One Earth
Review

Sustained Antarctic Research: A 21st Century Imperative

Mahlon C. Kennicutt II,[1,*] David Bromwich,[2] Daniela Liggett,[3] Birgit Njåstad,[4] Lloyd Peck,[5] Stephen R. Rintoul,[6] Catherine Ritz,[7] Martin J. Siegert,[8] Alan Aitken,[9] Cassandra M. Brooks,[10] John Cassano,[11] Sanjay Chaturvedi,[12] Dake Chen,[13] Klaus Dodds,[14] Nicholas R. Golledge,[15] Céline Le Bohec,[16,17] Marcelo Leppe,[18] Alison Murray,[19] P. Chandrika Nath,[20] Marilyn N. Raphael,[21] Michelle Rogan-Finnemore,[22] Dustin M. Schroeder,[23] Lynne Talley,[24] Tony Travouillon,[25] David G. Vaughan,[5] Lifan Wang,[26] Allan T. Weatherwax,[27] Huigen Yang,[28] and Steven L. Chown[29]
[1]Department of Oceanography, Texas A&M University, College Station, TX 77843, USA
[2]Department of Geography, The Ohio State University, Columbus, OH 43210, USA
[3]Gateway Antarctica, Department of Geography, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand
[4]Norwegian Polar Institute, 9296 Tromsø, Norway
[5]British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK
[6]CSIRO Oceans & Atmosphere, Centre for Southern Hemisphere Oceans Research, Australian Antarctic Program Partnership, Hobart, 7000 TAS, Australia
[7]Institut des Géosciences de l'Environnement, University of Grenoble Alpes/CNRS, 38 058 Grenoble Cedex 9, France
[8]Grantham Institute and Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK
[9]School of Earth Sciences, University of Western Australia, Perth, WA 6008, Australia
[10]Environmental Studies Program, University of Colorado Boulder, Boulder, CO 80309, USA
[11]Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, CO 80309, USA
[12]Faculty of Social Sciences, Department of International Relations South Asian University, Akbar Bhavan, Chankyapuri, New Delhi 110021, India
[13]State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, MNR, Hangzhou 310012, China
[14]Department of Geography, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK
[15]Antarctic Research Centre, Victoria University of Wellington, 6140 Wellington, New Zealand
[16]Université de Strasbourg, CNRS, IPHC UMR 7178, 23 rue Becquerel, 67000 Strasbourg, France
[17]Centre Scientifique de Monaco, Département de Biologie Polaire, 8, quai Antoine 1er, MC 98000 Monaco, Principality of Monaco
[18]Chilean Antarctic Institute, Punta Arenas, Chile
[19]Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA
[20]Scientific Committee on Antarctic Research, c/o Scott Polar Research Institute, University of Cambridge, Lensfield Road, Cambridge CB2 1ER, UK
[21]University of California Los Angeles, Department of Geography, Los Angeles, CA 90095, USA
[22]Council of Managers of National Antarctic Programs Secretariat, Christchurch 8140, New Zealand
[23]Department of Geophysics, Stanford University, Palo Alto, CA, USA
[24]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92037, USA
[25]Research School of Astronomy and Astrophysics, Australian National University, Canberra, Australia
[26]Department of Phyics & Astronomy, Texas A&M University, College Station, TX 77843, USA
[27]Merrimack College, 315 Turnpike Street, North Andover, MA 01845, USA
[28]Polar Research Institute of China, 451 Jinqiao Road, Pudong Xinqu, Shanghai Shi, China
[29]School of Biological Sciences, Monash University, Clayton, VIC 3800, Australia
*Correspondence: mckennicutt@gmail.com
https://doi.org/10.1016/j.oneear.2019.08.014

The view from the south is, more than ever, dominated by ominous signs of change. Antarctica and the Southern Ocean are intrinsic to the Earth system, and their evolution is intertwined with and influences the course of the Anthropocene. In turn, changes in the Antarctic affect and presage humanity's future. Growing understanding is countering popular beliefs that Antarctica is pristine, stable, isolated, and reliably frozen. An aspirational roadmap for Antarctic science has facilitated research since 2014. A renewed commitment to gathering further knowledge will quicken the pace of understanding of Earth systems and beyond. Progress is already evident, such as addressing uncertainties in the causes and pace of ice loss and global sea-level rise. However, much remains to be learned. As an iconic global "commons," the rapidity of Antarctic change will provoke further political action. Antarctic research is more vital than ever to a sustainable future for this One Earth.

Introduction

Antarctica and the Southern Ocean ("the Antarctic") are intrinsic to the Earth system. Although remote, the Antarctic region is interconnected with the northern world by oceanic and atmospheric couplings, geopolitics, and international agreements. Climate variability and change are transmitted from low to high latitudes. In turn, change in the Antarctic has profound implications for the rest of the planet. The fate of Antarctic ice sheets determines, to a large degree, sea level, and the Southern Ocean plays a dominant role in global heat and greenhouse gas budgets. Therefore, scientific investigations of the Antarctic are critical to understanding the history and future trajectories of our planet.[1] In the latter case, this raises critical questions about the viability of current socioeconomic arrangements as the planet evolves to states beyond that experienced throughout human history.[2–6]

The Antarctic region also sustains some of the planet's most iconic species (e.g., whales, penguins, and albatrosses) and provides a range of important ecosystem services.[7] Despite past whaling, sealing, fisheries, and krill harvesting, no anthropogenic extinctions have been recorded in the region, but consensus is growing that changing climate and resource exploitation interests pose threats to the region.[7–9] Calls for expanding long-term research across the region have become more strident in anticipation of regulatory challenges that will require information on system changes.[7,10–13]

The global value of sustained scientific research in the Antarctic is best illustrated by policy responses to observations of ozone depletion over Antarctica. Long-term stratospheric ozone monitoring from the Antarctic continent led to the recognition of a developing ozone hole above Antarctica in the mid-1980s.[14] Realization of the implications for life on Earth was swift and yielded an unprecedented rapid, globally agreed response to phase out the chlorofluorocarbons (CFCs) responsible for depletion. Discerning a causal link between the strengthening and poleward shift of the westerly winds over the Southern Ocean, along with their influence on Antarctic life, transformed the debate.[15–17] Continued long-term assessment of these changes and system-wide effects will be critical if international goals are to be met. Some complexity remains, with indications that, despite the universal ratification of the Montreal Protocol[18] and its instruments, CFC-11 (trichlorofluoromethane) concentrations in the atmosphere are increasing.[19] This is an example of how Antarctic observations and research are critical to identifying global threats and assessing the efficacy of control measures. Today, Antarctic observations play a similar role regarding climate change and sea-level rise.

Five years ago, a community-driven process identified the highest priorities and set an ambitious agenda for Antarctic research (Box 1).[20,21] Horizon Scanning—a systematic approach to retrieve, sort, organize, and prioritize information pertinent to the question posed—was used to identify the most important scientific questions from many.[22] The first Antarctic Science Horizon Scan ("the Scan") was followed by an assessment of the technology and infrastructure required to deliver the research. The Antarctic Roadmap Challenges ("the ARC"; Box 1) assessment included estimates of both cost and time to delivery.[23] It was recognized that identifying questions was a first step, but answers were the goal. The ARC provided a path to implementation.

Since then, the imperatives for Antarctic research have grown. Climate change poses an existential threat to society and the future of the planet, with the urgent need "… to bring all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects …."[26] Scientific understanding of the Antarctic is essential for this common cause. This is clearly articulated in the alternatives for the region presented from a 2070 vantage: one presenting an environmentally, as well as a politically, unrecognizable Antarctic region and world; and the other closer to that experienced throughout human history.[9]

Here, we review progress against the priorities set out by the Scan and ARC, recognizing across each theme where progress has been made, where it is lagging, and what new challenges have arisen. In doing so, we recognize that the delivery of evidence does not guarantee a change in policy and that opinions vary on what policies should be adopted among the diverse stakeholders, states, and constituencies that are the 21st century world.

The progress assessment is ordered according to the seven clusters of questions identified by the Scan: (1) Antarctic atmosphere and global connections, (2) Southern Ocean and sea ice in a warming world, (3) ice sheets and sea level, (4) the dynamic Earth: probing beneath Antarctic ice, (5) life on the precipice, (6) near-Earth space and beyond, and (7) human presence in Antarctica.[21] An eighth topic, regarding effective engagement of diverse audiences, assesses the impact, delivery, and uptake of the Scan and ARC outputs with a goal of discerning lessons

Box 1. The First Antarctic and Southern Ocean Science Horizon Scan and the Antarctic Roadmap Challenges (ARC) Project: The Process

The first Antarctic and Southern Ocean Science Horizon Scan (the Scan)[20] was based on wide consultation with the community to develop a collective, international view of the most important future directions in Antarctic research.[20,21] A final list of 80 highest priority questions, distilled from nearly 1,000 questions submitted by the community, was agreed at a retreat attended by 75 representatives from 22 countries.[24] Attendees included researchers, national program directors or managers, and policy makers. Retreat participants were selected to ensure balance among disciplinary expertise, geographical origins, gender, stage of career, and representation of SCAR partner organizations and other stakeholders. The Scan outcomes were articulated as an "Antarctic Science Roadmap" (the Roadmap).[21] A new team of 60 experts was assembled to conduct the Antarctic Roadmap Challenges (ARC) project.[23,25] Participants included logisticians and operations experts, experienced Antarctic researchers, policy makers, select Scan contributors, and national Antarctic program personnel from 22 countries. A workshop was convened to consider a series of papers submitted by the Antarctic science community, survey results, summaries from the Scan, and other documents addressing future Antarctic research directions, essential technologies, and logistics requirements. The ARC project answered the question, "How will national Antarctic programs meet the challenges of delivery of Antarctic science over the next 20 years?" As entities that fund and support Antarctic science, national Antarctic programs face many practical and technical issues. ARC addressed four of seven challenges: availability of essential technologies, extraordinary logistics requirements (access), supporting infrastructure and international cooperation.[23] Challenges related to human resources, energy demands, and long-term sustainable funding were not considered.

learned for effective communication that influences societal actions. Experts assessed progress by reviewing the scientific literature published in the last 5 years (Tables S1–S15). A transdisciplinary and critical perspective on progress was assured by including stakeholder representatives and others not involved in the Scan or ARC projects. Indications of progress do not infer that the Scan was the cause, as much research was already underway and other non-scientific factors were at play. The notation Q.## refers to specific Scan questions (Tables S1–S14).[20,21]

Antarctic Atmosphere and Global Connections

Tropical oceans influence Antarctic climate on a variety of time scales via atmospheric teleconnections (Figure 1 and Tables S1 and S2).[27] These tropical impacts are most apparent today in West Antarctica and are primarily linked to the tropical and subtropical Pacific Ocean. El Niño-Southern Oscillation (ENSO) variability on interannual timescales is the most prominent influence. These tropical forces modulate the impacts from the ozone hole in the stratosphere above Antarctica that propagate into the weather-active troposphere. These tropical and polar forces govern the behavior of the westerly winds around Antarctica affecting Southern Ocean circulation, sea-ice extent, heat and carbon sequestration, and oceanic biogeochemistry. The north/south pressure gradient over the Antarctic is expressed as the Southern Annular Mode, and understanding of its variation and change, and the causes and consequences thereof, are improving (Q.1, Q.3, Q.4, and Q.11). There is a growing understanding of the global atmospheric-oceanic coupled system (aka ''oceanic-atmospheric bridge'') from model simulations and correlations of observations and how polar modes are relayed through northern and southern mid to low latitudes possibly influencing, and predicting, distant global weather phenomena (e.g., monsoon rainfall patterns).[28,29]

While descriptions of climate variability and change in Antarctica are improving, direct continent-wide observations of atmospheric variables, such as temperature and pressure, only date to the 1950s. Indirect measures of temperatures from ice core records augment observations as far back as 2000 years before present, and the number of ice cores is growing.[30] In these records, broad-scale cooling was apparent until 1900 followed by warming in the Antarctic western hemisphere. Spatial extrapolations of surface air temperature measurements demonstrated that warming extends from the Antarctic Peninsula into central West Antarctica, but there has been little or no recent change in East Antarctica.[31] Trends in the Southern Annular Mode and tropical influences are suggested as causal factors. Antarctic precipitation for the last 200 years is also derived from reconstructions of ice core records and here too, both record availability and understanding of the underlying variation and its mechanisms is advancing.[32] Large but opposing trends are found across West Antarctica, especially for recent

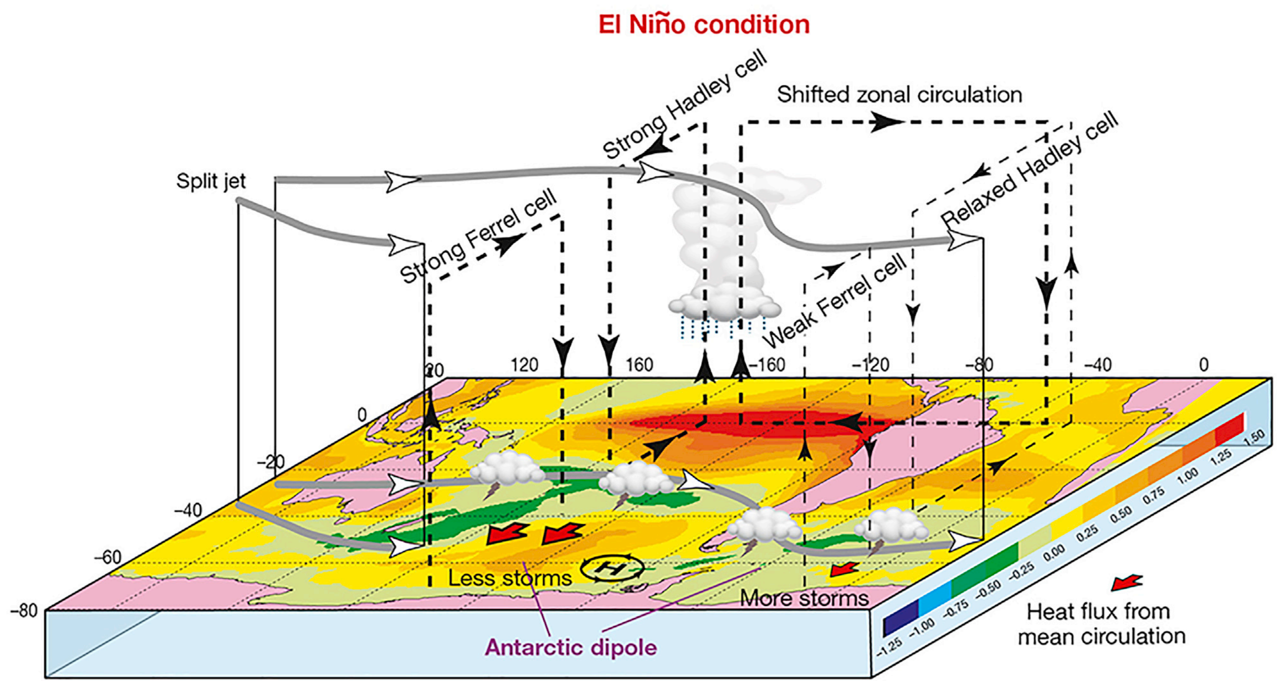

Figure 1. A Schematic Illustration of Key Aspects of the "Antarctic Atmosphere and Global Connections" Theme
Remote atmospheric circulation changes are caused by warm sea-surface temperatures in the tropical Pacific Ocean accompanying the El Niño-Southern Oscillation (ENSO). The mechanisms involved include (1) Rossby wave trains emanating from the tropical Pacific, leading to an anomalous high pressure center in the Amundsen Sea (weakened Amundsen Sea low); (2) meridional circulations exhibiting zonal asymmetry because of contrasting sea surface temperature anomalies in the tropical Pacific and tropical Atlantic: the Hadley cell is strengthened and contracted (weakened) in the South Pacific (South Atlantic); (3) equatorward shifting of the subtropical jet and storm tracks in the South Pacific and poleward shifting of storm tracks in the South Atlantic; and (4) an enhanced (weakened) Ferrel cell in the South Pacific (South Atlantic). This contributes to more poleward heat transport in the lower atmosphere of the South Pacific and less poleward heat transport in the South Atlantic. As a result, storm activity decreases in the Pacific sector of Antarctica but increases in the Atlantic sector.[27]
 This figure has been modified from the original source.

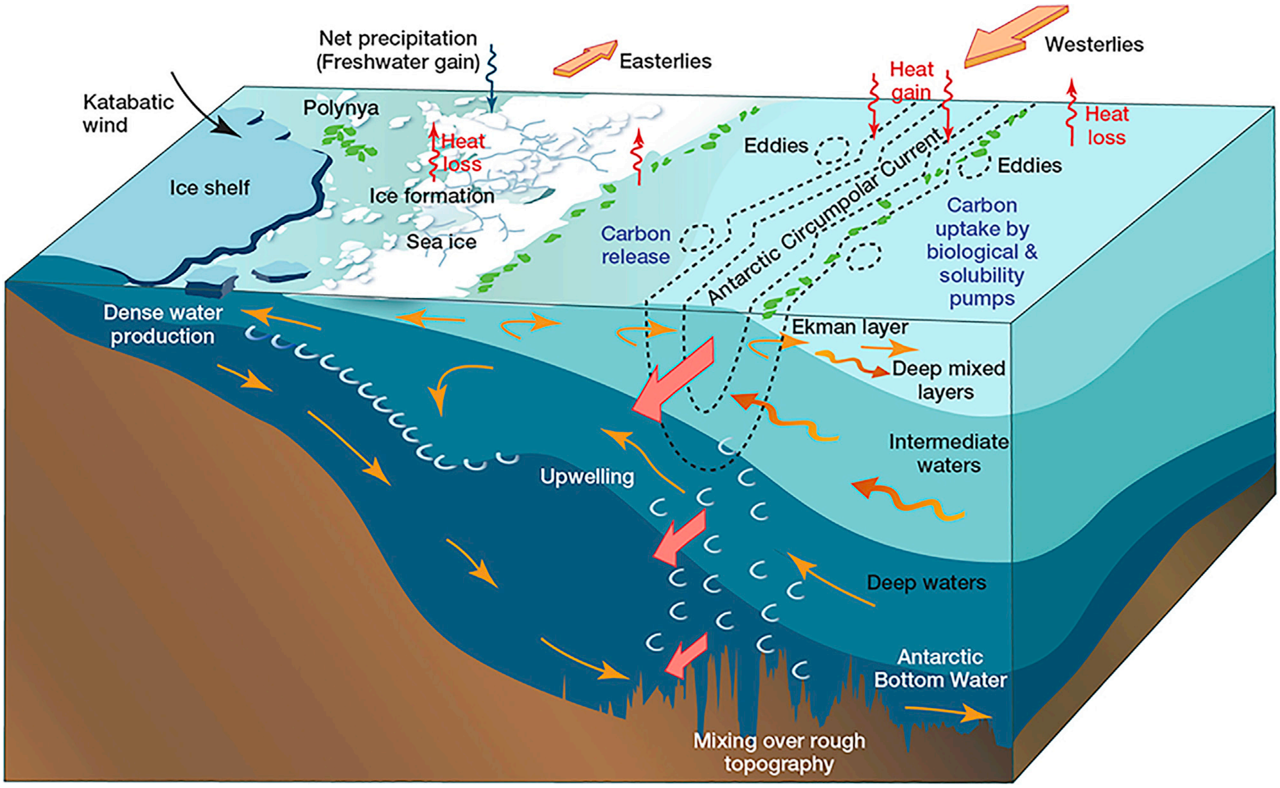

Figure 2. A Schematic Illustration of Key Aspects of the "Southern Ocean and Sea Ice" Theme
The ocean circulation is driven by wind forcing and exchange of heat and freshwater at the sea surface. The Antarctic Circumpolar Current circles the continent from west to east. Deep water flows southward and upwells to the sea surface. Part of the upwelled water returns north as dense Antarctic bottom water, and the rest returns as lighter water that supplies the intermediate layers of the ocean, producing an overturning circulation with two counter-rotating cells. Sea ice plays an important role in driving the overturning circulation, contributing to the formation of both dense bottom and lighter intermediate water.

decades, while precipitation changes are muted in East Antarctica. After considering the influence of the Southern Annular Mode, a steady spatially variable increase in precipitation remains, likely caused by global warming (Q.6 and Q.8).[31]

The role of extreme atmospheric events in the surface air mass balance above Antarctica is being explored. The impact of the top 10% of daily precipitation events across Antarctica has been evaluated using a regional atmospheric model simulation.[33] A key attribute of precipitation events is the penetration of warm, moist air masses over the ice sheet. Extreme precipitation events dominated the annual total being primarily responsible for interannual variations in snowfall. These results complicate interpretation of ice core records based on annual samples, pointing to the need for finer-scale records. The importance of surface melting for the future evolution of the Antarctic ice sheet was emphasized by the "ice-cliff instability" hypothesis, discussed below and the realization that widespread melting on Antarctic ice shelves could lead to break-up.[3,34] The extended summer melting event on the Ross Ice Shelf and Marie Byrd Land in 2016 originated from the poleward advection of maritime air into the continent linked to a strong ENSO event in the tropical Pacific Ocean.[35] Such extreme events may become more frequent as strong ENSOs become more common with consequences for the stability of the Ross and other large ice shelves (Q.2, Q.8, and Q.9). Projected increases in precipitation due to a changing climate may mitigate sea-level rise by partially offsetting ice melt loss.[36]

Cloud prediction is the largest uncertainty in atmospheric models over land ice, sea ice, and the ocean, with profound impacts on coupling with the underlying surfaces.[37] Predicting the correct proportions of cloud liquid water and cloud ice that govern the downward radiative fluxes from the atmosphere to the Earth's surface is especially challenging. A sensitivity study empirically demonstrated the importance of these surface radiation errors for simulations of large-scale Southern Hemisphere atmospheric and oceanic circulation.[38] Projections of future atmospheric change over the Southern Ocean remain uncertain, and persistent biases in climate models (including representation of clouds, winds, sea ice and ocean circulation, and stratification) require improvement (Q.7).

Southern Ocean and Sea Ice in a Warming World

The Southern Ocean connects the upper and lower limbs of the global overturning circulation that largely sets the capacity of the ocean to store and transport heat and greenhouse gases, especially carbon dioxide (Figure 2 and Tables S3 and S4). Recent insights into the dynamics of the overturning circulation suggest the upwelling and downwelling limbs of the circulation are localized by interactions of water flow with sea-floor topography (Q.12, Q.14, Q.19, and Q.21).[39–41] The buoyancy added by northward transport and melt of sea ice is now recognized as essential to transforming deep water to intermediate water in the upper cell of Southern Ocean overturning.[42–44] The strength of the Southern Ocean overturning circulation varies from decade to decade,[45] but understanding of sensitivities to changes in forcings remains incomplete.

Compelling evidence from models and observations shows that the Southern Ocean is the dominant contributor to ocean storage of anthropogenic heat and carbon dioxide, which is then swept northward by the overturning circulation, delaying warming near Antarctica and increasing the ocean inventory of anthropogenic heat and carbon dioxide further north (Q.6, Q.12, Q.14, Q.22, and Q.23).[46–48] At the time of the Scan, evidence from models and atmospheric observations suggested that the Southern Ocean carbon sink had declined, raising the prospect of a potential positive climate feedback. Recent ocean observations suggest that the decline in the 2000s was due to unanticipated decadal variability in the strength of the carbon sink, which has since returned to values observed in the 1990s.[49]

Since the Scan, Antarctic sea ice has shifted from record high to record low extents (Q.15, Q.17, and Q.23).[50] This dramatic, and unanticipated, shift underscored incomplete understanding of processes influencing Antarctic sea ice distributions. The decline in sea-ice extent has been linked to several local and remote forcing mechanisms.[17,51–53] Little was known about the impact of ocean surface waves on sea ice and ice shelves in 2014. Several studies have now demonstrated that surface waves can drive the break-up of sea ice and, in the absence of this protective buffer, contribute to destabilizing ice shelves (Q.18).[54–56] Basal ice-shelf melt by ocean heat transport beneath ice shelves, discussed further below, varies with time and is linked by atmospheric teleconnections to low latitude climate variability described above.[57] It is now known that melt from ice shelves and icebergs influences ocean circulation, sea-ice extent, and the rate of global temperature rise (see Q.14–16 and Q.23).[58,59]

Patterns of change in the Southern Ocean have been shaped by ocean circulation, particularly the overturning cells (Q.12–Q.23). Southern Hemisphere oceans are responsible for most of the last 15 years of increase in global ocean heat content.[60] Antarctic bottom water continues to warm, freshen, and reduce in volume, contributing to changes in ocean heat content and sea level,[61] reflecting multi-decadal trends and responses to episodic events such as iceberg calving.[62,63] The ocean and sea ice respond to and drive extreme events, for example, the recurrence of the Weddell Polynya[64] and recent reductions in sea-ice extent. Future responses will be driven by passive heat advection, freshwater inputs, and changing ocean currents.[41,47,48]

Antarctic Ice Sheets and Sea Level

Present-day continental Antarctic ice substantially contributes to global sea-level rise and will be increasingly important in the future (Figure 3 and Tables S5 and S6). While Antarctica's contribution remains the major uncertainty in extreme sea-level projections, especially on timescales of centuries to millennia, significant progress in addressing this uncertainty has been made. The loss of Antarctic ice on land is expressed far beyond the southern polar regions as global sea-level rise has widespread socioeconomic consequences.[65]

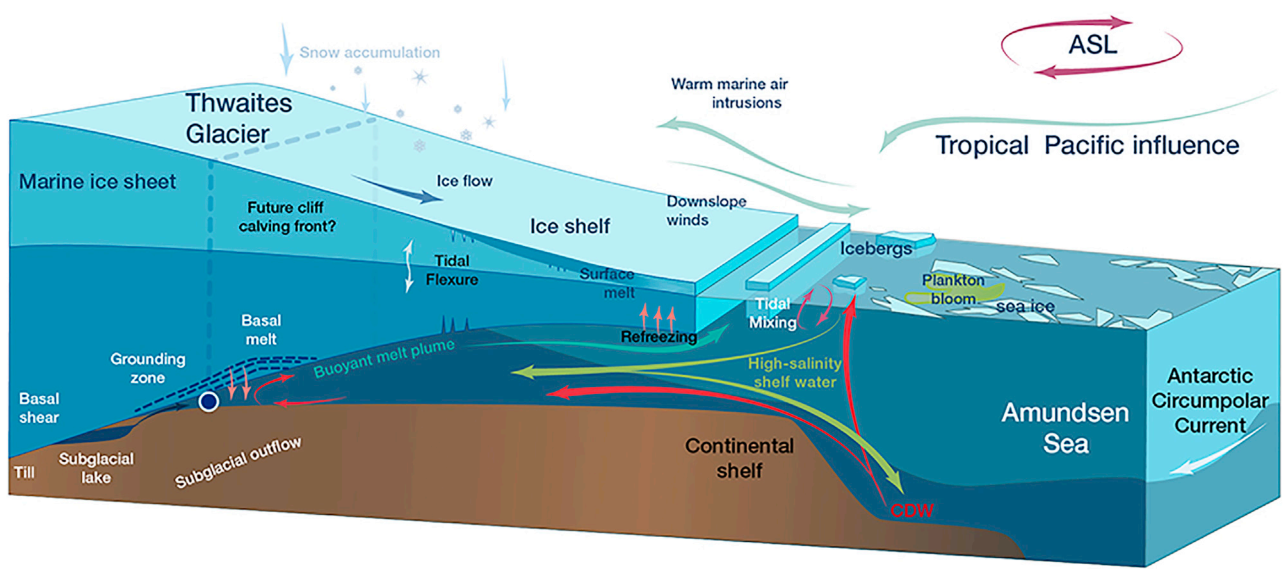

Figure 3. A Schematic Illustration of Key Aspects of the "Antarctic Ice Sheets and Sea Level" Theme
The principal influences on Antarctic glaciers such as snow, winds, and calving fronts are pictured using Thwaites Glacier as an example (CDW, Circumpolar Deep Water; ASL, the Amundsen Sea Low). Changes in marine ice sheets are initiated by changes in atmospheric and oceanic drivers that affect ocean circulation, surface precipitation accumulation, and summer surface-melt rate. Warm, dense mid-depth ocean water surrounding the Antarctic continental shelf is upwelled onto the continental shelf toward the ice fronts and ice-shelf grounding zones along troughs, causing increased melting and retreat at the ice-ocean interfaces. This thins the ice shelves, reducing drag along their sides and at local pinning points on sea-floor highs, which in turn reduces the buttressing. Thinning ice shelves lead to faster grounded-ice flow, leading to further thinning and causing previously grounded ice to float as the grounding zone retreats. Marine ice-sheet retreat is accelerated by surface-meltwater-driven hydrofracturing or other processes that lead to rapid calving of the ice shelf and ice front. Loss of the ice shelf may lead to cliff failure dramatically increasing the rate of grounded marine-terminating glacier calving. Changes in snow accumulation over glacier catchments can affect the timing of collapse and mitigate a portion of the sea-level contribution. This figure has been modified from the original source.[66]

Improved satellite observations indicate that the contribution of Antarctica to sea-level rise has increased in recent years.[67,68] The ice loss is concentrated in West Antarctica where the thinning of floating ice shelves is causing glacier flow to accelerate and grounding lines to retreat.[69,70] Several Scan questions relate to the need for a better understanding of processes underlying ice loss (Q.24–Q.27, and Q.29). As described above, thinning of ice shelves by ocean-driven basal melt is the primary contributor to accelerated mass loss from the Antarctic ice sheet (Q.30 and Q.31).[67,71] While most effort has focused on West Antarctica, recent studies reveal that some ice shelves in East Antarctica, once thought to be frozen in time, are also exposed to ocean heat and are experiencing rapid rates of basal melt.[72] These studies have concluded that the East Antarctic Ice Sheet as a whole is losing mass.[69] There is emerging agreement that the Marine Ice-Sheet Instability grounding-line retreat is triggered by ice-shelf thinning or destruction. Ice-shelf weakening is intensified, in addition to the basal melting by ocean warming described above, by changes in ocean circulation, hydrofracturing, and the loss of sea ice (Figure 3).[34,55,73,74] Biases in oceanic general circulation models (OGCMs) lead to uncertainties in estimates of the magnitude of future warm-water incursions.[75] With the advent of model intercomparison projects,[76] some OGCMs now include sub-ice-shelf cavities in their formulations.

Precise bathymetry is important for coupled ice-ocean models, but more detailed data are needed to improve forecasts (Q.24). Similarly, while understanding of internal ice-sheet processes has improved, feedbacks between them that may underly rapid ice-sheet retreat remain undefined. A feedback with the solid Earth, in which ice retreat leads to bedrock uplift and stabilization, may slow future ice loss (Q.40).[77,78] Other ice-ocean-atmosphere feedbacks have only recently been identified, and some, such as increasing meltwater slowing overturning circulation, have the potential to increase contributions to global sea-level rise.[5]

Recently, numerical ice-sheet models have incorporated more rigorous simulations of grounding line retreat. Several model intercomparisons have established benchmarks for simulations of Marine Ice-Sheet Instability (Q.25).[79] A second process, Marine Ice-Cliff Instability, has emerged as potentially significant for extreme projections,[3] although the necessity of including this process in models remains unclear.[80] Recent work has shown that the Thwaites Glacier, a major ice stream draining into the Amundsen Sea, may be under threat of collapse due to the nature and rates of bed changes. Some models simulate that a threshold for irreversible grounding line retreat has been, or is about to be, crossed in the next century and the probability of retreat is higher in warmer scenarios (Figure 3).[81,82] There have been several attempts to identify tipping points in terms of mean global warming, where parts of Antarctica ice sheets begin irreversible retreat (Q.28). Some suggest that avoidance of serious retreat requires a commitment to representative concentration pathway of 2.6 Watts/m^2.[3,4] Others suggest that a long-term tipping point exists at ~2°C of global warming.[79] However, tipping points are difficult to predict as ice-sheet dynamics are complex, and not all parts of an ice sheet are expected to simultaneously or similarly respond to global warming. Improved, finer-scale models are essential to validating these predictions.

Dynamic Earth: Probing beneath Antarctic Ice

The Dynamic Earth questions address the geological characteristics and processes beneath the ice (Tables S7 and S8). With only ~2% of the continent's bedrock exposed, these questions are best advanced by geophysical surveys and direct-access drilling (Figure 4). The challenge, given the scale of the continent, is survey coverage and density of sampling. Proxy-based studies of geological records provide further insights. The Scan questions remain essential to comprehending how geology is linked to ice sheet and climate processes in the past, present, and future. Progress has been made on a few of the questions, but most remain largely unanswered due to several factors.

The geophysical exploration of the continent is incomplete, hampering answers to questions in this theme. Despite 50 years of airborne geophysical surveying of Antarctica, continental coverage remains limited due to remoteness and the hostile conditions. The utility of existing data is restricted by spatial extent and resolution, logistical compromises, and platform and equipment limitations. However, there has been progress in measuring the magnetic field anomaly through airborne geophysical campaigns.[83,84] Similarly, knowledge of subglacial topography remains limited (Q.39), but existing and planned data compilations and analyses are progressing (Q.24, Q.26, and Q.27).[85,86] Magnetic field observations, seismic tomography, and radiometric radar analyses assist in defining geothermal heat flux (Q.36). Contradictory results indicate that more integrated regional and continental surveys will be necessary to advance understanding of the role of geothermal heat flux in geological processes and ice flow.[87,88] Although several nations are conducting systematic surveys, international cooperation and data intercomparability are lacking. A successful program, in this regard, is the Polar Earth Observing Network (POLENET), which has led to advances in knowledge of lithospheric properties through a combination of satellite, airborne, and ground-based measurements (Q.37 and Q.38).[89,90] This network of sensors is investigating systems-scale interactions of the solid earth, the cryosphere, the oceans, and the atmosphere. These measurements evaluate ice-sheet "budgets" to better understand polar ice-sheet contributions to global sea levels.

Progress in accessing climate records in subglacial environments is limited (Q.34). Attempts have been made to advance drilling technologies to access sub-ice targets[91,92], but none have achieved routine use. Ice coring is internationally coordinated[93] and, while these activities focus on retrieving ice samples for paleoclimate records, access to and sampling of the underlying bed are essential for validating models.[94] A rock-coring project to extend records of climate to the interior of the continent remains an aspiration.[95] Progress has been made in collecting proxy data from oceanic coring.[96] The challenge will be to integrate oceanic geological records with those from the interior of the continent, providing a more complete and varied record of past climates.

Existing data would be more impactful if they were organized within multi-disciplinary frameworks. Promisingly, international collaborations are emerging to use radar to investigate ice-sheet internal structure.[97] These efforts will advance understanding of geothermal heat flux, gaining knowledge of geological processes and their impact on ice flow.[98] There is a growing appreciation of multi-technique analyses in geophysics, and some

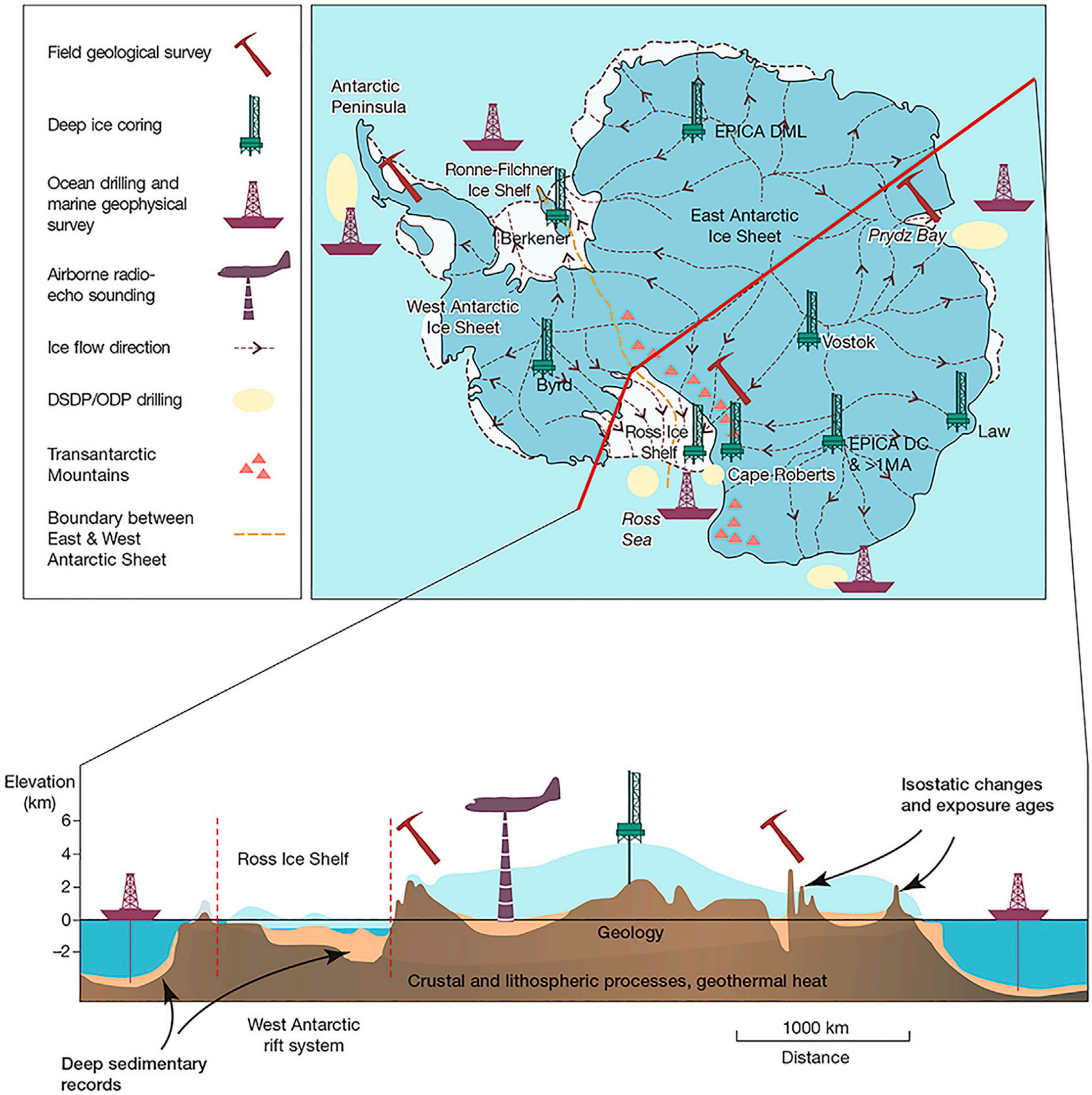

Figure 4. A Schematic Illustration of Key Aspects of the "Dynamic Earth: Probing beneath the Ice" Theme

The techniques and locations of past and current Antarctic subsurface sampling and/or measurements are presented. Questions addressing the geological characteristics and processes beneath the ice are best advanced by geophysical surveys and direct-access drilling on land and in the ocean. Surveys; sediment, ice, and rock sampling; and proxy-based studies of geological records provide insights into how geology is linked to ice-sheet and climate processes in the past, present, and future. The geophysical exploration of the continent is incomplete, and continental coverage remains limited due to remoteness and the hostile conditions. Integration and adoption of standard methodologies based on field geological surveys, deep ice coring (including basement sampling), ocean drilling, geophysical surveys, and continental airborne surveys are essential. Note that no deep sedimentary cores have been obtained from beneath the present grounded-ice cover.

projects are making data widely available.[99] Improvements in numerical modeling of geological processes are essential.[100] While vital to quantitative knowledge, and the only means to forecast future responses, models are currently limited by definition of inputs and the availability of validating datasets, such as those discussed above, beneath Antarctic ice sheets and in the interior of the continent. Other important questions have emerged since the Scan, including detecting and quantifying the presence of groundwater in Antarctica.[101] Projects are underway to make the first measurements; however, the geological and glaciological significance of continental groundwater remains unknown.

Antarctic Life on the Precipice

Antarctic Life on the Precipice is an expansive area of research given the scope of the life sciences, including consideration of the human-environment interface, the state of and trends in life-sustaining processes, questions of adaptational responses to change, and the efficacy of conservation practices given threats to biodiversity (Figure 5 and Tables S9 and S10).

Biodiversity and ecosystem responses to environmental changes are a major focus of Antarctic life sciences research. Progress has been made on understanding the effects of extreme events on biodiversity (Q.63). For example, ice-shelf loss leads to the loss of under ice-shelf communities while

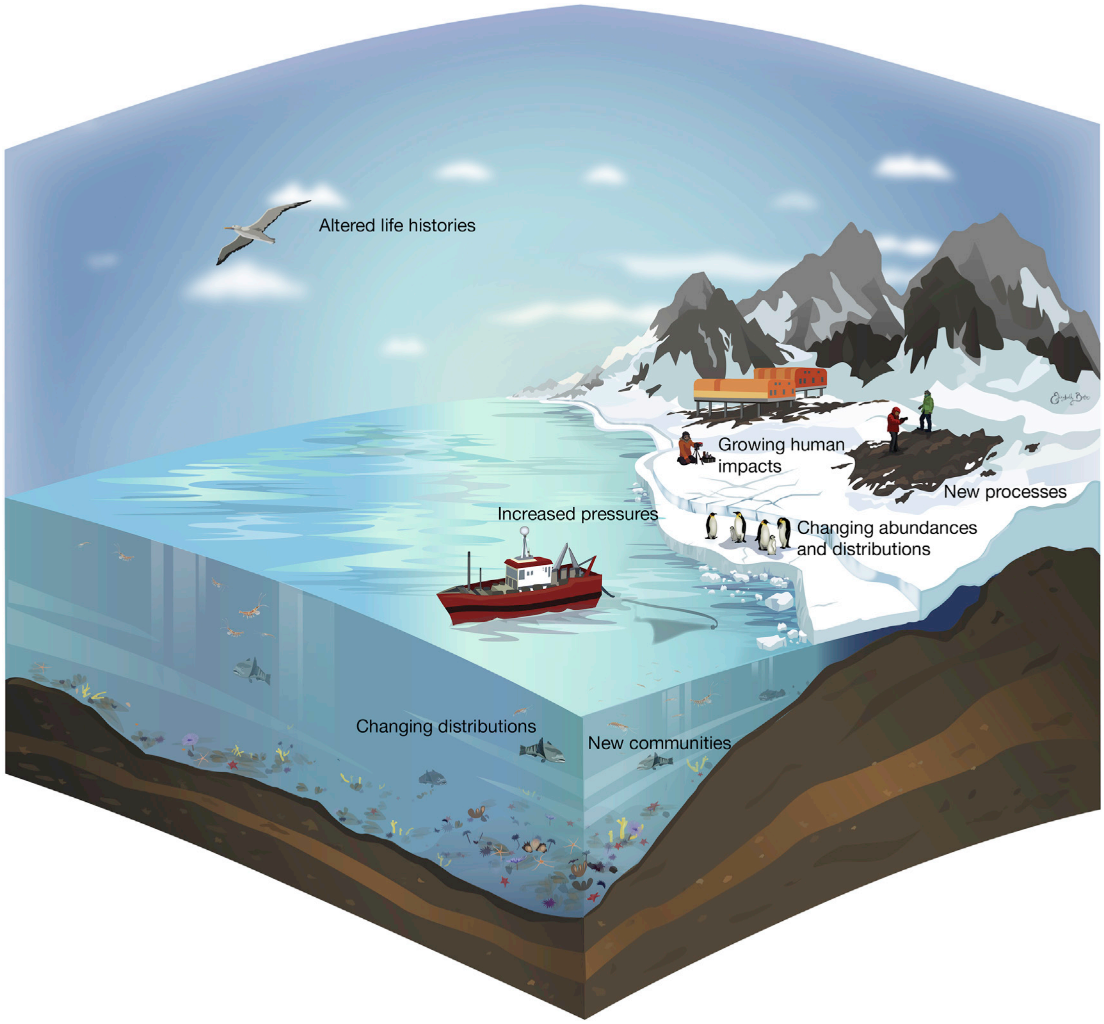

Figure 5. A Schematic Illustration of Key Aspects of the "Antarctic Life on the Precipice" Theme
Changing living environments in Antarctica provide new challenges for life sciences research. Recent research findings include (i) the discovery of new communities where ice shelves have disintegrated, (ii) high speciation rates among fish and brittle stars in marine systems, (iii) altered plant abundances and distributions and changing bird life histories in response to changing westerly winds, (iv) declining penguin abundance for some species and rapidly shifting distributions for others, (v) significant impacts of infrastructure including facilitation of the introduction of invasive species, and (vi) the discovery of microbial life in subglacial settings.

opening ocean and seabed areas to new colonization.[102–104] These events alter community structure and diversity, favoring carbon sequestration and resulting in greater CO_2 uptake.[105] The Brunt Ice Shelf collapse in the Weddell Sea provides a recent example of an extreme event that has eliminated habitat for the world's second largest Emperor penguin colony,[106] reprising a previous extreme event in East Antarctica.[107] In terrestrial systems, a flood event during 2001–2002 in the McMurdo Dry Valleys changed the system dramatically in the years that followed, with asynchronous responses among different components of the living environment.[108] Responses to slower change (e.g., non-extreme events) have also been documented. For example, changes in climate, in part due to an increasingly positive Southern Annular Mode, have led to drying in East Antarctica, re-arranging moss assemblages from those dominated by moisture-preferring endemics to those dominated by more drought tolerant widely distributed species.[109] On the Antarctic Peninsula, moss communities have shown rapid increases in microbial productivity and moss growth and accumulation rates since the 1950s, across a record spanning of more than 150 years.[110] In marine systems along the Antarctic Peninsula, southward shifts in the distribution of krill, leading to declines of abundance in the north and increases in the south, have also been documented, with profound implications for predators, ecosystems, and their interactions with fishing interests in krill.[111] Questions that remain largely unaddressed include the effects of year-round ice-free intertidal conditions on biodiversity (Q.57 and Q.60), the impact of introductions of alien species (Q.54 and Q.55), the response of Antarctic marine species to changing soundscapes (Q.51), and the synergistic effects of multiple stressors on Antarctic biota (Q.50). Studies of the effects of changing ocean front dynamics are also limited (Q.22 and

Q.65). What future sea-ice loss and habitat loss will mean for winter-breeding seals, effects on pelagic and epontic productivity, and impacts on benthic resource supply remains poorly known (Q.59 and Q.60).[7] Prominent Antarctic drivers are altered climate and resulting changes in Southern Ocean physical and chemical properties, sea-ice extent and phenology, pollution, invasive species, and direct human impacts, including fisheries activities.[112] Approaches have broadened, but large-scale studies assessing multiple, potentially cumulative drivers acting in synergy remain scarce. Likewise, questions in the life sciences theme require long-term monitoring, repeated observations, and/or extended time series. Such questions include those that address the impacts of changing environments, tectonics, volcanism, and ice-sheet mass loss on biodiversity, and the effects of ozone hole recovery on ecosystems (Q.11, Q.23, Q,41, Q.46, and Q.63). Yet such long-term research is uncommon.

Answers to questions about biological adaptations, including the resilience of organisms and changes in ecosystem functioning, have advanced. Understanding of species-level physiological responses to acidification and to temperature change continues to develop, and temperature effects appear to elicit greater responses (Q.49).[113] Advances have been made in identifying the most vulnerable ecosystems and predicting their responses to environmental changes (Q.48). However, there are few studies of the cascading effects from future sea-ice reduction or habitat or ecosystem loss. Genome-enabled studies have improved understanding of adaptations,[114,115] mutation rates, and gene flow (Q.43, Q.44, Q.54, and Q.64). Characterization of the Antarctic icefish genome revealed cold-adapted phenotypes (a lack of functional hemoglobin genes and red blood cells), genes encoding antifreeze glycoprotein involved in protection from ice damage, adaptations to the high concentration of oxygen dissolved in cold Antarctic waters, and possibly compromised control of biological rhythms in polar light environments.[115] Better comprehension of differential expression patterns of genes and dispersal in Antarctic environments in macrobiota and microbial systems have contributed to knowledge of adaptation.[116–118] Other areas, such as "-omics" analyses of biodiversity for ecological forecasting, have made less progress (Q.64). Understanding of paleo-ecosystem responses to previous warmer periods and past extreme events has improved with the identification of refugia during glacial maxima, which made the survival of life possible during ice ages, and the contribution of Antarctic biodiversity to global species richness (Q.45 and Q.46), furthering knowledge of the evolution of Antarctic biodiversity.[119–122] Some progress has been made on subglacial ecosystems and biogeochemical processes in isolated systems (Q.45).[123]

Novel contaminants are arriving in Antarctica, and progress has been made in understanding impacts at the cellular, physiological, and population levels, furthering knowledge of the responses of potentially sensitive biota (Q.52 and Q.53).[124–126] The ubiquity of plastics and microplastics in the Southern Ocean is now widely recognized, but impacts on Antarctic biota remain to be fully investigated, although it is known that macro-plastics pose a significant threat to seabirds.[127,128]

Understanding of climate interactions with invasive species and diseases is limited. Invasive species research has identified the sources and types of propagules as well as their pathways to Antarctica (Q.54).[8,129,130] Distinguishing range shifts from introductions remains underinvestigated, as do studies of potential impacts (Q.55).[131,132] Climate-change impacts on establishment likelihood have been evaluated, although species distribution modeling is underutilized. There are few investigations of how climate-change effects on sea ice and physical access to fishing grounds will affect fisheries, krill stocks, and krill-dependent predators. Little is known about changes in marine biogeochemistry that might be caused by fishery-induced fluctuations in krill stocks (Q.58 and Q.61).[111,133,134]

Understanding of direct human impacts on the Antarctic, such as large-scale human modifications associated with the emplacement of infrastructure, will require long time-series monitoring (Q.74, Q.75, Q.76, and Q.80). While relatively few Antarctic terrestrial sites have witnessed large-scale modification, more than half of the accessible coastline is estimated to have been affected.[135] "Human footprint" assessments of infrastructure and associated activities in ice-free areas are developing using remote sensing techniques. Indications of large-scale environmental modification are emerging. Threats to Antarctic biodiversity from increasing global exploitation of ecosystem services, among other stressors, remains an unrealized research priority (Q.58 and Q.61), although the importance of investigating global stressors has been identified.[112,136]

Human-associated viruses have infected Antarctic marine mammals and birds, and diseases have been studied using genomic technologies (Q.56 and Q.80).[137] Climate-change effects on these interactions remains largely unknown and are an important focus for future research. Improving biosecurity measures in Antarctica is fundamental, as it has been shown that alien species and pathogens can be resilient.

The recently adopted Ross Sea Marine Protected Area (MPA), the second international MPA adopted in Antarctica, is an example of progress in implementing conservation measures. However, the efficacy of these MPAs in meeting protection objectives (Q.66) remains unknown, particularly given some of the trade-offs required for approval.[12,138] Research is underway to assess and monitor the MPAs, including how they might protect ecosystem processes despite resource extraction. By contrast, in terrestrial systems, substantial work has covered the effectiveness of the current Antarctic Specially Protected Area system in representing the Antarctic's ecoregions (known as Antarctic conservation biogeographic regions) and biodiversity more generally.[139,140] The work has also indicated how the protected area system can be expanded and what might be required to meet either regional or global aspirations.[8] Evolutionary potential assessments of protected areas have not, but they should be made. A systematic evaluation of *ex situ* conservation has not been undertaken, although the first Antarctic genetic repository has been established (Q.67). This effort needs expansion and procedures to preserve and make samples widely available need to be agreed.

Near-Earth Space and Beyond: Eyes on the Sky

The Eyes on the Sky questions address two foci, astronomy and near-Earth space (geospace), that use Antarctica as a platform to gaze spaceward. The stable atmospheric conditions, radio quiet areas, and year-round observations have led to an array

Figure 6. An Image of Important Infrastructure in the Antarctic that Underpins Key Research in the "Near-Earth Space and Beyond: Eyes on the Sky" Theme
Antarctica has several important advantages for studies of space-related phenomena, both solar-terrestrial and astronomical. Extremely stable atmospheric conditions and expanses of radio quiet areas, together with the ability to observe objects continuously throughout the long winter or summer, offer unique conditions for observing the aurora australis (southern lights), distant stars, supernova explosions, and the cosmic microwave background. Pictured above is the 10 m South Pole Telescope (left) and the IceCube Neutrino Detector (right) at South Pole Station, framed by the aurora. The IceCube array searches for elusive particles called neutrinos, believed to emanate from exotic astrophysical objects such as quasars and black holes, while the South Pole Telescope explores the afterglow of the Big Bang. Closer to Earth, optical and radio experiments investigate the southern lights, which are produced by electrons (and protons) that strike the gases in the upper atmosphere. Electrical currents that are produced during such auroral displays can have deleterious effects on space-borne and ground-based technological systems, disrupting satellite electronics, global positioning satellite signals, and power grids and exposing people to radiation.[141]

of world-class facilities and laboratories in Antarctica (Figure 6 and Tables S11 and S12).

Astronomy questions address the origin of the universe and its content. Recently, the field of astrophysics has undergone a technological revolution. In the past, observations were photonic in nature, capturing information across the electromagnetic spectrum. Information now comes from gravitational wave[142,143] and high-energy particle observatories.[144,145] The "multi-messenger" astrophysics era began with the South Pole IceCube Neutrino Observatory, which identified the first high-energy neutrino source.[146,147] The Event Horizon Telescope, a network that includes the South Pole Telescope, captured the first image of a black hole.[148] This discovery confirmed several elements of general relativity and enables the study of dark matter.

The South Pole Telescope is one of several observatories[149,150] in Antarctica that study the Cosmic Microwave Background radiation, the oldest electromagnetic radiation in the universe. Precise measurements of the Cosmic Microwave Background are critical to validate models of the universe. To achieve greater resolution, observatories will increase detector density from hundreds to tens of thousands by the early 2020s. These improvements may lead to the discovery of primordial gravitational waves originating in the early universe, that, if observed, would confirm cosmic inflation models. The discovery of B-mode polarization of the Cosmic Microwave Background caused by gravitational lensing is testing theories of the formation of the universe.[151] The multi-messenger approach is rapidly advancing the search for dark matter. Sources of gravitational waves, such as neutron stars or black hole mergers, release high-energy neutrino emissions. Laser Interferometer Gravitational-Wave Observatory and IceCube collaborations have revealed cosmic explosions,[142,145,152] previously unseen by conventional photonic observations. The understanding of the full nature of dark matter remains aspirational. IceCube is designed to detect neutrinos originating from the decay of dark matter.[147]

Antarctica is a key observing platform and a unique window for the study of a broad range of geophysical phenomena, spanning magnetic and geographic latitudes. The high-latitude middle and upper atmosphere is a complex system with energetic and dynamical inputs coupled with internal feedback processes. From the outer magnetosphere and solar wind, energetic particles and waves follow magnetic field lines into the middle and upper atmospheric system. From the lower atmosphere gravity waves, planetary waves, and tidal waves propagate upward, depositing energy and momentum. Within the system, a mixture of neutral constituents and ionized gases, complex chemical reactions, and magnetic and electric fields generate several processes with local and global feedbacks.

Since the Scan, instrumentation for geospace research has increased, and progress has been made in understanding the sources of atmospheric gravity waves in and around Antarctica,[153] the effects of energetic particle precipitation,[154] and magnetic and neutral atmospheric "interhemispheric conjugacy." For example, atmospheric gravity wave observations from the McMurdo lidar[155] and the Antarctic Gravity Wave Instrument Network all-sky imager[153] have characterized polar vortex waves. The NASA Balloon Array for Radiation-belt Relativistic Electron Losses mission has observed localized and temporally constrained energetic particle precipitation associated with radio wave activity.[156,157] The interhemispheric impacts of polar vortex variability during stratospheric warmings have now been recognized.

The term "space weather" generally refers to Sun condition, the solar wind, and geospace events that affect the performance and reliability of space-borne and ground-based systems. Besides emitting the solar wind, the Sun periodically releases billions of tons of matter via coronal mass ejections. Immense clouds of material can move toward Earth, causing large magnetic storms that disrupt radio and Global Positioning Satellite signals, shut down electrical systems, and expose people to radiation. Antarctic observations are critical to devising innovative responses to real-time events and improving space weather forecasts.[158]

Human Presence in Antarctica

A complex network of legal and political regimes and obligations underpin questions about the status of present, and possible future of, the Human Presence in Antarctica (Tables S13, S14, and S16). Antarctic governance, geopolitics, and tourism research has explored the geopolitical configurations of power in the Antarctic and beyond (Q.76 and Q.78).[159] Assessments of pressures on the Antarctic are co-entangled with global resource futures.[160] Antarctic tourism is experiencing rapid growth and diversification, which has led to novel regulatory options being proposed.[161] As Antarctica changes and anthropogenic pressures increase, these relationships will require re-examination.

Understanding future human engagement with the Antarctic requires integration of research in political geography, international law, and international relations focusing on concepts of science, peace, and global legal norms as well as barriers to access (Q.77). Recent research on the politics and political importance of science and peace in the Antarctic builds on preceding work.[162,163] The next generation of research will need to address how the politics of anticipation (either environmental or non-environmental anticipation and cultures of forecasting)[164] are tied to the distribution of capacities, the symbolic and material dimensions, and the role played by different actors with interests in Antarctica and beyond.

Geoengineering options are being discussed as a potential solution to mitigate climate-change impacts,[165,166] although the techniques often do not address ocean acidification or greenhouse gas emissions reduction, especially those that manipulate solar radiation. The assessments of the impacts of geoengineering are only now starting to be made;[166,167] except for discussions of controversial proposals for iron fertilization of the Southern Ocean.[168–170] Research in the broader Antarctic region on geoengineering impacts has yet to be undertaken (Q.74 and Q.75) and more transdisciplinary methodologies will be required. Equally, the identification and classification of ecosystem services, of political and economic importance in other regions of the planet, have seen little progress in the Antarctic. One exception is the mapping of ecosystem services in the Weddell Sea (Q.79), although the importance of research in this area is now recognized.[7,171]

Many questions of human presence build on future trajectories and scenarios, which, as discussed above, will benefit from refinements. The politics of knowledge production must be connected to political and ideological effects. Scientific knowledge does not necessarily lead to anticipatory action designed to repair or restore ecological states. There is an implicit assumption that if more reliable and robust information is available, then rationality and evidence will underpin actions. In contrast, research on human behavior concludes that "affect-based framings" drive motivations that lead to action. Science-based evidence from the Antarctic is adversely affected by larger societal trends, such as skepticism about authority figures, data and information overload, paranoia about elites and their agendas, and indifference and apathy due to the "hyper-object" effect—issues (such as climate change) of such vast temporal and spatial dimensions that they challenge traditional ideas about how to motivate people to action.[172]

In the future, lessons from the field of the politics of anticipation in environmental futures will need to be utilized to better communicate the importance of Antarctic research.[173–177] Lessons learned about how change is communicated through media images, artwork, whalers' logs, diaries, newspapers, and the like[178–180] will be essential to framing complex concepts in understandable ways. These improved framings are needed as knowledge counters long-held popular assumptions that Antarctic environments are pristine, stable, isolated, and reliably frozen. Communicating urgencies to the public is hampered by gaps in our understanding of how people and society are motivated to make better choices, especially if these choices entail sacrifices today to avoid catastrophic outcomes in a distant future.

Engaging Diverse Audiences

There is an extensive literature on engaging diverse audiences within the field of science communication; however, epistemological and methodological challenges remain.[181,182] Research on climate-change communication has grown over the last decade, partly focusing on the benefits of communicating science via advocates, brokers, and "science translators."[183,184] Public engagement with science is changing, and with it our understanding of the importance of sentiments in climate-change discourse. Emerging concepts include gendered and other intersectional responses;[185,186] the utilization of augmented reality, virtual reality, and other digital visualization tools in communicating messages;[187,188] and active engagement based on "establishing trusted two-way communication."[184,189] The Antarctic community has much to learn from science communication research, although these lessons are being applied.[190–194] Research is increasing understanding of the linkages between knowledge, sentiment, and action in science as well as governance.

The goal of engaging diverse audiences is informed by the lessons learned from assessing how, by whom, and why the outputs from the Scan and ARC were used. Scan and ARC planning documents explicitly defined the intended audiences (Tables S15 and S16).[24,25] One audience was the international Antarctic research community, including the International Science Council's Scientific Committee on Antarctic Research (SCAR).[195] SCAR is the premier international body facilitating scientific research in, from, and about the Antarctic, and under whose auspices the Scan was undertaken. SCAR's dual mission includes providing independent science advice to the Antarctic Treaty System linking science to policy. Another audience was the funders and supporters of Antarctic research, including the coordinating body, the Council of Managers of National Antarctic Programs (COMNAP), under whose auspices ARC was undertaken.[196] A third audience was the Antarctic Treaty System and its array of associated organizations, committees, and observers that depend on scientific advice for decision and policy making (Table S16). And finally, there were audiences such as non-governmental environmental and advocacy groups, academia and teachers, next-generation scientists, and the public. The delivery of Scan and ARC outputs was assessed to discern the lessons learned and where improvements might be pursued (Table S15).

Scan publications were widely used by the scientific community with citations in the peer-reviewed literature, dissertations and theses, book chapters, and policy papers, spanning all Antarctic disciplines (Table S15). Several post-Scan publications address and/or expand on Scan priorities.[130,197,198] The Scan is referred to in national Antarctic science plans and calls for proposals. Several non-Antarctic horizon scans reference the Scan as an exemplar model. SCAR's strategic plan (2017–2022) describes how the Scan was used "… to guide research priorities and research directions over the next six years and beyond …."[199] The Scan has served as justification for the formation of new SCAR Scientific Research Programs, existing SCAR groups have framed priorities based on the Scan, and international workshops, meetings, and conferences have been organized within the Scan framework.

The ARC project was the first action attributable to the Scan and was directed at the governmental entities that fund and provide logistical support for Antarctic research. The outcomes of ARC were widely distributed and contributed to a restructure of COMNAP's Expert Groups. ARC provided individual National Antarctic Programs with a better understanding of future science support needs. National Antarctic policies highlight science as a policy goal and tool and often point to the themes identified by the Scan. Several countries have incorporated Scan questions into their strategic planning and have used the outcomes to judge the importance of existing programs and projects, and whether realignments are needed.

It is early to judge how the Scan has informed ideas and practices of Antarctic governance and conservation. SCAR has reported information about the Scan to the Antarctic Treaty Parties. Reports of Antarctic Treaty Consultative Meetings (ATCMs), the Committee on Environmental Protection (CEP), and the Science Committee of the Convention for the Conservation of Antarctic Marine Living Resources (SC-CCAMLR) refer to the Scan and/or ARC (Table S15).

Regarding outreach to the public, the organizers of the Scan conducted many media interviews before and after the Scan event, including print, TV, and radio, and made presentations to multiple organizations. Media ecologies are rapidly changing, posing opportunities and challenges for communicating the co-production of knowledge and understanding of the importance of the Antarctic to the rest of the world.[200]

The Scan and ARC influenced diverse audiences, lending insight into how future research and information can be more effectively mobilized and utilized. Many factors determine the influence, reception, and uptake of futures studies.[22] Judging impact and uptake can be elusive due to limited acknowledgment of usage beyond periodical literature attribution. In the policy arena, the origins and pathways to advice are often obscured as it is blended with other inputs and influenced by non-scientific factors. In the future, the findings of Antarctic research need to be more widely distributed via social media and emerging alternative forms of communication, such as short videos, hashtag campaigning, and podcasts.

Conclusions and Outlook

The view from the south is, more than ever, dominated by ominous signs of change. Over the past 5 years, addressing the priorities identified by the Scan have led to new insights of global significance (Tables S1–S14). While much has been accomplished, much remains to be learned, and a renewed commitment to gathering further knowledge will quicken the pace of our understanding of Earth systems and beyond.

Current knowledge of the Antarctic is constrained by a lack of critical observations, due in large part to the vastness, remoteness, and inaccessibility of much of the region and exacerbated by often-severe weather conditions and yearly months of darkness. The ARC identified "access" to the continent and surrounding oceans as one of the major challenges in implementing the Scan Antarctic science roadmap.[21,23] In contrast to direct physical access, the ability to view the globe from satellites, and with airborne sensors, has revolutionized Earth, and at the same time Antarctic, science.[201] Observations support the development, refinement, and calibration of Earth system models for forecasting futures. For the Antarctic, improved models are needed that accurately represent key elements of the Antarctic system, including the atmosphere, the ocean, sea ice, ice sheets and shelves, the solid earth beneath the ice and sea, and the biota and ecosystems within; and the interactions, couplings, and feedbacks between these spheres. Underpinning observations are process studies that further inform model development and parametrization while also serving as validating datasets. There are a range of activities addressing the need for Earth system observations, model development, and process studies, including the Group on Earth Observations (GEO),[202] the Global Climate Observing System (GCOS) of the World Meteorological Organization,[203] the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO),[204] national space agencies (e.g., US National Aeronautics and Space Administration Earth Observations [NEO][205] and the European Space Agency Observing the Earth[206]), the SCAR programs described above, and others.

As an intrinsic part of the Earth system, a commitment to an ambitious and sustained Antarctic research plan going forward is essential, including:

- Gathering multi-year data via integrated region-wide suites of autonomous instruments monitoring surface to lower stratosphere atmospheric state, turbulent and radiative fluxes, and atmospheric composition to advance atmospheric and climate models.
- Enhancing observations of the Southern Ocean, in tandem with atmospheric observing systems above, via an integrated observing system that illuminates the "blind spot" in present ocean observing efforts below sea ice and floating ice shelves and on the Antarctic continental shelf, delivering the process-level understanding needed to clarify the vulnerabilities of the Antarctic ice sheet and sea ice to ocean change.
- Expanding deployments of instrumental arrays that capitalize on the revolution in ocean sciences brought about

by autonomous instruments (e.g., profiling floats and animal-borne sensors). These arrays will collect continuous observations that cover the full ocean depth equipped with a broad suite of physical and biogeochemical sensors. Observations provide the mechanistic understanding necessary for anticipating the impacts of Southern Ocean change on climate, sea level, and biogeochemical cycles and the cascading effects on biota and ecosystems.
- Combining the broad-scale ocean observations above with detailed process studies and a hierarchy of numerical simulations to better define the sensitivities of Southern Ocean overturning circulation (and therefore the ocean heat and carbon sink) to changes in forcings.
- Systematically and comprehensively surveying the Antarctic continental ice sheet to improve knowledge of ice-sheet dynamics and critical thresholds that accelerate ice loss and sea-level rise.
- Expanding the coverage of high-resolution swath bathymetry surveys of the bed beneath the Antarctic ice sheet by aircraft and/or satellites to develop better representations of grounding line dynamics in models.
- Developing and deploying multi-sensor autonomous (adaptive and self-managing) unmanned underwater vehicles in difficult to sample, biological "hotspots" and rapidly changing environments that complement the observatories above. Observatory networks should also be placed in key coastal regions, such as Wilkes Land and Aurora and Recovery Glaciers. These networks will detect early signs of change, the onset of tipping points, and better define forcings serving as an early warning system of impending, possibly irreversible, change.
- Implementing a coordinated network of systematic, interdisciplinary circumpolar oceanographic campaigns to produce biological time series, coordinated with the ocean and atmosphere observing above, to elucidate biotic-abiotic interactions and to monitor the status and trends of indicators of the health and trajectories of Antarctic ecosystems.
- Establishing a complementary terrestrial circumpolar life observatory network to provide terrestrial/coastal biological time series to detect and monitor species colonization, local extinctions, and invasions.

Beyond the future research directions above, there are a series of important efforts that need to be undertaken in the Antarctic that complement and support enhanced observations and modeling. These additional elements are presented for the Scan themes; however, most are transdisciplinary and cross-cut themes with progress in one area dependent on developments in others, calling for international coordination, cooperation, and integration for greatest effect. A final set of research priorities addresses effective communication with stakeholders that will fortify calls to action.

Ongoing priorities for future Antarctic atmospheric research are:

- Refining the details about teleconnections between low, mid, and high latitudes.[207]
- Increasing computational capacity to improve atmosphere-ocean coupled climate simulations via large-ensembles treatment of small-scale processes that better isolate the effects of natural variability and highlight anthropogenic signals.

Ongoing priorities for future Southern Ocean, sea ice, ice sheet, and sea-level research are:

- Improving definition of the role of variability in Antarctic sea ice and ocean-ice-shelf interactions as key forces driving future climate and sea-level change.
- Setting the boundary conditions for future trajectories of, and rates of change in, the West and East Antarctic Ice Sheets to better constrain understanding of the societal consequences of sea-level rise.[5,67]
- Augmenting understanding of the processes underlying, and the geographical distributions of, basal hydrology, ice damage, calving, ice cliff failure processes, and hydrofracturing, refining ice-sheet model parameterization and improving forecasts.
- Continuing and expanding model intercomparison experiments to further illuminate key processes that are essential to improving coupled ocean/sub-ice-shelf cavity/ice-sheet models within a global system context.[6,208]

Ongoing priorities for future Antarctic solid earth sciences research are:

- Completing comprehensive geophysical exploration of the continent, improving access to subglacial environments, integrating synthesis of existing and future data, and improving numerical models of geological processes.
- Collecting further marine sedimentary records to advance understanding of past changes in ocean circulation by identifying forcings and ice sheet-ocean interactions that are difficult to directly observe; establishing a network of trans-continental sites to complement ongoing and planned oceanic expeditions and recover unique paleoclimate records from Antarctica's interior that will expand knowledge of the past and validate forecasts.
- Adopting holistic systems models to co-determine glacial, subglacial, and oceanic processes and responses to improve forecasts.

Ongoing priorities for future Antarctic life sciences research are:

- Continuing to improve understanding of the factors that lead to loss of biodiversity, how ecosystems respond to changing environments, identifying biological adaptations, defining strategies of resilience, and assessing the efficacy of conservation practices.
- Exploring and better defining the complex downstream implications of ozone hole recovery and its relationship to the Southern Annular Mode for Antarctic and Southern Hemisphere ecosystems.[15,16]

Ongoing priorities for future Antarctic social sciences and humanities research are:

- Improving our understanding of human interactions with the environment, better defining possible governance responses in the face of change and discerning flow-on effects in the Antarctic from external geopolitical influences.

- Defining how changing Antarctic ecosystem services will affect resource regulation as pressures to capitalize on its resources increase.[7,12]
- Exploring the role of civic epistemologies in driving interactions within the complex network of organizations in Antarctica to better understand why scientific agreement on climate change fails to stimulate political action.
- Improving messaging of Antarctic urgencies to diverse audiences by exploring the use of augmented and virtual reality and artificial intelligence in communicating complex scientific datasets and concepts to immerse people in a region of the planet most will never visit.
- Utilizing big data via supercomputing and artificial intelligence to better understand human decision making and behavior using agent-based models and how this applies to Antarctic science communication.
- Exploring the role of "surveillance capitalism" and "predictive economies of action" concepts in the context of Antarctic data economies, including how data are collected and used to influence and manipulate human behavior.
- Evaluating the implications of earthly surveillance in geopolitics, economics, and culture as "capital."

In closing, the slogan of the 2019 UN Climate Action Summit (UNCAS)[209] is "a race we can win," a win that is only attainable if a credible and effective path to the future is defined. Credibility—the capability to persuade others that something will happen or be successful—is fundamental to the global debate on climate change and how societies will, or will not, respond. In this review, the critical role of Antarctic science in "making the case" for concerted action is highlighted. A better understanding of the drivers, underlying processes, feedbacks, transitions, tipping points, and rates of change within the Antarctic region will, in large measure, dictate how "winnable" this race will be. Critical thresholds that foretell changes of state, sometimes irreversible, are needed to provide unambiguous signposts of trouble ahead and indicate necessary course corrections. This review summarizes not only what we know, but more importantly what we do not yet know. As 2019 UNCAS states "… there is a growing recognition that affordable, scalable solutions are available now that will enable us all to leapfrog to cleaner, more resilient economies …." But the central question remains, is there "… the political will necessary to move forward on ambitious climate action for the benefit of all aspects of society … "?[209] It is abundantly clear that no one nation can accomplish the ambitious Antarctic research roadmap laid out in this review and that climate change calls for an "all-nations" commitment to common cause as the window for action on climate change closes.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2019.08.014.

ACKNOWLEDGMENTS

M.C.K. acknowledges the contributions of all those who contributed to the original Horizon Scan and Antarctic Roadmap Challenges projects and to the research that has since been done to address their outcomes. The Tinker Foundation played a significant role through partial funding of the original projects and support of the Tinker-Muse Prize for Science and Policy in Antarctica. M.C.K. and S.L.C. acknowledge the editing and review assistance of Lucy Klein of Monash University.

AUTHOR CONTRIBUTIONS

M.C.K. and S.L.C. served in the roles of conceptualization, supervision, project administration, writing original draft, writing review and editing. B.N., C.R., D.B., D.L., L.P., M.J.S., S.R.R., and T.T. served in the roles of section lead author, writing original draft, writing review and editing. A.A., A.M., C.M.B., C.L.B., D.C., D.M.S., D.G.V., H.Y., J.C., K.D., L.T., L.W., M.L., M.N.R., M.R.-F., N.R.G., P.C.N., and S.C. served in the roles of section supporting author, writing original draft, writing review and editing.

DECLARATION OF INTERESTS

M.C.K is a past-president of SCAR (2008-2012), and S.L.C. is president of SCAR (2016–2020). The remaining authors declare no competing interests other than a life-long appreciation and a personal commitment to preserving the majesty of Antarctica, an obligation to future generations to be good stewards of our planet, and a pledge to strive for a brighter, more sustainable future.

REFERENCES

1. Dutton, A., Carlson, A.E., Long, A.J., Milne, G.A., Clark, P.U., DeConto, R., Horton, B.P., Rahmstorf, S., and Raymo, M.E. (2015). Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science *349*, aaa4019.
2. Gasson, E., DeConto, R.M., and Pollard, D. (2016). Modeling the oxygen isotope composition of the Antarctic ice sheet and its significance to Pliocene sea level. Geology *44*, 827–830.
3. DeConto, R.M., and Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. Nature *531*, 591–597.
4. Golledge, N.R., Kowalewski, D.E., Naish, T.R., Levy, R.H., Fogwill, C.J., and Gasson, E.G. (2015). The multi-millennial Antarctic commitment to future sea-level rise. Nature *526*, 421.
5. Golledge Keller, E.D., Gomez, N., Naughten, K.A., Bernales, J., Trusel, L.D., and Edwards, T.L. (2019). Global environmental consequences of twenty-first century ice-sheet melt. Nature *566*, 65–72.
6. Colleoni, F., Santis, L.D., Montoli, E., Olivo, E., Sorlien, C.C., Bart, P.J., Gasson, E.G.W., Bergamasco, A., Sauli, C., Wardell, N., et al. (2018). Past continental shelf evolution increased Antarctic ice sheet sensitivity to climatic conditions. Sci. Rep. *8*, 11323.
7. Rogers, A.D., Frinault, B.A.V., Barnes, D.K.A., Bindoff, N.L., Downie, R., Ducklow, H.W., Friedlaender, A.S., Hart, T., Hill, S.L., Hofmann, E.E., et al. (2019). Antarctic futures: an assessment of climate-driven changes in ecosystem structure, function, and service provisioning in the Southern Ocean. Annu. Rev. Mar. Sci. *12*, https://doi.org/10.1146/annurev-marine-010419-011028.
8. Chown, S.L., Brooks, C.M., Terauds, A., Bohec, C.L., van Klaveren-Impagliazzo, C., Whittington, J.D., Butchart, S.H.M., Coetzee, B.W.T., Collen, B., Convey, P., et al. (2017). Antarctica and the strategic plan for biodiversity. PLoS Biol. *15*, e2001656.
9. Rintoul, S.R., Chown, S.L., DeConto, R.M., England, M.H., Fricker, H.A., Masson-Delmotte, V., Naish, T.R., Siegert, M.J., and Xavier, J.C. (2018). Choosing the future of Antarctica. Nature *558*, 233–241.
10. Brooks, C.M., Crowder, L.B., Curran, L.M., Dunbar, R.B., Ainley, D.G., Dodds, K.J., Gjerde, K.M., and Sumaila, U.R. (2016). Science-based management in decline in the Southern Ocean. Science *354*, 185–187.
11. Trivelpiece, W.Z., Hinke, J.T., Miller, A.K., Reiss, C.S., Trivelpiece, S.G., and Watters, G.M. (2011). Variability in krill biomass links harvesting and climate warming to penguin population changes in Antarctica. Proc. Natl. Acad. Sci. U S A *108*, 7625–7628.
12. Brooks, C.M., Ainley, D.G., Abrams, P.A., Dayton, P.K., Hofman, R.J., Jacquet, J., and Siniff, D.B. (2018). Antarctic fisheries: factor climate change into their management. Nature *558*, 177–180.
13. Lee, C.K.F., Duncan, C., Owen, H.J.F., and Pettorelli, N. (2018). A new framework to assess relative ecosystem vulnerability to climate change. Conserv. Lett. *11*, e12372.

14. Farman, J.C., Gardiner, B.G., and Shanklin, J.D. (1985). Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction. Nature *315*, 207–210.
15. Bornman, J.F., Barnes, P.W., Robson, T.M., Robinson, S.A., Jansen, M.A.K., Ballaré, C.L., and Flint, S.D. (2019). Linkages between stratospheric ozone, UV radiation and climate change and their implications for terrestrial ecosystems. Photochem. Photobiol. Sci. *18*, 681–716.
16. Weimerskirch, H., Louzao, M., de Grissac, S., and Delord, K. (2012). Changes in wind pattern alter albatross distribution and life-history traits. Science *335*, 211–214.
17. Wang, G., Hendon, H.H., Arblaster, J.M., Lim, E.-P., Abhik, S., and van Rensch, P. (2019). Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016. Nat. Commun. *10*, 13.
18. United Nations Development Program. Montreal Protocol. https://www.undp.org/content/undp/en/home/2030-agenda-for-sustainable-development/planet/environment-and-natural-capital/montreal-protocol.html.
19. Montzka, S.A., Dutton, G.S., Yu, P., Ray, E., Portmann, R.W., Daniel, J.S., Kuijpers, L., Hall, B.D., Mondeel, D., Siso, C., et al. (2018). An unexpected and persistent increase in global emissions of ozone-depleting CFC-11. Nature *557*, 413–417.
20. Kennicutt, M.C., Chown, S.L., Cassano, J.J., Liggett, D., Massom, R., Peck, L.S., Rintoul, S.R., Storey, J.W.V., Vaughan, D.G., Wilson, T.J., et al. (2014). Polar research: six priorities for Antarctic science. Nat. News *512*, 23.
21. Kennicutt, M.C., Chown, S.L., Cassano, J.J., Liggett, D., Peck, L.S., Massom, R., Rintoul, S.R., Storey, J., Vaughan, D.G., Wilson, T.J., et al. (2015). A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond. Antarct. Sci. *27*, 3–18.
22. Wintle, B.C., Kennicutt, and Sutherland, W.J. Scanning horizons in research, policy and practice. In Conservation Research, Policy and Practice. Sutherland, W.J., Brotherton, P., Davies, Z., Pettorelli, N., Vira, B., Vickery, J., eds. (Cambridge University). https://doi.org/10.1017/9781108638210.
23. Kennicutt, M.C., Kim, Y.D., Rogan-Finnemore, M., Anandakrishnan, S., Chown, S.L., Colwell, S., Cowan, D., Escutia, C., Frenot, Y., Hall, J., et al. (2016). Delivering 21st century Antarctic and Southern Ocean science. Antarct. Sci. *28*, 407–423.
24. Scientific Committee on Antarctic Research. The Horizon Scan. https://www.scar.org/about-us/horizon-scan/process/.
25. Council of Managers of National Antarctic Programs. Antarctic roadmap challenges. https://www.comnap.aq/Projects/SitePages/ARC.aspx.
26. United Nations Climate Change. The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.
27. Yuan, X., Kaplan, M.R., and Cane, M.A. (2018). The interconnected global climate system - a review of tropical - polar teleconnections. J. Clim. *31*, 5765–5792.
28. Liu, T., Li, J., Li, Y., Zhao, S., Zheng, F., Zheng, J., and Yao, Z. (2018). Influence of the may Southern annular mode on The South China Sea summer monsoon. Clim. Dyn. *51*, 4095–4107.
29. Prabhu, A., Kripalani, R., Oh, J., and Preethi, B. (2017). Can the Southern annular mode influence the Korean summer monsoon rainfall? Asia Pac. J. Atmos. Sci. *53*, 217–228.
30. Stenni, B., Curran, M.A.J., Abram, N.J., Orsi, A., Goursaud, S., Masson-Delmotte, V., Neukom, R., Goosse, H., Divine, D., van Ommen, T., et al. (2017). Antarctic climate variability on regional and continental scales over the last 2000 years. Clim. Past *13*, 1609–1634.
31. Nicolas, J.P., and Bromwich, D.H. (2014). New reconstruction of Antarctic near-surface temperatures: multidecadal trends and reliability of global reanalyses. J. Clim. *27*, 8070–8093.
32. Medley, B., McConnell, J.R., Neumann, T.A., Reijmer, C.H., Chellman, N., Sigl, M., and Kipfstuhl, S. (2018). Temperature and snowfall in Western Queen Maud Land increasing faster than climate model projections. Geophys. Res. Lett. *45*, 1472–1480.
33. Turner, J., Phillips, T., Thamban, M., Rahaman, W., Marshall, G.J., Wille, J.D., Favier, V., Winton, V.H.L., Thomas, E., Wang, Z., et al. (2019). The dominant role of extreme precipitation events in Antarctic snowfall variability. Geophys. Res. Lett. *46*, 3502–3511.
34. Kingslake, J., Ely, J.C., Das, I., and Bell, R.E. (2017). Widespread movement of meltwater onto and across Antarctic ice shelves. Nature *544*, 349–352.
35. Nicolas, J.P., Vogelmann, A.M., Scott, R.C., Wilson, A.B., Cadeddu, M.P., Bromwich, D.H., Verlinde, J., Lubin, D., Russell, L.M., Jenkinson, C., et al. (2017). January 2016 extensive summer melt in West Antarctica favoured by strong El Niño. Nat. Commun. *8*, 15799.
36. Medley, B., and Thomas, E.R. (2019). Increased snowfall over the Antarctic Ice Sheet mitigated twentieth-century sea-level rise. Nat. Clim. Change *9*, 34.
37. Hyder, P., Edwards, J.M., Allan, R.P., Hewitt, H.T., Bracegirdle, T.J., Gregory, J.M., Wood, R.A., Meijers, A.J.S., Mulcahy, J., Field, P., et al. (2018). Critical Southern Ocean climate model biases traced to atmospheric model cloud errors. Nat. Commun. *9*, 3625.
38. Kay, J.E., Wall, C., Yettella, V., Medeiros, B., Hannay, C., Caldwell, P., Bitz, C., Kay, J.E., Wall, C., Yettella, V., et al. (2016). Global climate impacts of fixing the southern ocean shortwave radiation bias in the Community Earth System Model (CESM). J. Clim. *29*, 4617–4636.
39. Thompson, A.F., and Naveira Garabato, A.C. (2014). Equilibration of the Antarctic circumpolar current by standing meanders. J. Phys. Oceanogr. *44*, 1811–1828.
40. Tamsitt, V., Drake, H.F., Morrison, A.K., Talley, L.D., Dufour, C.O., Gray, A.R., Griffies, S.M., Mazloff, M.R., Sarmiento, J.L., Wang, J., et al. (2017). Spiraling pathways of global deep waters to the surface of the Southern Ocean. Nat. Commun. *8*, 172.
41. Rintoul, S.R. (2018). The global influence of localized dynamics in the Southern Ocean. Nature *558*, 209–218.
42. Abernathey, R.P., Cerovecki, I., Holland, P.R., Newsom, E., Mazloff, M., and Talley, L.D. (2016). Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. Nat. Geosci. *9*, 596–601.
43. Haumann, F.A., Gruber, N., Münnich, M., Frenger, I., and Kern, S. (2016). Sea-ice transport driving Southern Ocean salinity and its recent trends. Nature *537*, 89–92.
44. Pellichero, V., Sallée, J.-B., Chapman, C.C., and Downes, S.M. (2018). The Southern Ocean meridional overturning in the sea-ice sector is driven by freshwater fluxes. Nat. Commun. *9*, 1789.
45. DeVries, T., Holzer, M., and Primeau, F. (2017). Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. Nature *542*, 215–218.
46. Frölicher, T.L., Sarmiento, J.L., Paynter, D.J., Dunne, J.P., Krasting, J.P., and Winton, M. (2015). Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. J. Clim. *28*, 862–886.
47. Armour, K.C., Marshall, J., Scott, J.R., Donohoe, A., and Newsom, E.R. (2016). Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. Nat. Geosci. *9*, 549.
48. Chen, H., Morrison, A.K., Dufour, C.O., and Sarmiento, J.L. (2019). Deciphering patterns and drivers of heat and carbon storage in the southern ocean. Geophys. Res. Lett. *46*, 3359–3367.
49. Landschützer, P., Gruber, N., Haumann, F.A., Rödenbeck, C., Bakker, D.C.E., van Heuven, S., Hoppema, M., Metzl, N., Sweeney, C., Takahashi, T., et al. (2015). The reinvigoration of the Southern Ocean carbon sink. Science *349*, 1221–1224.
50. Parkinson, C.L. (2019). A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. Proc. Natl. Acad. Sci. U S A *116*, 14414–14423.
51. Stuecker, M.F., Bitz, C.M., and Armour, K.C. (2017). Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring season. Geophys. Res. Lett. *44*, 9008–9019.
52. Schlosser, E., Haumann, F.A., and Raphael, M.N. (2018). Atmospheric influences on the anomalous 2016 Antarctic sea ice decay. Cryosphere *12*, 1103–1119.
53. Meehl, G.A., Arblaster, J.M., Chung, C.T.Y., Holland, M.M., DuVivier, A., Thompson, L., Yang, D., and Bitz, C.M. (2019). Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. Nat. Commun. *10*, 14.
54. Kohout, A.L., Williams, M.J.M., Dean, S.M., and Meylan, M.H. (2014). Storm-induced sea-ice breakup and the implications for ice extent. Nature *509*, 604–607.
55. Massom, R.A., Scambos, T.A., Bennetts, L.G., Reid, P., Squire, V.A., and Stammerjohn, S.E. (2018). Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell. Nature *558*, 383–389.
56. Squire, V.A. (2018). A fresh look at how ocean waves and sea ice interact. Philos. Trans. A. Math. Phys. Eng. Sci. *376*.
57. Paolo, F.S., Padman, L., Fricker, H.A., Adusumilli, S., Howard, S., and Siegfried, M.R. (2018). Response of Pacific-sector Antarctic ice shelves to the El Niño/southern oscillation. Nat. Geosci. *11*, 121.
58. Merino, N., Le Sommer, J., Durand, G., Jourdain, N.C., Madec, G., Mathiot, P., and Tournadre, J. (2016). Antarctic icebergs melt over the

Southern Ocean: climatology and impact on sea ice. Ocean Model. *104*, 99–110.

59. Bronselaer, B., Winton, M., Griffies, S.M., Hurlin, W.J., Rodgers, K.B., Sergienko, O.V., Stouffer, R.J., and Russell, J.L. (2018). Change in future climate due to Antarctic meltwater. Nature *564*, 53–58.
60. Roemmich, D., Church, J., Gilson, J., Monselesan, D., Sutton, P., and Wijffels, S. (2015). Unabated planetary warming and its ocean structure since 2006. Nat. Clim. Change *5*, 240–245.
61. Purkey, S.G., Johnson, G.C., Talley, L.D., Sloyan, B.M., Wijffels, S.E., Smethie, W., Mecking, S., and Katsumata, K. (2019). Unabated bottom water warming and freshening in the South Pacific Ocean. J. Geophys. Res. Oceans *124*, 1778–1794.
62. Snow, K., Rintoul, S., Sloyan, B., and Hogg, A. (2018). Decrease in density and volume of Adélie Land Bottom Water induced by iceberg calving. Geophys. Res. Lett. *45*, 2380–2387.
63. Menezes, V.V., Macdonald, A.M., and Schatzman, C. (2017). Accelerated freshening of Antarctic bottom water over the last decade in the Southern Indian Ocean. Sci. Adv. *3*, e160426.
64. Campbell, E.C., Wilson, E.A., Moore, G.W.K., Riser, S.C., Brayton, C.E., Mazloff, M.R., and Talley, L.D. (2019). Antarctic offshore polynyas linked to Southern Hemisphere climate anomalies. Nature *570*, 319–325.
65. Treuer, G. (2018). The psychology of Miami's struggle to adapt to sea-level rise. Bull. At. Sci. *74*, 155–159.
66. Scambos, T.A., Bell, R.E., Alley, R.B., Anandakrishnan, S., Bromwich, D.H., Brunt, K., Christianson, K., Creyts, T., Das, S.B., DeConto, R., et al. (2017). How much, how fast?: a science review and outlook for research on the instability of Antarctica's Thwaites Glacier in the 21st century. Glob. Planet. Change *153*, 16–34.
67. IMBIE Team (2018). Mass balance of the Antarctic ice sheet from 1992 to 2017. Nature *558*, 219–222.
68. Bamber, J.L., Westaway, R.M., Marzeion, B., and Wouters, B. (2018). The land ice contribution to sea level during the satellite era. Environ. Res. Lett. *13*, 063008.
69. Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M.J., and Morlighem, M. (2019). Four decades of Antarctic ice sheet mass balance from 1979–2017. Proc. Natl. Acad. Sci. U S A *116*, 1095–1103.
70. Milillo, P., Rignot, E., Rizzoli, P., Scheuchl, B., Mouginot, J., Bueso-Bello, J., and Prats-Iraola, P. (2019). Heterogeneous retreat and ice melt of Thwaites Glacier, West Antarctica. Sci. Adv. *5*, eaau3433.
71. Ice Sheet Mass Balance Inter-Comparison Exercise. http://imbie.org/about-the-project/.
72. Rintoul, S.R., Silvano, A., Pena-Molino, B., van Wijk, E., Rosenberg, M., Greenbaum, J.S., and Blankenship, D.D. (2016). Ocean heat drives rapid basal melt of the Totten ice shelf. Sci. Adv. *2*, e1601610.
73. Bell, R.E., Chu, W., Kingslake, J., Das, I., Tedesco, M., Tinto, K.J., Zappa, C.J., Frezzotti, M., Boghosian, A., and Lee, W.S. (2017). Antarctic ice shelf potentially stabilized by export of meltwater in surface river. Nature *544*, 344–348.
74. Trusel, L.D., Frey, K.E., Das, S.B., Karnauskas, K.B., Munneke, P.K., Van Midgard, E., and Van Den Broeke, M.R. (2015). Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios. Nat. Geosci. *8*, 927.
75. Little, C.M., Horton, R.M., Kopp, R.E., Oppenheimer, M., Yip, S., Little, C.M., Horton, R.M., Kopp, R.E., Oppenheimer, M., and Yip, S. (2015). Uncertainty in twenty-first century CMIP5 sea level projections. J. Clim. *28*, 838–852.
76. CMIP5 Community Storage Server. About the Coupled Model Intercomparison Project Phase 5 (CMIP5). http://cmip5.whoi.edu/?page_id=55.
77. Gomez, N., Pollard, D., and Holland, D. (2015). Sea-level feedback lowers projections of future Antarctic Ice-Sheet mass loss. Nat. Commun. *6*, 8798.
78. Larour, E., Seroussi, H., Adhikari, S., Ivins, E., Caron, L., Morlighem, M., and Schlegel, N. (2019). Slowdown in Antarctic mass loss from solid Earth and sea-level feedbacks. Science *364*, eaav7908.
79. Pattyn, F., Schoof, C., Perichon, L., Hindmarsh, R.C.A., Bueler, E., de Fleurian, B., Durand, G., Gagliardini, O., Gladstone, R., Goldberg, D., et al. (2012). Results of the marine ice sheet model intercomparison project, MISMIP. Cryosphere *6*, 573–588.
80. Edwards, T.L., Brandon, M.A., Durand, G., Edwards, N.R., Golledge, N.R., Holden, P.B., Nias, I.J., Payne, A.J., Ritz, C., and Wernecke, A. (2019). Revisiting Antarctic ice loss due to marine ice-cliff instability. Nature *566*, 58–64.
81. Seroussi, H., Nakayama, Y., Larour, E., Menemenlis, D., Morlighem, M., Rignot, E., and Khazendar, A. (2017). Continued retreat of Thwaites Glacier, West Antarctica, controlled by bed topography and ocean circulation. Geophys. Res. Lett. *44*, 6191–6199.
82. Arthern, R.J., and Williams, C.R. (2017). The sensitivity of West Antarctica to the submarine melting feedback. Geophys. Res. Lett. *44*, 2352–2359.
83. Scientific Committee on Antarctic Research. Antarctic Digital Magnetic Anomaly Project. https://www.scar.org/science/admap/admap/.
84. Golynsky, A.V., Ferraccioli, F., Hong, J.K., Golynsky, D.A., von Frese, R.R.B., Young, D.A., Blankenship, D.D., Holt, J.W., Ivanov, S.V., Kiselev, A.V., et al. (2018). ADMAP2 Magnetic anomaly map of the Antarctic links to grid (grd) files. PANGAEA. https://doi.org/10.1594/PANGAEA.892724.
85. Paxman, G.J.G., Jamieson, S.S.R., Ferraccioli, F., Bentley, M.J., Ross, N., Watts, A.B., Leitchenkov, G., Armadillo, E., and Young, D.A. (2019). The role of lithospheric flexure in the landscape evolution of the Wilkes subglacial basin and transantarctic mountains, East Antarctica. J. Geophys. Res. Earth Surf. *124*, 812–829.
86. British Antarctic Survey. Bedmap2. https://www.bas.ac.uk/project/bedmap-2/.
87. Martos, Y.M., Catalán, M., Jordan, T.A., Golynsky, A., Golynsky, D., Eagles, G., and Vaughan, D.G. (2017). Heat flux distribution of Antarctica unveiled. Geophys. Res. Lett. *44*, 11417–11426.
88. Burton-Johnson, A., Halpin, J.A., Whittaker, J.M., Graham, F.S., and Watson, S.J. (2017). A new heat flux model for the Antarctic Peninsula incorporating spatially variable upper crustal radiogenic heat production. Geophys. Res. Lett. *44*, 5436–5446.
89. Nield, G.A., Whitehouse, P.L., Van der Wal, W., Blank, B., O'Donnell, J.P., and Stuart, G.W. (2018). The impact of lateral variations in lithospheric thickness on glacial isostatic adjustment in West Antarctica. Geophys. J. Int. *214*, 811–824.
90. POLENET: The Polar Observing Network. http://polenet.org/.
91. Liu, G., Talalay, P., Wang, R., Yang, Y., Hong, J., Gong, D., Liu, A., and Fan, D. (2019). Design parameters of hot-water drilling systems. Water *11*, 289.
92. Rapid Access Drill. http://www.rapidaccessicedrill.org/.
93. Scientific Committee on Antarctic Research. International Partnership in Ice Core Sciences. https://www.scar.org/science/ipics/ipics.
94. Siegert, M.J., and Kennicutt, M.C. (2018). Governance of the exploration of subglacial Antarctica. Front. Environ. Sci. *6*, 103.
95. Wikipedia. ANDRILL. https://en.wikipedia.org/wiki/ANDRILL.
96. International Ocean Discovery Program. https://www.iodp.org/.
97. Scientific Committee on Antarctic Research. Antarchitecture Action Group. https://www.scar.org/science/antarchitecture/home/.
98. Jordan, T.A., Martin, C., Ferraccioli, F., Matsuoka, K., Corr, H., Forsberg, R., Olesen, A., and Siegert, M.J. (2018). Geothermal anomaly facilitates ice-flow variability in East Antarctic Ice Sheet interior. Sci. Rep. *8*, 16785.
99. Norwegian Polar Institute. Quantarctica. http://quantarctica.npolar.no/.
100. Whitehouse, P.L., Gomez, N., King, M.A., and Wiens, D.A. (2019). Solid earth change and the evolution of the Antarctic ice sheet. Nat. Commun. *10*, 503.
101. Siegert, M.J., Kulessa, B., Bougamont, M., Christoffersen, P., Key, K., Andersen, K.R., Booth, A.D., and Smith, A.M. (2018). Antarctic subglacial groundwater: a concept paper on its measurement and potential influence on ice flow. In Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes, *461*, M.J. Siegert, S.S.R. Jamieson, and D.A. White, eds. (Geological Society), pp. 197–214.
102. Ingels, J., Aronson, R.B., and Smith, C. (2018). The scientific response to Antarctic ice-shelf loss. Nat. Clim. Change *8*, 848–851.
103. Sahade, R., Lagger, C., Torre, L., Momo, F., Monien, P., Schloss, I., Barnes, D.K.A., Servetto, N., Tarantelli, S., Tatian, M., et al. (2015). Climate change and glacier retreat drive shifts in an Antarctic benthic ecosystem. Sci. Adv. *1*, e1500050.
104. Clark, G.F., Stark, J.S., Johnston, E.L., Runcie, J.W., Goldsworthy, P.M., Raymond, B., and Riddle, M.J. (2013). Light-driven tipping points in polar ecosystems. Glob. Change Biol. *19*, 3749–3761.
105. Barnes, D.K.A., Fleming, A., Sands, C.J., Quartino, M.L., and Deregibus, D. (2018). Icebergs, sea ice, blue carbon and Antarctic climate feedbacks. Philos. Trans. A. Math. Phys. Eng. Sci. *A376*, 20170176.
106. Fretwell, P.T., and Trathan, P.N. (2019). Emperors on thin ice: three years of breeding failure at Halley Bay. Antarc. Sci. *31*, 133–138.
107. Ancel, A., Cristofari, R., Fretwell, P.T., Trathan, P.N., Wienecke, B., Boureau, M., Morinay, J., Le Maho, Y., and Le Bohec, C. (2014). Emperors in

hiding: when ice breakers and satellites complement each other in Antarctic exploration. PLoS One *9*, e100404.

108. Gooseff, M.N., Barrett, J.E., Adams, B.J., Doran, P.T., Fountain, A.G., Lyons, W.B., McKnight, D.M., Priscu, J.C., Sokol, E.R., Takacs-Vesbach, C., et al. (2017). Decadal ecosystem response to an anomalous melt season in a polar desert in Antarctica. Nat. Ecol. Evol. *1*, 1334–1338.
109. Robinson, S.A., King, D.H., Bramley-Alves, J., Waterman, M.J., Ashcroft, M.B., Wasley, J., Turnbull, J.D., Miller, R.E., Ryan-Colton, E., Benny, T., et al. (2018). Rapid change in East Antarctic terrestrial vegetation in response to regional drying. Nat. Clim. Change *8*, 879–884.
110. Amesbury, M.J., Roland, T.P., Royles, J., Hodgson, D.A., Convey, P., Griffiths, H., and Charman, D.J. (2017). Widespread biological response to rapid warming on the Antarctic Peninsula. Curr. Biol. *27*, 1616–1622.
111. Atkinson, A., Hill, S.L., Pakhomov, E.A., Siegel, V., Reiss, C.S., Loeb, V.J., Steinberg, D.K., Schmidt, K., Tarling, G.A., Gerrish, L., and Sailley, S.F. (2019). Krill (*Euphausia superba*) distribution contracts southward during rapid regional warming. Nat. Clim. Change *9*, 142–147.
112. Chown, S.L., and Brooks, C.M. (2019). The state and future of Antarctic environments in a global context. Annu. Rev. Environ. Resour. *44*, 15.1–15.30.
113. Peck, L.S. (2018). Antarctic marine biodiversity: adaptations, environments and responses to change. Oceanograph. Mar. Biol. Annu. Rev. *56*, 105–236.
114. Kelley, J.L., Peyton, J.T., Fiston-Lavier, A.-S., Teets, N.M., Yee, M.-C., Johnston, J.S., Bustamante, C.D., Lee, R.E., and Denlinger, D.L. (2014). Compact genome of the Antarctic midge is likely an adaptation to an extreme environment. Nat. Commun. *5*, 4611.
115. Kim, B.M., Amores, A., Kang, S., Ahn, D.H., Kim, J.H., Kim, I.C., Lee, J.H., Lee, S.G., Lee, H., Lee, J., et al. (2019). Antarctic blackfin icefish genome reveals adaptations to extreme environments. Nat. Ecol. Evol. *3*, 469–478.
116. Moon, K.L., Chown, S.L., and Fraser, C.I. (2017). Reconsidering connectivity in the sub-Antarctic. Biol. Rev. Camb. Philos. Soc. *92*, 2164–2181.
117. JI, M., Greening, C., Vanwonterghem, I., Carere, C.R., Bay, S.K., Steen, J.A., et al. (2017). Atmospheric trace gases support primary production in Antarctic desert surface soil. Nature *552*, 400–403.
118. Halanych, K.M., and Mahon, A.R. (2018). Challenging Dogma Concerning Biogeographic Patterns of Antarctica and the Southern Ocean. Annu. Rev. Ecol. Evol. Syst. *49*, 355–378.
119. Barnes, D.K.A., and Hillenbrand, C.D. (2010). Faunal evidence for a late quaternary trans-Antarctic seaway. Glob. Change Biol. *16*, 3297–3303.
120. Rabosky, D.L., Chang, J., Title, P.O., Cowman, P.F., Sallan, L., Friedman, M., Kaschner, K., Garilao, C., Near, T.J., Coll, M., et al. (2018). An inverse latitudinal gradient in speciation rate for marine fishes. Nature *559*, 392–395.
121. Biersma, E.M., Jackson, J.A., Stech, M., Griffiths, H., Linse, K., and Convey, P. (2018). Molecular data suggest long-term *in situ* Antarctic Persistence within Antarctica's most speciose plant genus, *Schistidium*. Front. Ecol. Evol. *6*, 77.
122. O'Hara, T.D., Hugall, A.F., Wooley, S.N.C., Bribiesca-Contreras, G., and Bax, N.J. (2019). Contrasting processes drive ophiuroid phylodiversity across shallow and deep seafloors. Nature, 636–639.
123. Christner, B.C., Priscu, J.C., Achberger, A.M., Barbante, C., Carter, S.P., Christianson, K., Michaud, A.B., Mikucki, J.A., Mitchell, A.C., Skidmore, M.L., et al. (2014). A microbial ecosystem beneath the West Antarctic ice sheet. Nature *512*, 310–313.
124. Casà, M.V., Van, L.M., Weijs, L., Mueller, J., and Nash, S.B. (2019). First detection of short-chain chlorinated paraffins (SCCPs) in humpback whales (*Megaptera novaeangliae*) foraging in Antarctic waters. Environ. Pollut. *250*, 953–959.
125. Carravieri, A., Fort, J., Tarroux, A., Cherel, Y., Love, O.P., Prieur, S., Brault-Favrou, M., Bustamante, P., and Descamps, S. (2018). Mercury exposure and short-term consequences on physiology and reproduction in Antarctic petrels. Environ. Pollut. *237*, 824–831.
126. Tartu, S., Angelier, F., Wingfield, J.C., Bustamante, P., Labadie, P., Budzinski, H., Weimerskirch, H., Bustnes, J.O., and Chastel, O. (2015). Corticosterone, prolactin and egg neglect behavior in relation to mercury and legacy POPs in a long-lived Antarctic bird. Sci. Total Environ. *505*, 180–188.
127. Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., Pacherres, C.O., and Hughes, K.A. (2017). Microplastics in the Antarctic marine system: an emerging area of research. Sci. Total Environ. *598*, 220–227.
128. Isobe, A., Uchiyama-Matsumoto, K., Uchida, K., and Tokai, T. (2017). Microplastics in the Southern Ocean. Mar. Pollut. Bull. *114*, 623–626.
129. McGeoch, M.A., Shaw, J.D., Terauds, A., Lee, J.E., and Chown, S.L. (2015). Monitoring biological invasion across the broader Antarctic: a baseline and indicator framework. Glob. Environ. Change *32*, 108–125.
130. McCarthy, A.H., Peck, L.S., Hughes, K.A., and Aldridge, D.C. (2019). Antarctica: the final frontier for marine biological invasions. Glob. Change Biol. *25*, 2221–2241.
131. Hughes, K.A., and Convey, P. (2012). Determining the native/non-native status of newly discovered terrestrial and freshwater species in Antarctica - current knowledge, methodology and management action. J. Soil Sci. Environ. Manag. *93*, 52–66.
132. Aronson, R.B., Smith, K.E., Vos, S.C., McClintock, J.B., Amsler, M.O., Per-Olav, M., Ellis, D.S., Kaeli, J., Singh, H., Bailey, J.W., et al. (2015). No barrier to emergence of bathyal king crabs on the Antarctic shelf. Proc. Natl. Acad. Sci. U S A *112*, 12997–13002.
133. Melbourne-Thomas, J., Corney, S.P., Trebilco, R., Meiners, K.M., Stevens, R.P., Kawaguchi, S., Sumner, M.D., and Constable, A.J. (2016). Under ice habitats for Antarctic krill larvae: could less mean more under climate warming? Geophys. Res. Lett. *43*, 10–322.
134. Piñones, A., and Fedorov, A.V. (2016). Projected changes of Antarctic krill habitat by the end of the 21st century. Geophys. Res. Lett. *43*, 8580–8589.
135. Brooks, S.T., Jabour, J., van den Hoff, J., and Bergstrom, D.M. (2019). Our footprint on Antarctica competes with nature for rare ice-free land. Nat. Sustain. *2*, 185–190.
136. Trathan, P.N., Garcia-Borboroglu, P., Boersma, D., Bost, C.A., Crawford, R.J., Crossin, G.T., Cuthbert, R.J., Dann, P., Davis, L.S., De La Puente, S., et al. (2015). Pollution, habitat loss, fishing, and climate change as critical threats to penguins. Conserv. Biol. *29*, 31–41.
137. Cerdà-Cuéllar, M., Moré, E., Ayats, T., Aguilera, M., Muñoz-González, S., Antilles, N., Ryan, P.G., and González-Solís, J. (2019). Do humans spread zoonotic enteric bacteria in Antarctica? Sci. Total Environ. *654*, 190–196.
138. Liu, N., and Brooks, C.M. (2018). China's changing position towards marine protected areas in the Southern Ocean: implications for future Antarctic governance. Mar. Pol. *94*, 189–195.
139. Shaw, J.D., Terauds, A., Riddle, M.J., Possingham, H.P., and Chown, S.L. (2014). Antarctica's protected areas are inadequate, unrepresentative, and at risk. PLoS Biol. *12*, e1001888.
140. Wauchope, H.S., Shaw, J.D., and Terauds, A. (2019). A snapshot of biodiversity protection in Antarctica. Nat. Commun. *10*, 946.
141. United States Antarctic Program. USAP Photo Library. https://photolibrary.usap.gov/#1-1.
142. LIGO Caltech. Laser Interferometer Gravitational-Wave Observatory. https://www.ligo.caltech.edu/.
143. Virgo. http://www.virgo-gw.eu/.
144. Gaisser, T., and Halzen, F. (2014). IceCube. Annu. Rev. Nucl. Part. Sci. *64*, 101–123.
145. IceCube South Pole Neutrino Observatory. https://icecube.wisc.edu/.
146. Burns, E., Tohuvavohu, A., Bellovary, J.M.,, Blaufuss, E., Brandt, T.J., Buson, S., Caputo, R., Cenko, S.B., Christensen, N., Conklin, J.W., et al. (2019). Opportunities for multimessenger astronomy in the 2020s. ArXiv. https://arxiv.org/abs/1903.04461.
147. The IceCube Collaboration, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, et al. (2018). Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. Science *361*, eaat1378.
148. Event Horizon Telescope. https://eventhorizontelescope.org/.
149. The BICEP and Keck Array CMB Experiments. http://bicepkeck.org/.
150. Lockheed Martin. How we're shrinking the telescope: an up-close look at SPIDER. https://www.lockheedmartin.com/en-us/news/features/2016/webt-spider.html.
151. Staggs, S., Dunkley, J., and Page, L. (2018). Recent discoveries from the cosmic microwave background: a review of recent progress. Rep. Prog. Phys. *81*, 044901.
152. Albert, A., André, M., Anghinolfi, M., Ardid, M., Aubert, J.-J., Aublin, J., Avgitas, T., Baret, B., Barrios-Martí, J., Basa, S., et al. (2019). Search for multimessenger sources of gravitational waves and high-energy neutrinos with advanced LIGO during its first observing run, ANTARES, and IceCube. Astrophys. J. *870*, 134.
153. Moffat-Griffin, T. (2019). An introduction to atmospheric gravity wave science in the polar regions and first results from ANGWIN. J. Geophys. Res. Atmos. *124*, 1198–1199.

154. Turner, D.L., Claudepierre, S.G., Fennell, J.F., O'Brien, T.P., Blake, J.B., Lemon, C., Gkioulidou, M., Takahashi, K., Reeves, G.D., Thaller, S., et al. (2015). Energetic electron injections deep into the inner magnetosphere associated with substorm activity. Geophys. Res. Lett. *42*, 2079–2087.

155. Chu, X., Zhao, J., Lu, X., Harvey, V.L., Jones, R.M., Becker, E., Chen, C., Fong, W., Yu, Z., Roberts, B.R., et al. (2018). Lidar observations of stratospheric gravity waves from 2011 to 2015 at McMurdo (77.84°S, 166.69°E), Antarctica: 2. potential energy densities, lognormal distributions, and seasonal variations. J. Geophys. Res. Atmos. *123*, 7910–7934.

156. Halford, A.J., McGregor, S.L., Murphy, K.R., Millan, R.M., Hudson, M.K., Woodger, L.A., Cattel, C.A., Breneman, A.W., Mann, I.R., Kurth, W.S., et al. (2015). BARREL observations of an ICME-shock impact with the magnetosphere and the resultant radiation belt electron loss. J. Geophys. Res. Space Phys. *120*, 2557–2570.

157. NASA. BARREL mission overview. https://www.nasa.gov/mission-pages/rbsp/barrel/overview.

158. Lanzerotti, L.J. (2017). Space weather: historical and contemporary perspectives. Space Sci. Rev. *212*, 1253–1270.

159. Dodds, K., Hemmings, A.D., and Roberts, P. (2017). Handbook on the Politics of Antarctica (Edward Elgar Publishing).

160. Chaturvedi, S. (2018). The future of Antarctica: minerals, bioprospecting, and fisheries. In The Routledge Handbook of the Polar Regions, M. Nuttall, T.R. Christensen, and M. Siegert, eds. (Routledge), pp. 403–415.

161. Verbitsky, J. (2013). Antarctic tourism management and regulation: the need for change. Polar Rec. *49*, 278–285.

162. Elzinga, A. (2017). The continent for science. In Handbook on the Politics of Antarctica, K. Dodds, A.D. Hemmings, and P. Roberts, eds. (Edward Elgar Publishing), pp. 103–124.

163. Tamm, S. (2018). Peace vs. compliance in Antarctica: inspections and the environment. Polar J. *8*, 333–350.

164. Granjou, C., Walker, J., and Salazar, J.F. (2017). The politics of anticipation: on knowing and governing environmental futures. Futures *92*, 5–11.

165. Burns, W.C.G., and Strauss, A.L. (2013). Climate Change Geoengineering. Philosophical Perspectives, Legal Issues and Governance Frameworks (Cambridge University Press).

166. Irvine, P., Emmanuel, K., He, J., Horowitz, L.W., Vecchi, G., and Keith, D. (2019). Halving warming with idealized solar geoengineering moderates key climate hazards. Nat. Clim. Change *9*, 295–299.

167. Trisos, C.H., Amatulli, G., Gurevitch, J., Robock, A., Xia, L., and Zambri, B. (2018). Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. Nat. Ecol. Evol. *2*, 475–482.

168. Smetacek, V., Klaas, C., Strass, V.H., Assmy, P., Montresor, M., Cisewski, B., Savoye, N., Webb, A., d'Ovidio, F., Arrieta, J.M., et al. (2012). Deep carbon export from a Southern Ocean iron-fertilized diatom bloom. Nature *487*, 313–319.

169. Yoon, J.-E., Yoo, K.-C., Macdonald, A.M., Yoon, H.-I., Park, K.-T., Yang, E.J., Kim, H.-C., Lee, J.I., Lee, M.K., Jung, J., et al. (2018). Reviews and syntheses: ocean iron fertilization experiments – past, present, and future looking to a future Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) project. Biogeosciences *15*, 5847–5889.

170. Williamson, P., Wallace, D.W.R., Law, C.S., Boyd, P.W., Collos, Y., Croot, P., Denman, K., Riebesell, U., Takeda, S., and Vivian, C. (2012). Ocean fertilization for geoengineering: a review of effectiveness, environmental impacts and emerging governance. Process. Saf. Environ. Prot. *90*, 475–488.

171. Deininger, M., Koellner, T., Brey, T., and Teschke, K. (2016). Towards mapping and assessing Antarctic marine ecosystem services – the Weddell Sea case study. Ecosyst. Serv. *22*, 174–192.

172. Morton, T. (2013). Hyperobjects: Philosophy and Ecology after the End of the World (University of Minnesota Press).

173. Frame, B. (2019). A typology for Antarctic futures. Polar J. *9*, 1–11.

174. O'Reilly, J., and Salazar, J.F. (2017). Inhabiting the Antarctic. Polar J. *7*, 9–25.

175. Salazar, J.F. (2017). Antarctica and Outer Space: relational trajectories. Polar J. *7*, 259–269.

176. Salazar, J.F. (2017). Speculative fabulation: researching worlds to come in Antarctica. In Anthropologies and Futures: Researching Emerging and Uncertain Worlds, J.F. Salazar, S. Pink, A. Irving, and J. Sjoberg, eds. (Bloomsbury), pp. 151–170.

177. Salazar, J.F., and Barticevic, E. (2015). Digital storytelling Antarctica. Crit. Arts *29*, 576–590.

178. Bloom, L.E. (2017). Antarctica: feminist art practices and disappearing polar landscapes in the age of the Anthropocene. In Handbook on the Politics of Antarctica, K. Dodds, A.D. Hemmings, and P. Roberts, eds. (Edward Elgar Publishing), pp. 84–102.

179. Leane, E. (2016). Unstable places and generic spaces: thrillers set in Antarctica. In Popular Fiction and Spatiality - Reading Genre Settings, L. Fletcher, ed. (Palgrave Macmillan), pp. 25–43.

180. Stark, H., Schlunke, K., and Edmonds, P. (2018). Introduction: uncanny objects in the Anthropocene. Aust. Humanit. Rev. 22–30.

181. Anderson, P.V., Brockman, J.R., and Miller, C.R. (2019). Introduction. In New Essays in Technical and Scientific Communication: Research, Theory, Practice, P.V. Anderson, R.J. Brockmann, and C.R. Miller, eds. (Routledge).

182. Boycoff, M. (2019). Creative (Climate) Communications: Productive Pathways for Science, Policy and Society (Cambridge University Press).

183. Bolsen, T., and Shapiro, M.A. (2017). The US news media, polarization on climate change, and pathways to effective communication. Environ. Commun. *12*, 149–163.

184. Moser, S.C. (2016). Reflections on climate change communication research and practice in the second decade of the 21st century: what more is there to say? Wiley Interdiscip. Rev. Clim. Change *7*, 345–369.

185. Chapman, D.A., Lickel, B., and Markowitz, E.M. (2017). Reassessing emotion in climate change communication. Nat. Clim. Change *7*, 850–852.

186. Amarasekara, I., and Grant, W.J. (2018). Exploring the YouTube science communication gender gap: a sentiment analysis. Public Underst. Sci. *28*, 66–84.

187. Wang, S., Corner, A., Chapman, D., and Markowitz, E. (2018). Public engagement with climate imagery in a changing digital landscape. Wiley Interdiscip. Rev. Clim. Change *9*, e509.

188. Brossard, D., Belluck, P., Gould, F., and Wirz, C.D. (2019). Promises and perils of gene drives: navigating the communication of complex, post-normal science. Proc. Natl. Acad. Sci. U S A *116*, 7692–7697.

189. Fischhoff, B. (2019). Evaluating science communication. Proc. Natl. Acad. Sci. U S A *116*, 7670–7675.

190. Salmon, R.A., and Roop, H.A. (2019). Bridging the gap between science communication practice and theory: reflecting on a decade of practitioner experience using polar outreach case studies to develop a new framework for public engagement design. Polar Rec. 1–14.

191. Stevens, C., O'Connor, G., and Robinson, N. (2019). The connections between art and science in Antarctica: Activating Science*Art. Polar Rec. 1–8.

192. McLean, L., and Rock, J. (2016). The importance of Antarctica: assessing the values ascribed to Antarctica by its researchers to aid effective climate change communication. Polar J. *6*, 291–306.

193. Schroeter, S., Lowther, N., Kelman, E., and Arnold, M. (2015). Overcoming challenges to communicating Antarctic climate science. Polar J. *5*, 59–81.

194. Priestley, R. (2016). Dispatches from Continent Seven: An Anthology of Antarctic Science (AWA Press).

195. Scientific Committee on Antarctic Research. https://www.scar.org/.

196. Council of Managers of National Antarctic Programs. https://www.comnap.aq/SitePages/Home.aspx.

197. Cincinelli, A., Scopetani, C., Chelazzi, D., Lombardini, E., Martellini, T., Katsoyiannis, A., Fossi, M.C., and Corsolini, S. (2017). Microplastic in the surface waters of the Ross Sea (Antarctica): occurrence, distribution and characterization by FTIR. Chemosphere *175*, 391–400.

198. Xavier, J.C., Brandt, A., Ropert-Coudert, Y., Badhe, R., Gutt, J., Havermans, C., et al. (2016). Future challenges in southern ocean ecology research. Front. Mar. Sci. *3*, https://doi.org/10.3389/fmars.2016.00094.

199. Scientific Committee on Antarctic Research (2017). Strategic plan 2017-2022: connecting and building Antarctic research. 10.5281/zenodo.229139.

200. E. Leane and J. McGee, eds. (2019). Anthropocene Antarctica: Perspectives from the Humanities, Law and Social Sciences (Routledge, Taylor & Francis Group).

201. National Research Council (2008). Earth Observations from Space: The First 50 Years of Scientific Achievements (The National Academies Press).

202. Group on Earth Observations. About GEOSS. https://www.earthobservations.org/geoss.php.

203. World Meteorological Organization. Global Climate Observing System. https://public.wmo.int/en/programmes/global-climate-observing-system.

204. UNESCO. Intergovernmental Oceanographic Commission. http://www.ioc-unesco.org/.

205. NASA Earth Observations. https://neo.sci.gsfc.nasa.gov/.

206. European Space Agency. Observing the Earth. https://www.esa.int/Our_Activities/Observing_the_Earth.

207. Gillett, Z.E., Arblaster, J.M., Dittus, A.J., Deushi, M., Jöckel, P., Kinnison, D.E., Morgenstern, O., Plummer, D.A., Revell, L.E., Rozanov, E., et al. (2019). Evaluating the relationship between interannual variations in the antarctic ozone hole and southern hemisphere surface climate in chemistry–climate models. J. Clim. *32*, 3131–3151.

208. Nowicki, S.M.J., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., Gregory, J., Abe-Ouchi, A., and Shepherd, A. (2016). Ice sheet model intercomparison project (ISMIP6) contribution to CMIP6. Geosci. Model. Dev. *9*, 4521–4545.

209. UN Climate Action Summit 2019. https://www.un.org/en/climatechange/.