling studies that will be discussed later.

In order to better understand climate variability a detailed understanding of past climate is essential. Gaps in records of past climate archived in ice and sedimentary cores must be filled. This objective is accomplished by several differing approaches that increase the spatial and temporal coverage of climate records. Because of the remoteness of the continent, Antarctica is an ideal location to study local- to global-scale climate change. However, this remoteness has also prevented the collection of instrumental records, similar to those collected in the Northern Hemisphere, that are required to assess Antarctica's role in and response to environmental and climate change.

The continued study of surface and near-surface ice core records is essential. High-resolution ice core records are the most direct way to document climate with resolutions as fine as seasonal and, potentially, on time scales as long as a million years. Fundamental issues of spatial and temporal climatic and environmental variability still need to be addressed by determining the spatial variability of Antarctic climate over the last 200 years, and where the data are available, the last 1000 years. High-resolution ice core records are also critical for establishing spatial gradients in ice core properties as a complement to deep ice core records that support the objective of obtaining the oldest ice core record in Antarctica. The search for a 1.5 million year record of climate and greenhouse gases from Antarctica will extend knowledge of past climate change, much as the European Project for Ice Coring in Antarctica (EPICA) ice core supplemented the Vostok ice core climate record.

Complementary to ice core records are climate records contained in sedimentary sequences. Recovery and interpretation of sedimentary records of climate change are the objectives of several major programs including Antarctic Geological Drilling (ANDRILL; http://www.andrill.org/), Shallow Drilling on the Antarctic Continental Margin (SHALDRILL; http://www.shaldril.rice.edu), the Integrated Ocean Drilling Program (IODP; http://www.iodp.org/), and integrative synthesis programs such as SCAR's Antarctic Climate Evolution (ACE) program. Studies of the greenhouse world 50 MYA imply a higher "climate sensitivity" than currently accepted, suggesting the potential for additional positive feedbacks not currently represented in climate models.

Knowledge of the behavior of Polar Regions in a high-CO_2 world still remains one of the greatest uncertainties in predicting future climate response. There is a continuing need to recover Antarctic geological records beyond the age range of ice cores, dating as far back as 30–50 MYA when Earth's atmospheric CO_2 was two to four times higher than at present, the high end of the Intergovernmental Panel on Climate Change (IPCC) projections for 2100. Major scientific objectives in the geosciences include obtaining geological records that sample past Antarctic ice sheet dynamics and integrate climate and ice sheet proxy data with the latest generation of coupled ice sheet–climate models. Much remains to be accomplished in these research areas.

Finally, it will be essential to integrate sedimentary, ice, and instrumental records of climate change with climate and ice sheet models to constrain predictions of future change. Each type of climate record contributes differing spatial and temporal records of past climate change that together provide a comprehensive picture of climate forcings.

ANTARCTIC ORGANISMS, ECOSYSTEM, AND BIODIVERSITY

Research directions in the life sciences will build on current research being conducted by programs such as SCAR's Scientific Research Program Evolution and Biodiversity in Antarctica (EBA). Although significant advances have been made in recent years, Antarctica's biological and ecological domains remain, to a large extent, unexplored. Antarctic life scientists strive to understand the evolution and diversity of life in Antarctica to determine how evolution and biodiversity have produced Antarctic ecosystems. Understanding of ecosystem functioning is fundamental.

One of the most important recent developments in life sciences in the Antarctic is the increase in knowledge of biodiversity in the terrestrial and marine settings, especially the deep sea. We also know that organisms and biodiversity are beginning to change in response to climate change. There is a great need to describe the living residents of Antarctica and to better understand their origins. There is also a critical need to document nonendemic species as climate change affects floral and faunal ranges worldwide and the probability of alien introductions increases (Frenot et al., 2005).

Life sciences research in the Antarctic focuses on three main ecological topics that are important worldwide: changes in habitats, loss of biodiversity, and the effect of climate change. A first step in improving our basic understanding is to document what organisms are present. An excellent example of one such program is the Census of Antarctic Marine Life (CAML). The CAML investigated the distribution and abundance of Antarctica's marine biodiversity to develop a benchmark (http://www.caml.aq).

Life sciences research in Antarctica has a long history of studying adaptations, ecosystem function and structure, and the physiology of the unique organisms that inhabit Antarctica. Much research on these topics is expected to continue to address basic questions about life in the cold and dark, life in subglacial aquatic environments (which I will return to), and life at the extremes of our planet. Research objectives will require extension of observations beyond the traditional summer season and the application of modern methods in molecular genomics and proteomics.

Antarctic biodiversity and biogeography will remain a topic of high interest for years to come. An exemplary program is the SCAR Marine Biodiversity Information Network (SCAR-MarBIN; http://www.scarmarbin.be), which is the Antarctic node for the Ocean Biogeographic Information System (OBIS) and a companion project of CAML. The SCAR-MarBIN is a distributed system of interoperable databases that compiles and manages existing and new information on Antarctic marine biodiversity.

Subsequent to the Larsen Ice Shelf collapse, the first observations of cold seep communities in Antarctic were recorded. These unique communities and possibly hydrothermal vent communities are being considered as possible vulnerable marine areas in need of special protection. These sites also present opportunities to study unusual ecosystems that have only recently been identified in Antarctica.

The success of the Convention for the Conservation of Marine Living Resources (CCAMLR) in promoting an ecosystem management approach to Southern Ocean fisheries relies, to a considerable extent, on the marine biology undertaken by SCAR scientists. The changes in the Southern Ocean food webs attributable to recent fish, squid, and krill harvesting suggest that this research will be even more important in the future, especially in the establishment of marine protected areas and the monitoring of secondary effects of fishing on higher predators.

Today, Antarctica is almost 99.7% covered by permanent ice and snow, and evidence suggests that as recently as the Last Glacial Maximum, ice sheets were both thicker and much more extensive than they are now. Most, if not all, of the currently ice-free ground would have been overridden by ice during previous glaciations, suggesting that Antarctic preglacial terrestrial life was wiped out by successive glacial events. This, in turn, suggests that most, possibly all, contemporary terrestrial life has colonized the continent during subsequent periods of glacial retreat. A combination of recent biological and geological data compiled by Convey et al. (2008) challenges this paradigm. New and complex conclusions about terrestrial Antarctic biogeography suggest greater regionalization and evolutionary isolation than previously suspected for circum-Antarctic marine fauna. These findings require the adoption of a new biological paradigm within Antarctica and challenge current understanding of Antarctic glacial history. Future research that will flow from these investigations will have major implications for understanding the key role of Antarctica in the Earth system.

SUBGLACIAL AQUATIC ENVIRONMENTS

The study and exploration of subglacial aquatic environments is at its beginnings. Subglacial aquatic environment research by its nature is highly interdisciplinary and is poised to fundamentally change our view of how Antarctica responds as part of the Earth system. The study of these environments will contribute to a wide range of Antarctic scientific topics, including the tectonic evolution and history of the continent, the importance of subglacial hydrology in ice sheet and ice stream dynamics, and the adaptation of microbial life in these unique environments. It is also conjectured that these environments may hold records of the past climate of the interior of the continent and that outbursts of subglacial waters have been important processes over geologic time.

There are three major subglacial lake exploration programs projecting lake entry and sampling in 2011–2012. These projects include the long-term studies at Lake Vostok, the studies of subglacial Lake Ellsworth, and coordinated studies of the Whillans Ice Stream. International, field-intensive programs are exploring the Antarctic continent hidden beneath kilometers of ice in East and West Antarctica. These studies use a range of technologies and are providing a view of the basement beneath the Antarctic ice sheet never before seen. International coordination of the science is through a SCAR Group of Specialists (http://www.sale.scar.org/).

EXPLORATION BENEATH THE ICE

Three projects highlight future directions in Antarctic geosciences: Antarctica's Gamburtsev Province Project (AGAP), Ice and Climate Evolution of the Central Antarctic Plate (ICECAP), and Polar Earth Observing Network (POLENET). The AGAP is exploring the history of the East Antarctic ice sheet and lithospheric structure of the Gamburtsev subglacial mountains, a major mountain range buried by the East Antarctica Ice Sheet, which includes numerous subglacial lakes. AGAP is a multinational and multidisciplinary program that includes aerogeophysics, traverse programs, passive seismic experiments, and ice core and bedrock drilling.

The objective is to better understand the tectonic origin of the Gamburtsev Mountains, providing crucial new data for ice sheet and climate models (Bo et al., 2009). Fundamental questions to be addressed include

- What role does topography play in the nucleation of continental ice sheets?
- How are major elevated continental massifs formed within intraplate settings but without a straightforward plate tectonic mechanism?
- How do tectonic processes control the formation, distribution, and stability of subglacial lakes?
- Where is the oldest climate record in the Antarctic ice sheet?

The ICECAP is a collaborative program between the United States, the United Kingdom, and Australia to use a multi-instrumented long-range aircraft over three austral summers to survey portions of the East Antarctic Ice Sheet. The ICECAP is acquiring aerogeophysical observations to determine ice thickness and date internal layers in support of ice sheet modeling, observing flow regime change recorded in the internal layers. and studying crustal geology and subglacial hydrological systems from the perspective of processes controlling past and future change in the East Antarctic Ice Sheet.

The POLENET is a collaborative, international project to understand how the Earth's surface responds to changes in polar ice sheets. The POLENET project is collecting GPS and seismic data from stations at remote sites spanning much of Antarctica. Integrated GPS and seismic measurements are used to model how much ice has been lost over the past 10,000 years. A combination of ground-based and satellite data is used to determine where, and at what rate, the ice sheets are changing in response to recent climate change.

CRYOSPHERIC OBSERVATIONS AND MODELING

The Global Inter-agency IPY Polar Snapshot Year (GIIPSY) project collects data to understand the role of polar processes in climate change, the contribution of the polar ice sheet to sea level, and ice sheet and ocean interactions. An ambitious schedule of missions over the next several years is already planned. Satellite observations support a wide range of research efforts.

Some regions of Antarctica, particularly the peninsula, have warmed rapidly in recent years, contributing to the disintegration of ice shelves and accelerating the sliding of glaciers. These events have focused attention on the stability of the West Antarctic Ice Sheet (WAIS) as much of it is grounded below sea level. The WAIS Divide ice core will provide Southern Hemisphere climate and greenhouse gas records comparable in time resolution and duration to the Greenland ice cores. The WAIS Divide ice core will also be used to test models of WAIS history and stability.

Recent findings suggest that from 1957 through 2006, temperatures across Antarctica rose an average of 0.2°F (0.1°C) per decade, comparable to global warming rates. In East Antarctica, where temperatures had been thought to be falling, researchers have found a slight warming over the last 50 years.

There is growing consensus that the Antarctic ice sheet is experiencing net mass loss. The long-term trends in these data will be of interest for years to come. Sea level has risen in recent years, mostly because of thermal expansion of the world's ocean, glacier melt, and losses of mass from the Greenland ice sheet. However, as previously noted, the ice sheets of Antarctica are the major global reservoir of freshwater and represent by far the greatest potential for sea level rise in the future. The status of and trends in the Antarctic cryosphere will be of high interest for years to come (Rohling et al., 2009).

SOUTHERN OCEAN OBSERVING AND MODELING

As for Antarctica's cryosphere, a better understanding of the Southern Ocean is critical to anticipating and predicting response to climate change. The Southern Ocean has a global influence with the potential for significant feedbacks. There is evidence that changes in the Southern Ocean are underway, but sparse observations make interpretations difficult.

System-scale observations of the Southern Ocean are critical. Integrated multidisciplinary observations are necessary to understand and ultimately predict the response of biota to changes in physical drivers. An integrated, coordinated, and broadly multidisciplinary approach to a Southern Ocean observing system is being developed. Some elements are already in place, such as (1) repeat hydrography, (2) ships of opportunity, (3) Argo floats (http://www.argo.ucsd.edu/newsletter.html), (4) tagging of marine mammals (http://biology.st-andrews.ac.uk/seaos), (5) SCAR continuous plankton recorder, and (6) satellites (e.g., Sea-viewing Wide Field-of-view Sensor [SeaWiFS]; http://oceancolor.gsfc.nasa.gov/SeaWiFS).

Ocean acidification due to uptake of atmospheric carbon dioxide can be deleterious to many marine organisms and ecosystems. Predicted ocean acidification (McNeil and Matear, 2008) is expected to cause major changes in nutrients, phytoplankton diversity, biodiversity, biogeochemical cycles, marine community structure and robustness, and calcification rates while reducing behavioral capacity, growth, production, life span, and tolerance to environmental fluctuations. Following this growing problem will be a focus of research for years to come.

THE POLES AS A VANTAGE POINT

Antarctica possesses special advantages for astronomers with its clear skies, high plateau, low humidity, and stable atmosphere (Storey, 2005). Increasing investment in a range of telescopes at the South Pole and Dome C has provided major new facilities for the international community. Antarctic astronomy and astrophysics will address fundamental questions in the next decade, including

- locating first stars, first galaxies, and reionization tomography;
- defining the nature of the dark universe;
- detecting gravity waves;
- identifying exoplanets and the formation of exo-solar systems;
- exploring variations in fundamental constants;
- searching for extra dimensions; and
- defining the transient universe.

One program, IceCube (http://icecube.lbl.gov), is searching for neutrinos from the most violent astrophysical sources, events like exploding stars, gamma ray bursts, and cataclysmic phenomena involving black holes and neutron stars. The IceCube telescope could reveal the physical processes associated with the enigmatic origin of the highest-energy particles in nature.

Near-Earth space (geospace) is an integral part of the Earth system, providing the material link between the Sun and Earth, primarily through the polar regions. Research in this area will create an integrated, quantitative description of the upper atmosphere over Antarctica and its coupling to the geospace environment. The Super Dual Auroral Radar Network (SuperDARN; http://superdarn.jhuapl.edu/), an international radar network, studies the Earth's upper atmosphere, ionosphere, and connection into space.

CONCLUSIONS

The realities of conducting research in the southern polar regions bring with it great challenges but also great opportunities. The questions being asked by those with interests in Antarctica, the Southern Ocean and the Earth system are more complex and demanding than ever before. The critical role of scientific knowledge developed from the study of Antarctica and the Southern Ocean has never been more important in discerning the future of our planet. Antarctica and the Southern Ocean are a natural laboratories where global forces play out in ways not experienced or observable elsewhere on the planet. Antarctica also serves as a unique vantage point to look outwards from our planet to observe near-Earth space, our solar system and beyond. In a time of economic stress, it is important that resources be used to optimum affect, that investments in science in Antarctica be justified, and that the community develops and shares a collective vision of future scientific directions. A well-conceived strategy is not only essential but critical. This partial review of major themes in Antarctic science over the next 10–20 years illustrates what an exciting and productive time is in store for Antarctic scientists. A combination of scientific ideas and societal issues will drive future research directions. Twenty-first century Antarctic science and research will address complex questions that require holistic, interdisciplinary, international, and technologically intensive experiments that will require access to all of Antarctica. The need for access to data and data sharing will increase along with the necessity for ever-more-sophisticated data and information infrastructure to collect, store, archive, and synthesize the vast amounts of data that will be generated.

Antarctica evokes a sense of discovery as a location of unexplored places and the origin of surprising findings that inspire unconventional thinking. In the next few decades the Antarctic science community will build on its history of accomplishment and elevate the presence and importance of Antarctic science in the global conversation. There are opportunities for coordination, partnerships, and synergy that build on the historical international partnerships that epitomize Antarctic science. Where our community will be in 10 or 20 years is only limited by our imagination, as the future is in our hands!

LITERATURE CITED

Benedick, R. 1998. *Ozone Diplomacy*. Cambridge, Mass.: Harvard University Press.

Bo, S., M. J. Siegert, S. M. Mudd, D. Sugden, S. Fujita, C. Xiangbin, J. Yunyun, T. Xueyuan, and L. Yuansheng. 2009. The Gamburtsev Mountains and the Origin and Early Evolution of the Antarctic Ice Sheet. *Nature,* 459:690–693.

Convey, P., J. A. E. Gibson, C. D. Hillenbrand, D. A. Hodgson, P. J. A. Pugh, J. L. Smellie, and M. I. Stevens. 2008. Antarctic Terrestrial Life: Challenging the History of the Frozen Continent? *Biological Reviews,* 83:103–117.

Frenot, Y., S. L. Chown, J. Whinam, P. M. Selkirk, P. Convey, M. Skotnicki, and D. M. Bergstrom. 2005. Biological Invasions in the Antarctic: Extent, Impacts and Implications. *Biological Reviews,* 80:45–72.

McNeil, B. I., and R. J. Matear. 2008. Southern Ocean Acidification: A Tipping Point at 450-ppm Atmospheric CO_2. *Proceedings of the National Academy of Sciences of the United States,* 105(48):18,860–18,864.

Retamales, J., and M. Rogan-Finnemore. 2011 (this volume). "The Role of the Council of Managers of National Antarctic Programs." In

Science Diplomacy: Antarctica, Science, and the Governance of International Spaces, ed. P. A. Berkman, M. A. Lang, D. W. H. Walton, and O Young, pp. 231–239. Washington, D.C.: Smithsonian Institution Scholarly Press.

Rohling, E. J., K. Grant, M. Bolshaw, A. P. Roberts, M. Siddall, C. Hemleben, and M. Kucera. 2009. Antarctic Temperature and Global Sea Level Closely Coupled over the Past Five Glacial Cycles. *Nature Geoscience,* 2(7):500–504

Storey, J. W. V. 2005. Astronomy from Antarctica. *Antarctic Science,* 17(4):555–560.

Turner, J., R. A. Bindschadler, P. Convey, G. Di Prisco, E. Fahrbach, J. Gutt, D. A. Hodgson, P. A. Mayewski, and C. P. Summerhayes, eds. 2009. *Antarctic Climate Change and the Environment*. Cambridge: Scientific Committee on Antarctic Research.

Walton, D. W. H. 2011 (this volume). "The Scientific Committee on Antarctic Research and the Antarctic Treaty." In *Science Diplomacy: Antarctica, Science, and the Governance of International Spaces*, ed. P. A. Berkman, M. A. Lang, D. W. H. Walton, and O Young, pp. 75–88. Washington, D.C.: Smithsonian Institution Scholarly Press.