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

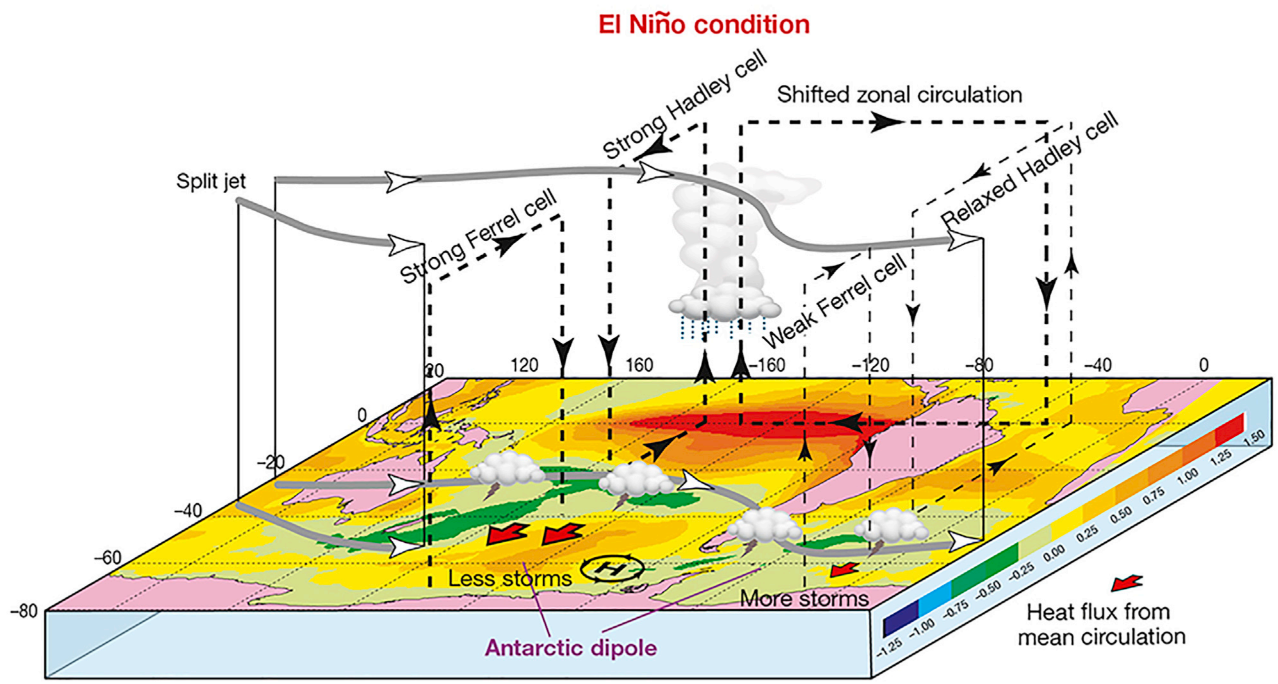


**Figure 1. A Schematic Illustration of Key Aspects of the "Antarctic Atmosphere and Global Connections" Theme**
Remote atmospheric circulation changes are caused by warm sea-surface temperatures in the tropical Pacific Ocean accompanying the El Niño-Southern Oscillation (ENSO). The mechanisms involved 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.

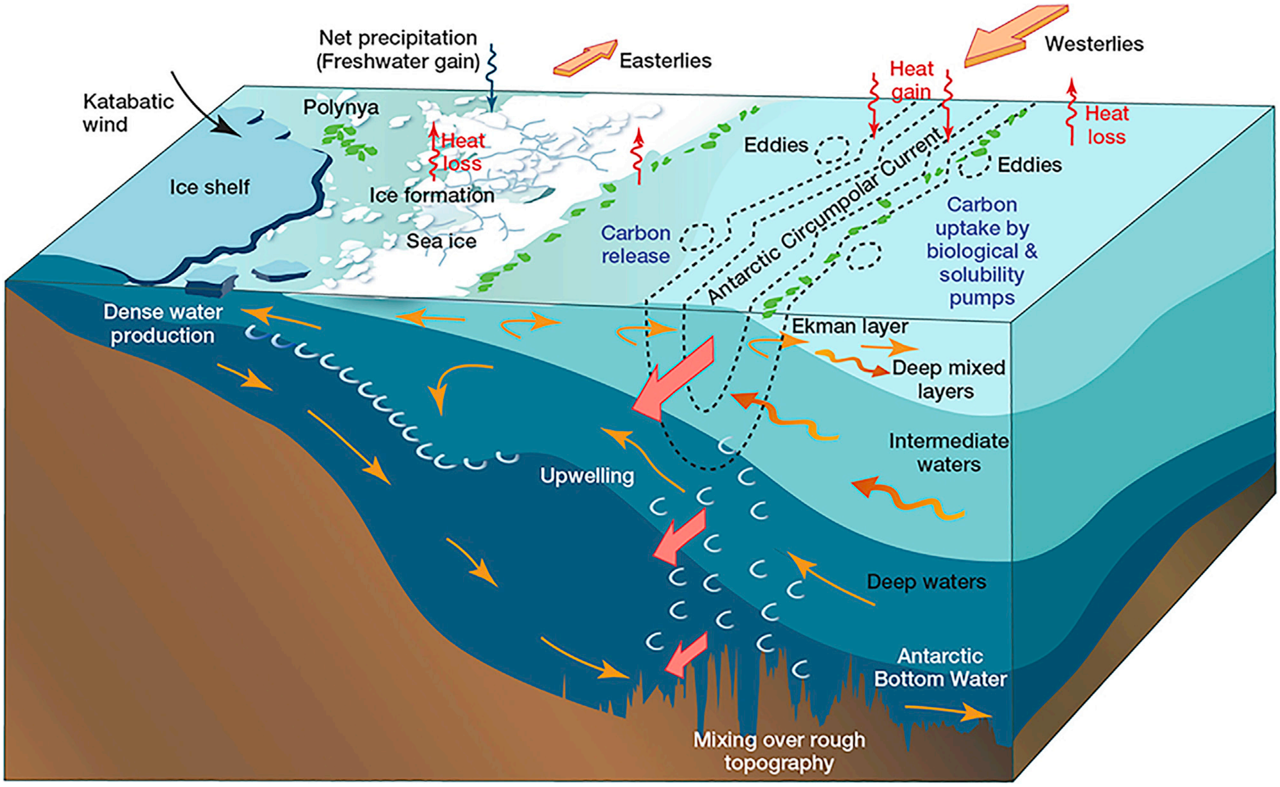


**Figure 2. A Schematic Illustration of Key Aspects of the "Southern Ocean and Sea Ice" Theme**
The ocean circulation is driven by wind forcing and exchange of heat and freshwater at the sea surface. The Antarctic Circumpolar Current circles the continent from west to east. Deep water flows southward 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]

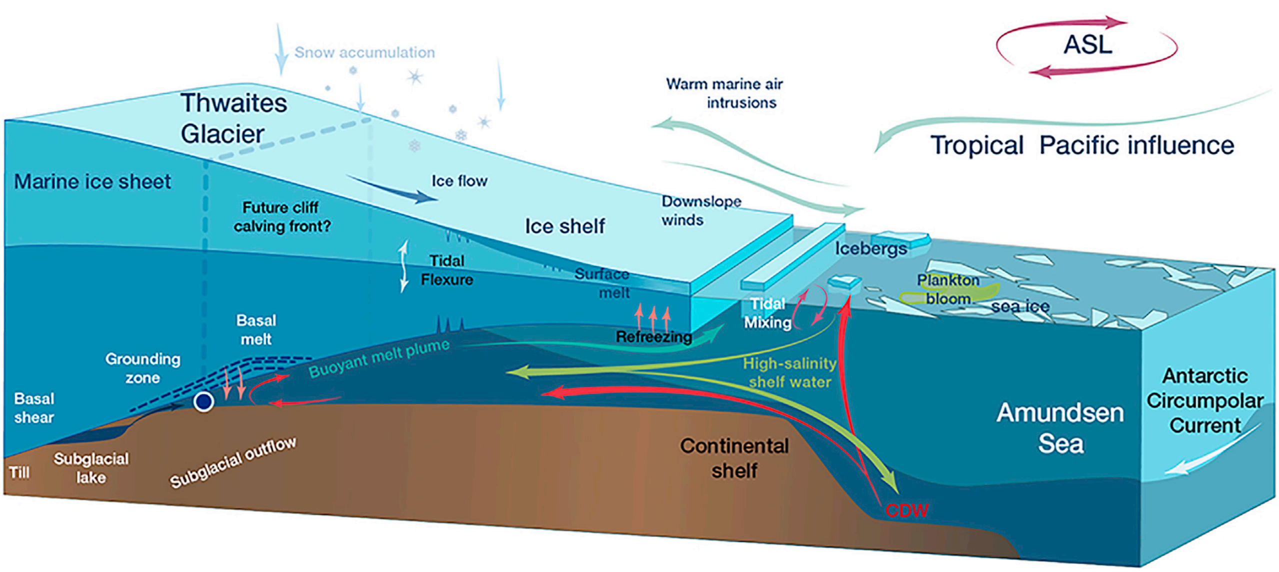


**Figure 3. A Schematic Illustration of Key Aspects of the "Antarctic Ice Sheets and Sea Level" Theme**

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

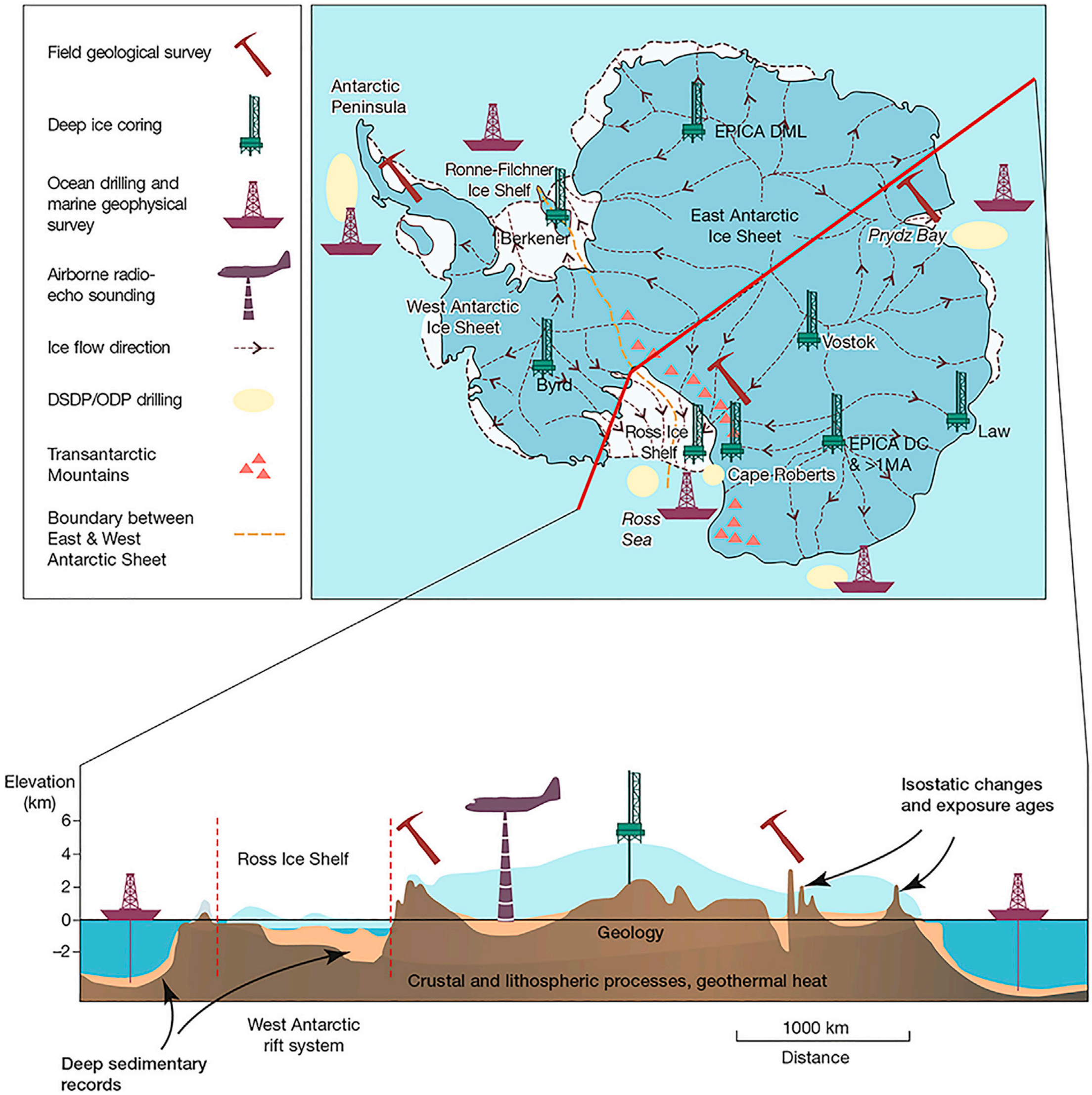


**Figure 4. A Schematic Illustration of Key Aspects of the "Dynamic Earth: Probing beneath the Ice" Theme**

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

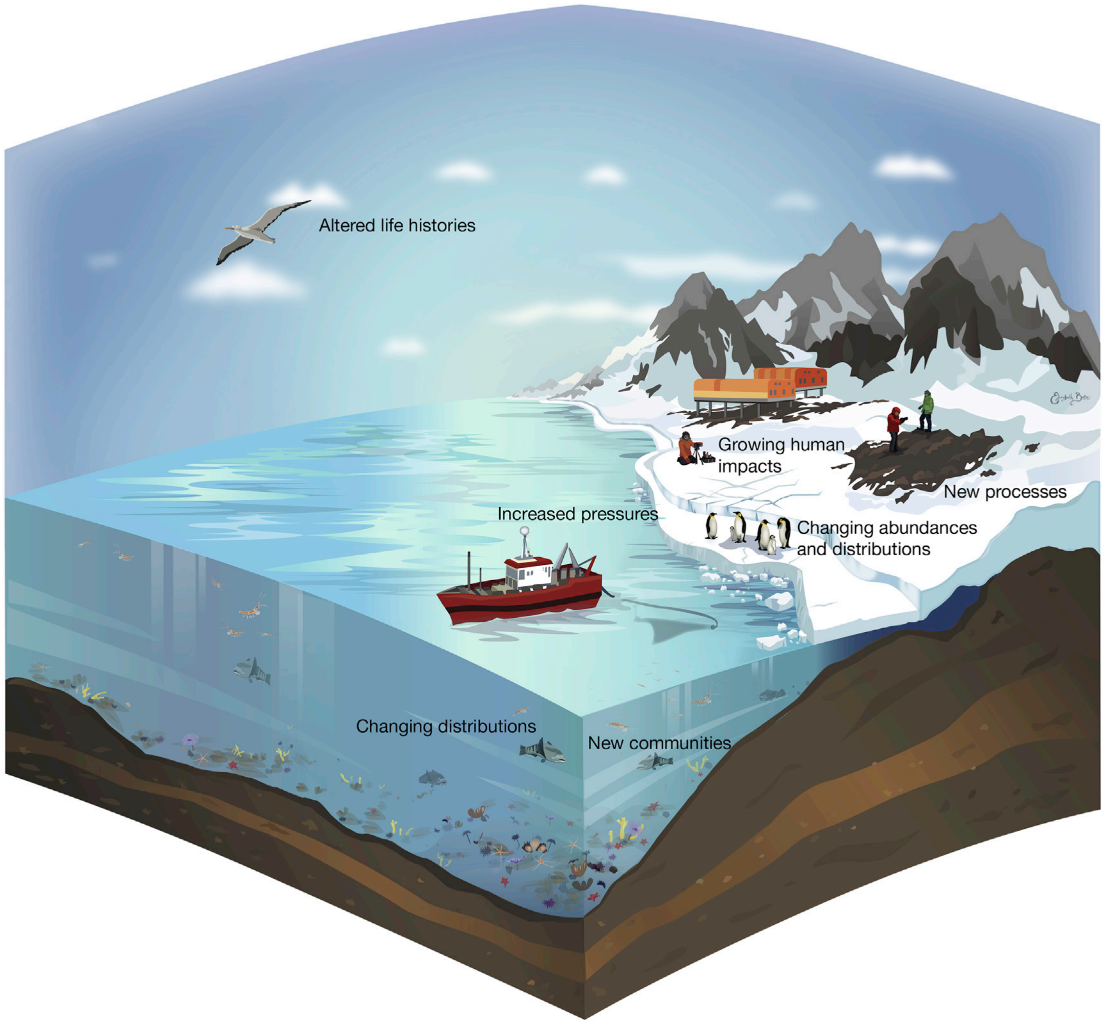


**Figure 5. A Schematic Illustration of Key Aspects of the "Antarctic Life on the Precipice" Theme**
Changing living environments in Antarctica provide new challenges for life sciences research. Recent research findings include (i) the discovery of new communities where ice shelves have disintegrated, (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/.

ONEEAR, Volume *1*

# Supplemental Information

# Sustained Antarctic Research:

# A 21st Century Imperative

**Mahlon C. Kennicutt II, David Bromwich, Daniela Liggett, Birgit Njåstad, Lloyd Peck, Stephen R. Rintoul, Catherine Ritz, Martin J. Siegert, Alan Aitken, Cassandra M. Brooks, John Cassano, Sanjay Chaturvedi, Dake Chen, Klaus Dodds, Nicholas R. Golledge, Céline Le Bohec, Marcelo Leppe, Alison Murray, P. Chandrika Nath, Marilyn N. Raphael, Michelle Rogan-Finnemore, Dustin M. Schroeder, Lynne Talley, Tony Travouillon, David G. Vaughan, Lifan Wang, Allan T. Weatherwax, Huigen Yang, and Steven L. Chown**

Table S1. Expert (subjective) assessments of progress toward answering the “Antarctic Atmosphere and Global Connections” questions supported by peer-reviewed literature citations. Comments by experts from crosscutting clusters are identified as ‘Crosscuts [name of cluster]’. The references cited are exemplars and not intended to be an exhaustive literature review.

| **Antarctic Science Horizon Scan Question**[1,2] | **Conclusions** |
|---|---|
| 1. How is climate change and variability in the high southern latitudes connected to lower latitudes including the Tropical Ocean and monsoon systems? | Recent studies of tropical - polar linkages associated with climate variability, on a variety of time scales, highlight the key role that Rossby waves, emanating from the tropics, play in forcing intra-seasonal to decadal variability in Antarctic and Southern Ocean climate.[3] Sea Surface Temperature (SST) anomalies, and both El Niño-Southern Oscillation (ENSO) and Madden-Julian oscillations (MJO), are identified as tropical forcing mechanisms for these waves which impact high southern latitude temperature, sea ice cover and zonal winds. These effects are most marked in West Antarctica and the Antarctic Peninsula. |
| 2. How do Antarctic processes affect mid-latitude weather and extreme events? | Research on the impact of Antarctica on mid-latitude weather can be traced to a 1998 paper that documented the impact of Antarctic katabatic winds on atmospheric pressure from the Antarctic to the sub-tropics of the Southern Hemisphere.[4] More recent work found that cold air outbreaks over the Ross, Amundsen and Bellingshausen Seas dominate the turbulent heat fluxes from the ocean to the atmosphere just north of the sea-ice edge and, as a result, the variability of the surface buoyancy forcing of the Southern Ocean.[5] The relationships between Antarctic spring ozone levels and Australian summer temperature has been documented although the role of coupled atmosphere-ocean processes for this Antarctic-Australia linkage remains unresolved.[6] |
| 3. How have teleconnections, feedbacks, and thresholds in decadal and longer-term climate variability affected ice sheet response since the Last Glacial Maximum, and how can this inform future climate projections? | Recent studies have documented relatively weak El Niño-Southern Oscillation-like variability in the early to mid-Holocene (~11,500-5,000 years ago) accompanied by stronger westerly winds. Opposite conditions have prevailed for the last 5,000 years. Climate model simulations spanning the Last Glacial Maximum must reproduce these conditions if projections are to be credible.[3] It has been concluded that high-latitude Southern Ocean processes may be one of the most important feedbacks to glacial-interglacial cycles with consequences for tropical and global climates.[3] |

| | |
|---|---|
| 4. What drives change in the strength and position of Westerly winds, and what are their effects on ocean circulation, carbon uptake and global teleconnections? | The Southern Annual Mode is a dominant source of variability in Southern Hemisphere climate impacting the strength of westerly winds and temperature anomalies in the high southern latitudes. Recent trends in Southern Annual Mode have been attributed to forcing from ozone loss opposed by forcing from greenhouse gas increases. Recent work also shows an influence from the tropical Pacific on the Southern Annual Mode.[7,8] The Southern Annual Mode, through changes in westerly wind strength, is thought to impact the circulation of the Southern Ocean, sea ice extent around Antarctica, heat and carbon sequestration in the Southern Ocean, and ocean biogeochemistry. Understanding of the importance of these interconnections continues to evolve. See Q.11. |
| 5. How did the climate and atmospheric composition vary prior to the oldest ice records? | The last time the Earth experienced atmospheric $CO_2$ concentrations like today was during the Pliocene, ~2.6-5.3 million years ago.[9] The global mean temperature was ~2ºC higher than today and, at times, global sea level was 10-20 m higher than present. Conditions were variable in Antarctica and the West Antarctic ice sheet may have collapsed.[10] East Antarctica had periods of high summer warmth with low shrubs growing far into the interior. At other times ice covered most of the landscape. Further ice and rock records are needed to better define these linkages and validate models. See Q.9. and Q.33. |
| 6. What controls regional patterns of atmospheric and oceanic warming and cooling in the Antarctic and Southern Ocean? | It is now clearer that some temperature changes over Antarctica are attributable to the impacts of the Antarctic Ozone Hole and atmospheric teleconnections from tropical latitudes (see Q.4 and Q.11). The relative role of natural versus anthropogenically forced multi-decadal variability, and its impacts on regional patterns of temperature and sea ice change, is unresolved for Antarctica and the Southern Ocean.[11,12,13] See Q.11.<br><br>**Crosscuts Southern Ocean**<br>Understanding of the role of Southern Ocean overturning in sweeping the anthropogenic heat anomaly from the Southern Ocean to intermediate depths at lower latitudes has improved.[14,15,16] Weak oceanic warming, seen at high southern latitudes, is due to wind driven oceanic upwelling while enhanced warming north of the Antarctic circumpolar current is associated with greenhouse gas-induced heat uptake and northward heat transport.[14] These results suggest that high Southern Ocean warming will respond on centennial or longer time scales due to the role of upwelling of deeper waters. See Southern Ocean section questions. |

| | |
|---|---|
| 7. How can coupling and feedbacks between the atmosphere and the surface (land ice, sea ice and ocean) be better represented in weather and climate models? | Cloud prediction is the largest uncertainty for atmospheric models over land ice, sea ice and the ocean with profound impacts on coupling with the underlying surfaces.[17,18] Capturing the correct balance of cloud liquid water versus cloud ice, that determines whether the downward radiative fluxes from the atmosphere to the surface are accurate, is especially challenging. Sensitivity studies fixing the shortwave radiation biases in the National Center for Atmospheric Research (NCAR) climate model demonstrated the importance of these surface radiation errors for predictions of large-scale atmospheric and oceanic circulation in the Southern Hemisphere.[19] Over the past few years several field projects have studied the role of clouds in the Southern Ocean climate system (e.g. Measurements of Aerosols, Radiation, and Clouds Over the Southern Ocean [MARCUS]).[20] Results from these studies will lead to improvements in the representation of this coupling in weather and climate models.<br><br>**Crosscuts Southern Ocean**<br>See above<br><br>**Crosscuts Antarctic Ice Sheet**<br>Coupling the various components of the climate system is a work in progress. This work is primarily achieved through intercomparison experiments.[21,22] See Q.25 and related questions in the Ice Sheet section. |
| 8. Does past amplified warming of Antarctica provide insight into the effects of future warming on climate and ice sheets? | Based on coupled ice sheet-climate modeling, and comparisons with conditions during the Pliocene and the last interglacial, it is suggested that hydrofracturing of buttressing ice shelves, caused by atmospheric warming, may create marine ice cliff instability (MICI). This instability may lead to Antarctic ice loss contributing more than a meter to sea-level rise by 2100 and more than 15 m by 2500, if emissions continue unabated.[9,23,24] Others have suggested that up to 0.25 m of sea-level rise from Antarctic ice loss can be expected by 2100.[25] Yet others have argued that MICI is unnecessary to reproduce paleo-sea-levels therefore, extreme estimates of sea-level rise by the end of this century may be overestimated.[26] See Q.11, Q.21, Q.31, Q,32, and Q.33.<br><br>**Crosscuts Antarctica Ice Sheet**<br>See above and Ice Sheet section questions. |

| | |
|---|---|
| 9. Are there $CO_2$ equivalent thresholds that foretell collapse of all or part of the Antarctic Ice Sheet? | Information from the ANDRILL-2A drill core, and complementary ice sheet modeling, show that polar climate and Antarctic ice sheet margins were highly dynamic during the early to mid-Miocene (~23-11 million years ago).[27] Changes in the inferred extent of the Antarctic ice sheet suggests that high southern latitudes were sensitive to relatively small changes in atmospheric $CO_2$ (between 280 and 500 ppm). Reconstructions through intervals of peak warmth indicate that the Antarctic ice sheet retreated beyond its terrestrial margin under atmospheric $CO_2$ conditions like those projected for the coming centuries. Past ice sheet response allows calibration and validation of models.[23,24] Understanding changes in past ocean circulation, based on marine sedimentary records, is one way to probe forcings and ice sheet/ocean interactions. Results from marine and ice-sheet drilling projects are expected to provide important new insights (e.g., International Ocean Discovery Program[28], the International Partnership in Ice Core Sciences[29] and Beyond the European Project for Ice Coring in Antarctica – Oldest Ice[30]).<br><br>**Crosscuts Antarctic Ice Sheet**<br>According to $CO_2$ proxies, it has been ~3 million years Before Present since $CO_2$ values reached those of the present day. The International Partnership in Ice Core Sciences[29] is searching for a 1.5-million-year ice core record. Among the projects with a goal to obtain such an ice core, the European Beyond EPICA project was recently launched and will begin drilling by 2020.[30] See Q.28. |
| 10. Will there be release of greenhouse gases stored in Antarctic and Southern Ocean clathrates, sediments, soils, and permafrost as climate changes? | There is little progress on this question, however a SCAR Expert Group, “Antarctic Permafrost and Soils” (AntPaS)[31], has been formed to address this and related questions. See Q.42.<br><br>**Crosscuts Dynamic Earth**<br>See above. |

| | |
|---|---|
| 11. Is the recovery of the ozone hole proceeding as expected and how will its recovery affect regional and global atmospheric circulation, climate and ecosystems? | Ozone recovery is proceeding much as expected with exceptions discussed below.[32] The magnitude of the hole has stabilized over the last decade, but the 2018/19 hole was one of the larger in recent years. It is predicted that it will be another 40 years before ozone levels return to those of 50 years ago. Understanding of the impacts of stratospheric ozone on the surface climate in the Southern Hemisphere continues to evolve. Extremes in Antarctic spring ozone have been linked to warmer (more ozone) and cooler (less ozone) than normal summers over large regions of the Southern Hemisphere, especially Australia.[33] It has been postulated that east-west displacements of the location of the springtime Antarctic ozone minimum could be responsible for regional climate variations during the austral springtime.[34] Projections of future Southern Hemisphere climate change, due to the recovery of the Ozone Hole, may be more impactful than currently thought. Ozone data for 2018/19 and predictions for the future can be found at “The 2018 Antarctic Ozone Hole Season” web page.[35] There is growing evidence that declines in lower stratospheric ozone can offset ozone layer recovery.[36] Increases in global emissions of CFC-111 are also being observed.[37] Linkages between changes in sea ice and recovering ozone levels have been reported.[38]<br><br>**Crosscuts Antarctic Life and Human Presence**<br>Understanding of the direct effects of ultraviolet radiation (especially UV-B) is well developed for marine and terrestrial systems.[39,40] Overall the expectation are for minor impacts from UV radiation compared with other drivers of marine systems[41], though some influence on ecosystem structure and function may be expected due to shifts between microbial heterotrophs and larger phytoplankton.[39]<br><br>For terrestrial systems, exposure to relevant levels of UV radiation is generally not damaging. Rather, the largest impacts are expected to come from changes in atmopsheric circulation patterns associated with ozone depletion and their influence on Antarctic plant communities, such as the replacement of endemic species which prefer wet conditions with more widespread drought tolerant taxa.[42,43,44] |

Table S2. Summary of qualitative (subjective) expert assessments of progress in answering “Antarctic Atmosphere and Global Connection” questions rated as: 1 - no or little progress, 2 - moderate progress, 3 - major progress and 4 - answered. When a question crosscuts other clusters an additional perspective(s) on progress is provided. (New) – indicates a question that was not originally identified as cross-cutting in the Scan. For detailed commentary on progress and supporting references see Table S1.

| Antarctic Science Horizon Scan Question[1,2] | Qualitative (Subjective) Rating (1-4) |
|---|---|
| 1. How is climate change and variability in the high southern latitudes connected to lower latitudes including the Tropical Ocean and monsoon systems? | **2-3**<br>Tropical oceans impact Antarctic climate on a variety of time scales but many interactions are yet to be explored.<br><br>**Crosscuts Southern Ocean (new): 2** |
| 2. How do Antarctic processes affect mid-latitude weather and extreme events? | **1**<br>Understanding of how mid-latitude weather and extreme events effect Antarctic processes, and vice versa has improved. Tools are in place to further advance knowledge on this question.<br><br>**Crosscuts Southern Ocean (new): 1** |
| 3. How have teleconnections, feedbacks, and thresholds in decadal and longer-term climate variability affected ice sheet response since the Last Glacial Maximum, and how can this inform future climate projections? | **1-2**<br>The absence of annually resolved records limits progress on this question. |
| 4. What drives change in the strength and position of Westerly winds, and what are their effects on ocean circulation, carbon uptake and global teleconnections? | **3**<br>Studies have defined the effect of the ozone hole on Westerly winds but there is much to learn that will improve predictions of future change. |
| 5. How did the climate and atmospheric composition vary prior to the oldest ice records? | **1-2**<br>More studies of the Pliocene in the Antarctic are needed, and collection of sediment and rock records will be required. |

| | |
|---|---|
| 6. What controls regional patterns of atmospheric and oceanic warming and cooling in the Antarctic and Southern Ocean? | **3**<br>The role of natural multi-decadal variability remains unresolved for both Antarctica and the Southern Ocean, but research is progressing.<br><br>**Crosscuts Southern Ocean: 2**<br>The role of Southern Ocean overturning in sweeping the anthropogenic heat anomaly from the Southern Ocean to intermediate depths at lower latitudes is better understood. |
| 7. How can coupling and feedbacks between the atmosphere and the surface (land ice, sea ice and ocean) be better represented in weather and climate models? | **2-3**<br>Cloud prediction is the largest uncertainty for atmospheric models over land ice, sea ice and the ocean but recent field campaigns focused on the study of Southern Ocean clouds should lead to advances on this question.<br><br>**Crosscuts Southern Ocean: 2**<br>Progress is needed in understanding Southern Ocean cloud/radiation bias in climate models.<br><br>**Crosscuts Antarctic Ice Sheet: 3**<br>Coupling the various components of the climate system is a work in progress that will be best achieved through model intercomparison experiments. |
| 8. Does past amplified warming of Antarctica provide insight into the effects of future warming on climate and ice sheets? | **2**<br>Research on this question is at its beginnings. Incorporating ozone variability could improve seasonal predictions.<br><br>**Crosscuts Antarctic Ice Sheet: 3**<br>This rating is based on ongoing efforts in ice sheet modelling. |
| 9. Are there $CO_2$ equivalent thresholds that foretell collapse of all or part of the Antarctic Ice Sheet? | **2**<br>It has been 3 million years Before Present since $CO_2$ values reached those of the present day. Additional geological records are needed. |

| | |
|---|---|
| | **Crosscuts Antarctic Ice Sheet: 2**<br>A better understanding of the temperature-$CO_2$ relationship is essential for identifying thresholds for ice sheet collapse. |
| 10. Will there be release of greenhouse gases stored in Antarctic and Southern Ocean clathrates, sediments, soils, and permafrost as climate changes? | **1**<br>Warming is causing changes in ice-free areas that may have ramifications for the release of stored greenhouse gases.<br><br>**Cross Cuts Dynamic Earth: 1** |
| 11. Is the recovery of the ozone hole proceeding as expected and how will its recovery affect regional and global atmospheric circulation, climate and ecosystems? | **3**<br>Ozone recovery is being affected by recent increases in chlorofluorocarbons that need to be investigated.<br><br>**Crosscuts Antarctic Life and Human Presence: 2**<br>There is limited work on the life sciences aspects of this question including the direct effects of UV radiation. The indirect effects via changing atmospheric circulation are expected to be more pronounced but remain largely unknown. |

Table S3. Expert (subjective) assessments of progress toward answering the "Southern Ocean and Sea Ice in a Warming World" questions supported by peer-reviewed literature citations. Comments by experts from crosscutting clusters are identified as 'Crosscuts [name of cluster]'. The references cited are exemplars and not intended to be an exhaustive literature review.

| **Antarctic Science Horizon Scan Question**[1,2] | **Conclusions** |
|---|---|
| 12. Will changes in the Southern Ocean result in feedbacks that accelerate or slow the pace of climate change? | Model studies have shown that meltwater from Antarctic ice sheets and shelves (usually absent in climate models) could have widespread implications, including slowing of the increase in average global temperatures and warming of subsurface ocean temperatures near Antarctica, and raising the possibility of a positive feedback driving further ice melt and sea-level rise.[45] Observations suggest that Southern Ocean carbon uptake has been reinvigorated in recent years, indicating variability in feedbacks to global warming.[46] The Southern Ocean dominates global ocean heat uptake, with the overturning circulation acting to transport anthropogenic heat (and carbon dioxide) northward and into the ocean interior.[14,15,47] Consequently, ocean warming is delayed in the Southern Ocean and accelerated to the north of the Antarctic Circumpolar Current. The dominance of southern hemisphere heat uptake in part reflects reduced uptake in the North Atlantic because of the cooling effect of aerosols. As aerosols decrease in the future, both the Southern Ocean and North Atlantic will take up anthropogenic heat.[48] See Q.1, Q.2, Q.4 and Q.6 for atmospheric linkages. |
| 13. Why are the properties and volume of Antarctic Bottom Water changing, and what are the consequences for global ocean circulation and climate? | Trends toward warmer, fresher, lighter and less voluminous Antarctic Bottom Water have been documented, contributing to ocean heat storage and sea-level rise.[49,50] The response to episodic events, like iceberg calving, has provided a "natural experiment" with which to assess the sensitivity of bottom water formation to changes in forcings.[51] |
| 14. How does Southern Ocean circulation, including exchange with lower latitudes, respond to climate forcing? | There is some recent evidence for decadal/multi-decadal variability in the Southern Ocean overturning circulation.[52] While a complete understanding of the sensitivity of the overturning to changes in forcing remains elusive, important progress has been made in understanding the dynamics of the overturning circulation.[53] Notable advances have included evidence that both the upwelling and downwelling limbs of the overturning |

| | |
|---|---|
| | circulation are highly localized as a result of interactions of the flow with topography[54,55] and recognition of the importance of sea ice melt in driving water mass transformations that connect the upper and lower branches of the overturning circulation.[56.57.58] See Q.1, Q.2, Q.4 and Q.6 for atmospheric linkages. |
| 15. What processes and feedbacks drive changes in the mass, properties and distribution of Antarctic sea ice? | New observations under Antarctic sea ice have revealed how pre-conditioning by ocean stratification can influence rates of sea ice growth.[59] Several potential feedbacks involving interactions between the ocean, atmosphere, sea ice and ice shelves have been identified, but few of the (often non-linear) non-radiative feedbacks have been quantified.[60] The dramatic shift in Antarctic sea ice extent from record high in 2014 to record low in 2017 has been attributed to changes in the atmosphere (linked to strong anomalies in tropical convection and shifts in major climate modes, like the Interdecadal Pacific Oscillation and the Southern Annular Mode) and consequent changes in upper ocean heat content.[61] See Q.17. |
| 16. How do changes in iceberg numbers and size distribution affect Antarctica and the Southern Ocean? | The freshwater input to the Southern Ocean from melting icebergs has been quantified and shown to reduce sea surface temperature and increase annual mean sea ice volume, with strong regional variations.[62] Little progress has been made in assessment of changes in iceberg supply and its impact on the Southern Ocean. |
| 17. How has Antarctic sea ice extent and volume varied over decadal to millennial timescales? | To date, focus has been largely on decadal scale variability of Antarctic sea ice extent. Regional trends in sea ice extent have been linked to well-known modes of climate variability, including El Niño and the Southern Annular Mode.[63] Model studies suggest that a slow response to open ocean convection events, like the Weddell Polynya, may also explain trends in sea ice extent.[64] Antarctic sea ice extent has decreased from a record high in 2014 to a record low in 2017, a rate of ice loss that surpasses the widely publicized decline in Arctic sea ice.[65] The precipitous decline has been linked to forcing from the tropics and the stratosphere, with a possible contribution from anthropogenic factors.[38,61] Little progress has been made on sea ice volume, although an updated dataset of sea ice thickness (European Space Agency Climate Change Initiative project on Sea Ice[66]) has promise for describing variability on timescales of a decade and shorter. See Q.1, Q.2, Q.11, Q.15 and Q.19. |
| 18. How will changes in ocean surface waves influence Antarctic sea ice and floating glacial ice? | Substantial progress has been made in understanding the influence of ocean surface waves on sea ice and ice shelves.[67,68,69,70,71] Waves cause sea ice break-up, rafting and |

| | |
|---|---|
| | variations in sea ice properties; altering ice floe size, distribution and concentrations. Loss of sea ice can allow ocean swell to reach ice shelves and cause fracturing. |
| 19. How do changes in sea ice extent, seasonality and properties affect Antarctic atmospheric and oceanic circulation? | The importance of brine rejection during sea ice formation in the creation of dense Antarctic Bottom Water has been recognized for many years, but less attention was paid to the impacts of sea ice melt. Several recent studies have shown that freshwater added by sea ice melt is critical for transforming dense water to lighter water in the upper branch of the Southern Ocean overturning circulation.[57,58,72] With respect to the atmosphere, modelling studies have shown that increased Antarctic sea ice can shift the Southern Hemisphere mid-latitude jet poleward in winter.[73] Similarly, Antarctic sea ice loss will act to shift the tropospheric jet equatorward, an internal negative feedback to the poleward shift associated with increased greenhouse gases. Antarctic sea ice loss is expected to have little effect on regional Antarctic air temperatures.[74] See Q.1, Q.2 and Q.17.<br><br>**Crosscuts Antarctic Atmosphere**<br>On local scales, Antarctic coastal air temperatures have increased (decreased) over the last 60 years as the Antarctic sea ice extent decreased (increased) with the trend reversing in 1979.[11] |
| 20. How do extreme events affect the Antarctic cryosphere and Southern Ocean? | In 2017, the Maud Rise polynya in the Weddell Sea opened for an extended period for the first time since the 1970s. Recurrence of this uncommon “extreme event” has been linked to the combined effect of unusually strong atmospheric storms and oceanographic preconditioning.[75,76] Anomalous winds over the Southern Ocean linked to an extreme El Niño Southern Oscillation event, a change in phase of the Interdecadal Pacific Oscillation, and internal variability associated with the Southern Annular Mode contributed to anomalous sea ice decay in 2016,[61,77,78,79] and to extensive summer melt on the West Antarctic Ice Sheet.[80]<br><br>**Crosscuts Antarctic ice sheet**<br>All processes leading to ice melt (at the surface or below the ice shelves) are strongly nonlinear. This nonlinearity may increase the impact of extreme warm events, especially on ice shelf collapse. Periods of above-normal precipitation can be thought of as extreme events that increase surface accumulation.[81,82] |

| | |
|---|---|
| 21. How did the Antarctic cryosphere and the Southern Ocean contribute to glacial/inter-glacial cycles? | Changes in Southern Ocean overturning circulation contribute to glacial/inter-glacial cycles by regulating the release or storage of carbon dioxide in the deep ocean, with sea ice and upper ocean stratification also influencing exchange with the atmosphere.[83,84,85,86]<br><br>**Crosscuts Antarctic ice sheet**<br>The Antarctic ice sheet contributed to sea level changes during glacial-interglacial cycles.[87] During the Last Glacial Maximum (LGM) Antarctic ice-sheet contribution to sea-level lowering (120 m in total) is estimated to be between 5-30 m with the most recent estimates in the lower part of this range (5-15 m).[87] |
| 22. How will climate change affect the physical and biological uptake of $CO_2$ by the Southern Ocean? | The mechanisms responsible for heat and carbon dioxide uptake and storage in the Southern Ocean, both in the present day and in the future, are now better understood. Both passive advection (e.g. transport of anomalous input of heat and carbon by an unchanged circulation) and changes in circulation (e.g. a change in strength of the overturning circulation) contribute to uptake and storage of $CO_2$.[14,15,53,88,89] Early results from the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project suggest that less $CO_2$ is taken up by the Southern Ocean than previously thought.[90] The response of Southern Ocean phytoplankton to climate change will vary with species, due to varying physiology and response to changes in iron supply.[91] See below.<br><br>**Crosscuts Antarctic life**<br>This is an active area of research that has produced advances over the past five years via modeling and controlled experiments to evaluate Southern Ocean biotic impact on dissolved inorganic carbon uptake. Ecosystem modeling under the RCP8.5 scenario with at least two phytoplankton functional types predicted significant increases in the importance of the biological pump in the Southern Ocean as a result of anthropogenic $CO_2$.[92] For example, experimental studies demonstrate that the interactive effects of carbon dioxide, light, temperature, and changing iron availability can impact the growth, production, and morphology in a species-specific manner when different phytoplankton species are considered.[93] The multi-factor effects of climate change; including increased carbon dioxide concentrations, acidification, changes in the temperature and structure of the water column, and the resulting implications for nutrient regimes; result in complex interactions. The influences of acidification are less clear than previously suggested. For pelagic systems, pteropods are more capable of shell repair than previously thought, but juvenile stages may be at risk.[94,95,96,97] |

| | |
|---|---|
| 23. How will changes in freshwater inputs affect ocean circulation and ecosystem processes? | New results affirm the importance of the freshwater flux added by sea ice melt to water mass transformations in the upper limb of overturning circulation.[45,57,58] See Q.12.<br><br>**Crosscuts Antarctic Life**<br>Changing freshwater inputs will have differing effects on ecosystem processes depending on the site, the ecosystem and the magnitude of the inputs. On land and beneath ice shelves, warming increases melt which affects ice shelf stability[98] and produces new open water in summer where it did not previously exist. This allows new aquatic ecosystems to be established. In marine environments, impacts from increased freshwater inputs will vary from the loss of some shallow coastal water assemblages to increased phytoplankton productivity and higher nutrient input to the ecosystem from terrestrial sources.[99] The spatial distribution of runoff around Antarctica influences sea ice cover and the stratification of water masses.[100] Strong freshwater forcing, leading to accelerations of the coastal current and sea ice removal, may result in a decrease in sea ice extent and volume effecting the feeding behaviors and reproduction of numerous species. |

Table S4. Summary of qualitative (subjective) expert assessments of progress in answering “Southern Ocean and Sea Ice in a Warming World” questions rated as: 1 - no or little progress, 2 - moderate progress, 3 - major progress and 4 - answered. When a question crosscuts other clusters an additional perspective(s) on progress is provided. (New) – indicates a question that was not originally identified as cross-cutting in the Scan. For detailed commentary on progress and supporting references see Table S3.

| **Antarctic Science Horizon Scan Question**[1,2] | **Qualitative (Subjective) Rating (1-4)** |
|---|---|
| 12. Will changes in the Southern Ocean result in feedbacks that accelerate or slow the pace of climate change? | **2**<br>The Southern Ocean dominates global ocean heat uptake, with the overturning circulation acting to transport anthropogenic heat (and carbon dioxide) northward and into the ocean interior, so changes in circulation may result in climate feedbacks.<br><br>**Crosscuts Antarctic Ice Sheet (new): 2**<br>Changes in the Southern Ocean due to input of ice melt have been shown to reduce global mean temperatures. |
| 13. Why are the properties and volume of Antarctic Bottom Water changing, and what are the consequences for global ocean circulation and climate? | **2**<br>Trends toward warmer, fresher, lighter and less voluminous Antarctic Bottom Water have been documented, contributing to ocean heat storage and sea level rise.<br><br>**Crosscuts Antarctic Ice Sheet (new): 2**<br>See above. |
| 14. How does Southern Ocean circulation, including exchange with lower latitudes, respond to climate forcing? | **2**<br>There is some recent evidence for decadal/multi-decadal variability in the Southern Ocean overturning circulation but understanding of the sensitivity of the circulation to changes in forcing remains incomplete. |

| | |
|---|---|
| 15. What processes and feedbacks drive changes in the mass, properties and distribution of Antarctic sea ice? | **2**<br>New observations under Antarctic sea ice have revealed how pre-conditioning by ocean stratification can influence rates of sea ice growth.<br><br>**Crosscuts Antarctic Ice Sheet (new): 2**<br>See above. |
| 16. How do changes in iceberg numbers and size distribution affect Antarctica and the Southern Ocean? | **2**<br>The freshwater input to the Southern Ocean from melting icebergs has been quantified and shown to reduce sea surface temperatures and increase annual mean sea ice volume. |
| 17. How has Antarctic sea ice extent and volume varied over decadal to millennial time scales? | **2**<br>A multi-decadal trend of slow expansion of Antarctic sea ice was interrupted by a sharp decline to record low levels in 2016 and has remained low, while regional trends in sea ice extent have been linked to well-known modes of climate variability. |
| 18. How will changes in ocean surface waves influence Antarctic sea ice and floating glacial ice? | **3**<br>Substantial progress has been made in understanding the influence of ocean surface waves on sea ice and ice shelves.<br><br>**Crosscuts Antarctic Ice Sheet (new): 2**<br>For floating glacial ice indirect impacts from sea ice are known. This process is seldom simulated in models. |
| 19. How do changes in sea ice extent, seasonality and properties affect Antarctic atmospheric and oceanic circulation? | **2**<br>Freshwater added by sea ice melt is critical for transforming dense water to lighter water in the upper branch of the Southern Ocean overturning circulation<br><br>**Crosscuts Antarctic Atmosphere: 2-3**<br>Changes in sea ice extent influence the location of the mid-latitude jet and air temperatures near the Antarctic coast. |

| | |
|---|---|
| 20. How do extreme events affect the Antarctic cryosphere and Southern Ocean? | **2**<br>Recurrence of an uncommon “extreme event” (e.g. opening of the Weddell Polynya) has been linked to the combined effect of unusually strong atmospheric storms and oceanographic preconditioning, while the recent shift from record high to record low sea ice extent provides another example of an extreme event in the coupled system.<br><br>**Crosscuts Antarctic Ice Sheet: 2**<br>The nonlinearity of processes leading to ice melt may increase the impact of extreme warming events. |
| 21. How did the Antarctic cryosphere and the Southern Ocean contribute to glacial-interglacial cycles? | **3**<br>There are new insights into the contribution of changes in Southern Ocean overturning circulation to glacial/inter-glacial cycles.<br><br>**Crosscuts Antarctic Ice Sheet: 3**<br>The Antarctic ice sheet contributes to sea level changes during glacial cycles. |
| 22. How will climate change affect the physical and biological uptake of $CO_2$ by the Southern Ocean? | **2**<br>Early results from profiling biogeochemical floats suggest that less $CO_2$ is taken up by the Southern Ocean than previously thought, and there is growing evidence that decadal variability in the Southern Ocean carbon sink is more pronounced than expected, but projections of future heat and carbon uptake remain uncertain.<br><br>**Crosscuts Antarctic Life: 2**<br>See above. |
| 23. How will changes in freshwater inputs affect ocean circulation and ecosystem processes? | **2**<br>The freshwater flux added by sea ice melt contributes to water mass transformations in the upper limb of overturning circulation. |

| | |
|---|---|
| | **Crosscuts Antarctic Life: 1-2**<br>Changing freshwater inputs will have differing effects on ecosystem processes depending on the site, the ecosystem and the magnitude of the inputs. A better understanding of biotic-abiotic (physical) process interactions is needed. |

Table S5. Expert (subjective) assessments of progress toward answering “Antarctic Ice Sheets and Sea Level” questions supported by peer-reviewed literature citations. Comments by experts from crosscutting clusters are identified as ‘Crosscuts [name of cluster]’. The references cited are exemplars and not intended to be an exhaustive literature review.

| **Antarctic Science Horizon Scan Question**[1,2] | **Conclusions** |
|---|---|
| 24. How does small-scale morphology in subglacial and continental shelf bathymetry affect Antarctic Ice Sheet response to changing environmental conditions? | Knowledge of bed morphology is essential in assessing where Marine Ice Sheet Instability (MISI) and eventually Marine Ice Cliff Instability (MICI) may occur in response to climate change. Major improvements have been made in the coverage of ice thickness measurements (Ice Bridge).[101] Integration of all data, for instance in Bedmap 3, and modelling approaches like BedMachine are expected to improve predictions.[102] The roughness of the bed is important and the most advanced ice sheet models would benefit from access to detailed data rather than from coarse-scale grids in grounding-line regions.[103] Bathymetry plays an important role in the access of warm water beneath ice shelves that triggers MISI. The knowledge of small-scale morphology is a limiting factor for ocean models. Progress has been made in mapping bathymetry.[104]<br><br>**Crosscuts Dynamic Earth**<br>Targeted high-resolution Radio Echo Soundings (RES) in ice stream troughs have been conducted.[104,105,106] There is an awareness of along/crossflow roughness in ice stream trunks. There is now good knowledge of Totten, Thwaites, and Pine Island Glacier and other ice sheets/shelves that are at risk. More data are needed, especially in grounding zones, to better define sub-ice shelf and sub-sea-ice bathymetry. Bedmap3 and Bed Machine will be important in addressing this question (see above). Related to Q.25, Q.26 and Q. 27 |

| | |
|---|---|
| 25. What are the processes and properties that control the form and flow of the Antarctic Ice Sheet? | The form and flow of the Antarctic Ice Sheet are governed by:<br>1) the material (rheological) properties of ice [There is a consensus on the deformation law (Glen flow law) but this law is modulated by ice anisotropy that develops with depth affecting ice deformation. The deformation properties are also dependent on the 3-D temperature field that affects viscosity. Finally, ice can be damaged due to intense deformation, for instance, at the shear margin of ice streams and this can affect deformation properties], and 2) the properties of the bed; i.e. roughness, hard rock, sediment (saturated or not) and water pressure at the ice-bed interface. [These properties govern the basal friction experienced by the slab of ice, and whether the ice-bed interface is at the melting point (see also geothermal flux). Radio echo sounding, primarily done to measure ice thickness, can provide information on the status of the ice-bed interface.[107]]<br><br>Among improvements in recent years, inverse methods in ice sheet models allow for retrieval of many of the characteristics (or at least the vertically integrated impact) based on observed velocity fields.[108] The main question remains – how do these fields (essentially basal friction and damage) vary in time, especially in the context of changes in ice geometry?<br><br>Efforts in modelling processes (friction law or basal hydrology) are being pursued but will need time-dependent observations of velocity fields for calibration.[109] 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 (MISI).[110,111] The numerical schemes on which ice sheet models are based have advanced considerably since the Scan. Multi-centennial simulations are now possible using anisotropic grids[112,113] and adaptive mesh refinements.[114,115,116] Similarly, inverse modelling of basal drag properties has improved simulations of present-day ice flow.[117] Ice sheet and ocean model parameterization and coupling must be improved. Intercomparison experiments based on idealized geometries[118] have investigated processes and feedbacks between ice sheet-ice shelves and the ocean. At continental-scales model intercomparisons are also being pursued.[21,119] See Q.7. |
| 26. How does subglacial hydrology affect ice sheet dynamics, and how important is it? | The Antarctic subglacial water system is active as mainly revealed by repeated surface altimetry.[120] This dynamic behavior improves knowledge of hydrological processes.[121] Subglacial hydrology affects ice dynamics through basal friction (see Q.25). There is some evidence that basal water moving in and out of subglacial lakes causes fluctuations in ice velocity.[122] This movement can be estimated by radar echo sounding and radar |

| | |
|---|---|
| | scattering behavior at the ice-bed interface.[123] Models for subglacial water flow have evolved in recent years with a variety of routing processes now considered.[120] The distribution of basal water, and its connectivity, is heterogenous and new observations, including sediment thickness, are necessary at a continental scale. Basal water production, which is an input to hydrology models, can be simulated by ice sheet models but depends on the value used for geothermal flux which remains poorly known (see Q.27).<br><br>**Crosscuts Dynamic Earth**<br>There is a better understanding of the location of basal water.[124,125] Radio Echo Sounding (RES) data of "modern quality", or from better technologies, is needed. Determination of water-saturated sediments is also needed. The presence of groundwater, and its influence, remains largely unknown. |
| 27. How do the characteristics of the ice sheet bed, such as geothermal heat flux and sediment distribution, affect ice flow and ice sheet stability? | Geothermal flux controls temperature within the ice, as well as where ice reaches the melting point, driving basal water production. Geothermal flux is poorly known. Up to now, several maps of geothermal flux have been proposed using different methods and the differences between these maps are important.[126] Within the program 'Solid Earth Response and influence on Cryosphere Evolution (SERCE)', an effort is being made to reconcile different ways of inferring geothermal flux.[127] Information about the geothermal flux value is also crucial in the search for sites where ice core records reach 1.5 million years Before Present.[128] Sediment distribution is important to ice sheet dynamics because deformation adds to ice velocity and can be an important influence, especially when the sediment is water-saturated. Short-term glacial isostatic adjustment can slow ice mass loss. This is known to be operative at least in the Amundsen Sea region.[116] There is an improved understanding of the processes involved in the evolution of the Antarctic Ice Sheet.[129]<br><br>**Crosscuts Dynamic Earth**<br>On heat flux, estimates are proxy-based and include assumptions that lead to inconsistent results. On sediment – radar data is available but has not been properly integrated into Bedmap. Ice sheet models do not use detailed geothermal distributions and the West and East Antarctic Ice Sheet may need to be differently treated. |
| 28. What are the thresholds that lead to irreversible loss of all or part of the Antarctic ice sheet? | Several authors estimate that the only way to avoid serious ice shelf retreat is to follow RCP2.6.[23,130] At centuries to millennium timescales, it has been estimated that a tipping point exists at, or around, 2°C of global warming.[131] However, for Thwaites Glacier there |

| | |
|---|---|
| | are concerns that a threshold for unstoppable grounding line retreat has been, or is about to be, crossed.[132,133,134] |
| 29. How will changes in surface melt over the ice shelves and ice sheet evolve, and what will be the impact of these changes? | Surface melt is important for its impact on calving, ice shelf break-up and marine ice cliff instability processes (although the MICI process is being debated). Projections reveal a scenario-independent doubling of Antarctic-wide melt by 2050 with projections diverging afterwards. By 2100, under the high emissions pathway, melt on several ice shelves could lead to ice shelf collapse, at least along the northeast Antarctic Peninsula.[134] However, run-off from surface rivers might limit the impact on ice-shelf breakup.[135] |
| 30. How do oceanic processes beneath ice shelves vary in space and time, how are they modified by sea ice, and do they affect ice loss and ice sheet mass balance? | Ice loss in Antarctica is mainly due to an acceleration of outlet glaciers and grounding line retreat driven by the thinning of floating ice shelves. High melt at the ice-shelves base results from the influx of relatively warm circumpolar deep water into cavities beneath ice shelves. The access of these cavities to the ocean varies from place-to-place depending on small-scale bathymetric channels.[136] For observed collapse events, the absence of sea ice makes the ice shelves more vulnerable to swell.[69]<br><br>**Crosscuts Southern Ocean**<br>Ocean-ice shelf interactions are influenced by teleconnections to the tropics.[137,138] |
| 31. How will large-scale processes in the Southern Ocean and atmosphere affect the Antarctic Ice Sheet, particularly the rapid disintegration of ice shelves and ice sheet margins? | In the Amundsen Sea area, the decadal variability of the ocean is found to control the variability of the basal melt via a non-linear relationship with ocean temperature.[139,140] The International Thwaites Glacier Collaboration[141] began in 2019 and will address specific questions about Thwaites Glacier and its future, and general questions about the West Antarctic ice sheet, with a goal of reducing uncertainty in future sea-level rise contributions. See. Q.8, Q.21, Q.32 and Q.33.<br><br>**Crosscuts Antarctic Atmosphere**<br>See above.<br><br>**Crosscuts Southern Ocean**<br>There is emerging evidence that ocean heat flux drives rapid basal melt in some parts of East Antarctica.[142] Work is being done on the importance of variability that is driven by tropical teleconnections (see Q.30). |

| | |
|---|---|
| 32. How fast has the Antarctic Ice Sheet changed in the past and what does that tell us about the future? | Improved understanding of how the Antarctic Ice Sheet responded to forcings in the past is crucial to improving the reliability of forecasts (see Q.8, Q.21, Q.31, and Q.33).[24] Past responses allow calibration and validation of ice sheet models.[23] Understanding changes in past ocean circulation, based on marine sedimentary records, is one way to identify forcings and ice sheet/ocean interactions. Results from marine[28] and ice-sheet drilling projects [30] will provide important advances in understanding (see Q.9). The last deglaciation (~20 - 10 thousand years Before Present) is the most documented rapid decrease of the Antarctic ice sheet in the past. Ice sheet mass balance estimates have been recently summarized.[143] Grounding line retreat rates have been estimated for the Ross sea sector.[144] Contributions to past sea level rise have been modelled.[23] The ice sheet mass balance inter-comparison exercise (IMBIE) project began pre-scan (2011) and produces estimates of ice sheet mass balance as a contribution the Intergovernmental Panel on Climate Change.[145] |
| 33. How did marine-based Antarctic ice sheets change during previous inter-glacial periods? | Information on past interglacial periods is mainly based on sea-level records from ice sheets in both the north and south. Greenland and Antarctic ice sheets are considered, and individual contributions are difficult to disentangle. For the last interglacial, the Greenland ice sheet is estimated to have contributed 0.6 to 3.5 m to sea level and West Antarctic Ice Sheet collapse could explain the remaining global sea-level rise of 6-9 m above present.[9] For Marine Isotope Stage11 and the Mid-Pliocene, with even higher sea-level stand, it is suggested that some parts of the East Antarctic Ice Sheet may have been involved.[23] See Q.8, Q.21, Q.31 and Q.32. |
| 34. How will the sedimentary record beneath the ice sheet inform our knowledge of the presence or absence of continental ice? | Stratigraphic changes identified through seismic surveys suggest former ice margin retreat positions and variable erosion rates. Nearshore sediment sequences provide information on the continuity of sedimentation from outlet glaciers which can be used to infer the presence or absence of terrestrial ice.<br><br>**Crosscuts Dynamic Earth**<br>There is some progress in identifying targets for research, such as subglacial lakes and basins, but reliable stratigraphic sequences have not been the subject of detailed seismic surveys.[146,147] A shallow sediment core has been retrieved from Lake Mercer, but disturbance is suspected. Much remains unknown. Progress in developing the Rapid Access Ice Drill (RAID)/ Fast drill has been limited.[148,149] |

Table S6. Summary of qualitative (subjective) expert assessments of progress in answering “Antarctic Ice Sheets and Sea Level” questions rated as: 1 - no or little progress, 2 - moderate progress, 3 - major progress and 4 - answered. When a question crosscuts other clusters an additional perspective(s) on progress is provided. (New) – indicates a question that was not originally identified as cross-cutting in the Scan. For detailed commentary on progress and supporting references see Table S5.

| **Antarctic Science Horizon Scan Question**[1,2] | **Qualitative (Subjective) Rating (1-4)** |
|---|---|
| 24. How does small-scale morphology in subglacial and continental shelf bathymetry affect Antarctic Ice Sheet response to changing environmental conditions? | **2-3**<br>Knowledge of bed morphology is essential to assessing ice sheet instability in response to climate change.<br><br>**Crosscuts Dynamic Earth: 2-3**<br>In terms of understanding how to do it - 3. In terms of getting the data and using the methods available - 2. Grounding lines remain an unresolved issue. |
| 25. What are the processes and properties that control the form and flow of the Antarctic Ice Sheet? | **3**<br>There is good knowledge of the present state of the ice sheet.<br>**2**<br>It remains difficult to simulate the time dependency of bed properties and water pressure at the ice bed interface. |
| 26. How does subglacial hydrology affect ice sheet dynamics, and how important is it? | **2**<br>There is some evidence that basal water moving in and out of subglacial lakes causes fluctuations in ice velocity. However, there are few observations and the underlying processes remain largely unknow.<br><br>**Crosscuts Dynamic Earth: 2**<br>There are important gaps in knowledge of important processes as above. |

| | |
|---|---|
| 27. How do the characteristics of the ice sheet bed, such as geothermal heat flux and sediment distribution, affect ice flow and ice sheet stability? | **2**<br>Geothermal flux controls temperature within the ice as well as where ice reaches the melting point driving basal water production. However, maps are inconsistent and incomplete.<br><br>**Crosscuts Dynamic Earth: 2**<br>On heat flux, measurements are proxy-based and make assumptions that have led to inconsistent results. On sediment – radar, it has not been integrated into Bedmap or ice sheet models. |
| 28. What are the thresholds that lead to irreversible loss of all or part of the Antarctic ice sheet? | **2**<br>The existence of various tipping points has been proposed. |
| 29. How will changes in surface melt over the ice shelves and ice sheet evolve, and what will be the impact of these changes? | **2**<br>Surface melt is important for its impact on calving, ice shelf break-up and marine ice cliff instability processes however, knowledge is limited on the underlying processes and forcings. |
| 30. How do oceanic processes beneath ice shelves vary in space and time, how are they modified by sea ice, and do they affect ice loss and ice sheet mass balance? | **2**<br>Ice loss in Antarctica is mainly due to an acceleration of outlet glaciers and grounding line retreat driven by the thinning of floating ice shelves. Most knowledge to date is based on modelling.<br><br>**Crosscuts Southern Ocean**<br>See above. |
| 31. How will large-scale processes in the Southern Ocean and atmosphere affect the Antarctic Ice Sheet, particularly the rapid disintegration of ice shelves and ice sheet margins? | **2**<br>In the Amundsen Sea area, the decadal variability of the ocean was found to control the variability of basal melt via a non-linear relationship with ocean temperature.<br><br>**Crosscuts Antarctic Atmosphere: 2**<br>See above. |

| | |
|---|---|
| | **Crosscuts Southern Ocean**<br>See above. |
| 32. How fast has the Antarctic Ice Sheet changed in the past and what does that tell us about the future? | **2**<br>Improved understanding of how the Antarctic Ice Sheet responded to forcings in the past is crucial to improving the reliability of forecasts. Most studies to date are for the last deglaciation. |
| 33. How did marine-based Antarctic ice sheets change during previous inter-glacial periods? | **2**<br>Information on past interglacial periods is mainly based on sea-level records in both the north and south. In these records it is difficult to disentangle contributions from the Greenland and Antarctic ice sheets. |
| 34. How will the sedimentary record beneath the ice sheet inform our knowledge of the presence or absence of continental ice? | **1**<br>Even if robust indicators of ice-free conditions can be extracted from sedimentary records, the difficulties of subglacial access means that only sparse point data could be recovered, making large-scale inferences about ice sheet presence/absence challenging.<br><br>**Crosscuts Dynamic Earth: 1**<br>Geological drilling on land ice has yet to be initiated. |

Table S7. Expert (subjective) assessments of progress toward answering “Dynamic Earth - Probing Beneath Antarctic Ice” questions supported by peer-reviewed literature citations. Comments by experts from crosscutting clusters are identified as ‘Crosscuts [name of cluster]’. The references cited are exemplars and not intended to be an exhaustive literature review.

| **Antarctic Science Horizon Scan Question**[1,2] | **Conclusions** |
|---|---|
| 35. How does the bedrock geology under the Antarctic Ice Sheet inform our understanding of supercontinent assembly and break-up through Earth history? | There is some progress on this question at local (fine resolution) and continental (low resolution) scales.[150] ADMAP2 offers an updated continent-wide view. However, resolution remains low in some places, and no drilling to bedrock (and sampling) limits interpretations. More quantitative geological approaches, including machine learning are not well developed for subglacial geology. |
| 36. Do variations in geothermal heat flux in Antarctica provide a diagnostic signature of sub-ice geology? | There has been extensive work on this question, but there remains a lack of consensus because of the diversity of proxy methods (e.g. from radar, magnetics, and seismic surveys) used to estimate heat flux variations.[126,151,152,153] A systematic attempt to reconcile differing proxy methods is needed, and further progress tied to geology is limited by a lack of direct sampling. The role of groundwater in modulating heat flux at the base of the ice sheet is largely unexplored but could potentially be a significant factor. There is an informative blog related to Q.36.[154] |
| 37. What is the crust and mantle structure of Antarctica and the Southern Ocean, and how do they affect surface motions due to glacial isostatic adjustment? | Progress has been made for several regions through seismic arrays[155], airborne programs[156] and continental-scale models.[151] There remain substantial gaps in high quality data coverage, especially in East Antarctica, though this is improving. Direct measurements of crustal motions have not been made for areas covered with ice due to the challenge of removing the ice flow signal. Including higher resolution data in Glacial isostatic adjustment (GIA) models is far from straightforward – but capabilities for complex models are improving. Modelling has assisted in understanding the sensitivity of isostatic changes to lithospheric structures.[157] |

| | |
|---|---|
| 38. How does volcanism affect the evolution of the Antarctic lithosphere, ice sheet dynamics, and global climate? | There has been some progress on the identification of volcanos using bed morphology[158], although the mapping accuracy is limited by false positives and data artifacts. There have also been detections of englacial ash layers[159], though this has not progressed as a theme, despite some efforts by the Scientific Committee on Antarctic Research (Antvolc).[160] Currently there is a lack of understanding of feedbacks of volcanism with ice sheets and their significance, except perhaps locally. There is an informative blog related to Q.38.[161]<br><br>**Crosscuts Antarctic Atmosphere**<br>See above.<br><br>**Crosscuts Antarctic Ice Sheet**<br>There is some evidence that subglacial volcanism may have occurred during the last glacial maximum, leading to subglacial melting.[162] Whether meltwater led to flow acceleration, and/or freshwater discharge, to the ocean remains unknown. |
| 39. What are and have been the rates of geomorphic change in different Antarctic regions, and what are the ages of preserved landscapes? | Recently limited work has been undertaken on landscape development using Radio Echo Sounding (RES) data, as well as thermochronological data. Most work has been regional, with some attempts at continental-scale assessments.[163,164,165] The Bedmap3 project, and the data used to build it, will address Q.39. |
| 40. How do tectonics, dynamic topography, ice loading and isostatic adjustment affect the spatial pattern of sea level change on all time scales? | Substantial conceptual progress has been made in recognizing the potential effects of dynamic topography and tectonics on paleoceanography, the ice sheet and past estimates of sea level.[129,166] Understanding is limited by a lack of consistency between models and a lack of data to constrain models leading to a high degree of uncertainty in predictions.<br><br>**Crosscuts Antarctic Ice Sheet**<br>See above. |
| 41. Will increased deformation and volcanism characterize Antarctica when ice mass is reduced in a warmer world, and if so, how will glacial- and ecosystems be affected? | There is limited progress on this question. For volcanism see Q38. Feedbacks between ice mass loss and tectonic activity need further study. It is unclear how to assess the role of deformation without good hydrological and hydrogeological models, as deformation-potential is controlled by fluid pressures. Groundwater dynamics may be important but there are few studies. |

| | |
|---|---|
| | **Crosscuts Antarctic Life**<br>There is little progress on the life sciences aspects of this question. General analyses of species richness and its spatial variability show that biodiversity is higher at geothermal sites for many groups; and the effect extends beyond the immediate geothermal, largely volcanic, areas; but little evidence is available.[167] |
| 42. How will permafrost, the active layer and water availability in Antarctic soils and marine sediments change in a warming climate, and what are the effects on ecosystems and biogeochemical cycles? | There is limited research mainly focused on the Antarctic Peninsula (see Q.10). SCAR has formed an expert group to investigate this topic, Antarctic Permafrost and Soils (Antpas), and advances are expected in next few years.[31] |

Table S8. Summary of qualitative (subjective) expert assessments of progress in answering “Dynamic Earth - Probing Beneath Antarctic Ice” questions rated as: 1 - no or little progress, 2 - moderate progress, 3 - major progress and 4 - answered. When a question crosscuts other clusters an additional perspective(s) on progress is provided. (New) – indicates a question that was not originally identified as cross-cutting in the Scan. For detailed commentary on progress and supporting references see Table S7.

| **Antarctic Science Horizon Scan Question**[1,2] | **Qualitative (Subjective) Rating (1-4)** |
|---|---|
| 35. How does the bedrock geology under the Antarctic Ice Sheet inform our understanding of supercontinent assembly and break-up through Earth history? | **2**<br>Machine learning approaches have not been adapted. Samples from the bed are key – hence fast drill/ Rapid Access Ice Drill are important technologies, but little progress has been made in perfecting these tools. |
| 36. Do variations in geothermal heat flux in Antarctica provide a diagnostic signature of sub-ice geology? | **1-2**<br>Available geothermal maps differ from each other making it difficult to resolve geology. *In situ* samples are key. |
| 37. What is the crust and mantle structure of Antarctica and the Southern Ocean, and how do they affect surface motions due to glacial isostatic adjustment? | **2-3**<br>Significant progress on this question but gaps in knowledge persist. Major advances have been accomplished by the Polar Observing Network (POLENET). Detailed models exist for lithospheric thickness and other variables, but data are needed for validations. |
| 38. How does volcanism affect the evolution of the Antarctic lithosphere, ice sheet dynamics, and global climate? | **1**<br>Many questions remain – knowing where volcanoes are is a first step – but understanding of the resultant processes is largely unknown [except perhaps Ross Island]. Ash layers in ice sheet layers may lend important clues.<br><br>**Crosscuts Antarctic Atmosphere: 1**<br>See above. |

| | |
|---|---|
| | **Crosscuts Antarctic Ice Sheet**<br>Field evidence shows that subglacial eruptions have occurred throughout the Cenozoic, but the impacts of these events on ice dynamics has not, and perhaps cannot, be determined from observations. |
| 39. What are and have been the rates of geomorphic change in different Antarctic regions, and what are the ages of preserved landscapes? | **2**<br>There are ideas on how to do this, but they need to be expanded continent-wide. Links to modelling need improvements. |
| 40. How do tectonics, dynamic topography, ice loading and isostatic adjustment affect the spatial pattern of sea level change on all time scales? | **2**<br>Dynamic topography may be important. Pore pressures may contribute to a better understanding of aseismicity.<br><br>**Crosscuts Antarctic Ice Sheet: 3**<br>Conceptual progress but there is a lack of data to constrain the models. |
| 41. Will increased deformation and volcanism characterize Antarctica when ice mass is reduced in a warmer world, and if so, how will glacial- and ecosystems be affected? | **1**<br>No known ongoing work on this question. |
| 42. How will permafrost, the active layer and water availability in Antarctic soils and marine sediments change in a warming climate, and what are the effects on ecosystems and biogeochemical cycles? | **1**<br>There is limited research that is mainly focused on the Antarctic Peninsula however, a Scientific Committee on Antarctic Research Expert Group has been recently formed to address this and other related questions.<br><br>**Crosscuts Antarctic Life**<br>See above. |

Table S9. Expert (subjective) assessments of progress toward answering “Antarctic Life on the Precipice” questions supported by peer-reviewed literature citations. Comments by experts from crosscutting clusters are identified as ‘Crosscuts [name of cluster]’. The references cited are exemplars and not intended to be an exhaustive literature review.

| **Antarctic Science Horizon Scan Question**[1,2] | **Conclusions** |
|---|---|
| 43. What is the genomic basis of adaptation in Antarctic and Southern Ocean organisms and communities? | Several important advances in understanding the genomic basis of adaptation in Antarctic single and multi-celled organisms have been made in the last five years. Comparative genomics with lower latitude species has provided key insights. For example, nearly 25% of the genome, of an Antarctic diatom (*Fragilariopsis cylindrus)*, was comprised of significantly divergent alleles that were differentially expressed in high latitude conditions including low temperature, darkness, limiting iron and high $CO_2$.[168] Likewise, important new information on Antarctic fishes has been produced via high quality genome sequencing. This work has shed light on evolutionary history of the cold-tolerant Antarctic Notothenoidei[169], rapid adaptation of cellular respiration[170] and subsequent gene loss of hemoglobin, including details of antifreeze glycoproteins evolution in addition to gene family adaptations to high oxygen in subzero Antarctic waters.[169] Full genome sequence of the iconic midge, *Belgica antarctica*, indicates that its genome is the smallest of any insect. Environmental extremes have constrained genome architecture but not gene content, leading to small genome size. Many genes related to external stimuli, development and metabolism reflect adaptations to the Antarctic environment.[171] Genomic studies have indicated that trace gas scavenging supports primary productivity in Antarctic soils. Atmospheric $H_2$, $CO_2$ and CO provide dependable sources of energy and carbon which support soil microbial communities. Thus, atmospheric energy sources could provide a basis for ecosystem function without solar or geological energy sources. The work has profoundly altered ideas about soil microbial adaptations in the Antarctic and has implications for exobiology.[172] See Q.47. |
| 44. How fast are mutation rates and how extensive is gene flow in the Antarctic and the Southern Ocean? | Oceanic fronts around Antarctica and the Southern Ocean are the main drivers of speciation and diversification processes playing a central role in limiting gene flow and generating genetic and phylogeographic structure. New insights regarding postglacial (e.g. Last Glacial Maximum) expansion, recolonization, recent diversification - in both terrestrial and marine environments - from a less ice-impacted refugium, and especially their rapidity, |

| | |
|---|---|
| | have been reported in vertebrates and invertebrates. Others are reconstructing past-demographic histories.[173,174] Changes in the permeability of the barriers, such as the Polar Front, due to global warming have also been highlighted.[175] High gene flows and rapid mutation rates have been identified, e.g. in sponges.[176] Rapid progress is being made in understanding the extent of gene flow and dispersal around the continent and in the Southern Ocean.[177,178] Many groups of organisms show extensive historic dispersal and connectivity with limited current dispersal, though for others significant patterns of current connectivity are evident. |
| 45. How have ecosystems in the Antarctic and the Southern Ocean responded to warmer climate conditions in the past? | Studies on the impacts on Antarctic ecosystems of past conditions fall into three main areas: 1. the recent past (decades); 2. the last 1 million years (the glacial cycles); and 3. the deep past (millions of years). Recent past research focusses on ongoing human-driven climate change and its impacts on biodiversity. There have been no warmer periods in this time. During the last million years there has been at least one warm period where Antarctica was very different, including the collapse of the West Antarctic Ice Sheet and the presence of an open seaway between the Ross and Weddell Seas.[179] This link allowed species to travel between sites now cut off and the signals of the link are present in the genetics of bryozoans.[179] Over the last million years there have been glacial cycles of warming and cooling. The contraction of available habitat during glacial extremes restricted biodiversity to refugia in both marine and terrestrial habitats.[180,181] In marine systems this repeated contraction and expansion of habitat has been termed the biodiversity pump, leading to increased biodiversity over time.[182] Significant progress has been made on this subject in terrestrial refugia.[183] Range extension and contractions of numerous species have been investigated mainly from the Last Glacial Maximum and the present, in order to project future distributions out to 2100 (see Q.44 regarding postglacial expansion, recolonization, and diversification from a less ice-impacted refugium).[173,174,184,185,186,187] Strong but lasting impacts of past global warming on baleen whales have been noted.[188] Transformations of landscape and ecosystems in response to past warmer climate have been documented in moss species compositions.[189] More recently, over the past 90 years, the distribution of the krill population in the southwest Atlantic sector has contracted southward.[190] Recent warming cycles in the Antarctic Peninsula Region, over the last 50 years, have had rapid and large effects on lichen vegetation.[191] In the deeper-time periods over millions of years there were warmer periods. These do not inform how current ecosystems will respond to climate change but could give insight into long-term changes in biodiversity if future warming continues unabated for many decades. In the last five years much research has elucidated adaptations to the cold (e.g. on the loss of hemoglobin in |

| | |
|---|---|
| | Channichthyid icefish) and the associated adaptations with this condition.[98,192] The reverse evolution of these conditions will require very long times and will not be relevant to current climate change, but groups currently not present in Antarctica that were present when sea temperatures were significantly warmer, such as shallow water sharks, could return in the medium- to longer-term.<br><br>**Crosscuts Antarctic Atmosphere and Southern Ocean**<br>See above. |
| 46. How has life evolved in the Antarctic in response to dramatic events in the Earth's history? | Several major adaptations of Antarctic species have been identified in relation to dramatic events in the Earth's history.[98,169,173,193,194] These include the evolution of antifreezes and cryoprotectants in terrestrial invertebrates, the emergence of Notothenioids as a species flock, antifreeze in fishes and the loss of hemoglobin in the Channichthyid ice fishes. These adaptations arose because of events such as the separation of Antarctica from South America and the subsequent cooling. All of these were known before the Horizon Scan and no new large-scale adaptations related to major events have been identified since. However, recent advances have been made in relation to the survival during past glacial maxima using phylogenetic approaches to identify likely refugia in both terrestrial and marine environments.[179,193,196] In both terrestrial and marine systems, geothermal heating has been identified as a potential heat source producing refugia during glacial maxima. Two recent global to semi-global analyses have shown the importance of the Antarctic for the evolution of global marine life, one showing extensive diversification of fishes and the other of brittle stars in the Antarctic in response to past changes in the Earth system.[195,196]<br><br>**Crosscuts Dynamic Earth**<br>See above |
| 47. How do subglacial systems inform models for the development of life on Earth and elsewhere? | The discovery of functioning microbial ecosystems underlying the Antarctic ice sheet in sublacial Lake Whillans[197] provided a critical advance in understanding of the requirements of ecosystem sustainability in the absence of light. In addition, extensive subglacial brine networks were revealed in the Taylor[198] and Victoria valleys[199], both of which have the potential to support subsurface microbial life at sustained subzero temperature and high salt - conditions that could be present in the subsurface of Mars or the icy moons of Jupiter (Europa) and Saturn (Enceladus) where ice shell-covered oceans exist. See Q. 42.<br><br>**Crosscuts Eyes on the Sky**<br>See above. |

| | |
|---|---|
| 48. Which ecosystems and food webs are most vulnerable in the Antarctic and Southern Ocean, and which organisms are most likely to go extinct? | Threats and stressors differ between terrestrial and marine environments. On land recent research has demonstrated significant regionalization, with sixteen ecoregions identified on the continent and eight more on the surrounding islands.[200] Some groups, such as mites and springtails have highly differentiated species groups between regions but data for others (e.g. rotifers, tardigrades) are too limited to make assessments. The main perceived threats are invasive species that will outcompete local species and the movement of species within Antarctica breaking down isolation.[201] Tourists and scientists have been identified as significant vectors for both processes. For plants recent data are sparse but some lichen species have been shown to be poor at resisting environmental change.[202] The most significant data thus far are for mosses in East Antarctica, demonstrating how drought resistant species are replacing species with preferences for moister environments, associated with increased drying due to the Southern Annular Mode.[203] Responses to warming have also been demonstrated in the moss communities of the Antarctic Peninsula with increases in growth rate and accumulation rate of mosses and increases in microbial productivity recorded from the early to mid-1900s but with records extending back to ca. 1850.[204] Indications are that systems will change profoundly. In the marine environment several threats have been identified.[98] King Crabs migrating from deeper water in shallow sites have the potential to alter communities.[205] Significant new research has been published in the last five years. Antarctic marine species have been shown to be vulnerable to warming with some especially vulnerable species such as the brittle star *Ophionotus victoriae.*[206] Many species seem resistant to acidification but some species, such as pteropods, are at risk from acidification.[207,208] Glacier retreat has been highlighted in recent years as being a major threat to assemblages living in nearshore sites where smothering by sediment can remove species on a large scale.[209,210] Research on the effects of warming have been done using *in situ* heating of surfaces to temperatures were $1^0$C or $2^0$ C above ambient.[206] These experiments showed that a $1^0$C increase dramatically improved performance in marine invertebrates, doubling growth rates, but a $2^0$C rise pushed some species to, or beyond, their limits. A recent, Antarctic-wide investigation has projected declines in the abundance of the emperor penguin of ≥ 50%.[211] |
| 49. How will threshold transitions vary over different spatial and temporal scales, and how will they impact ecosystem functioning under future environmental conditions? | At the time of the Scan, the SCAR program, "Antarctic Thresholds – Ecosystem Resilience and Adaptation (Ant-ERA) began aiming to identify tolerance limits and threshold effects and resistance and resilience to environmental change.[212,213] For the Antarctic region little is known about whether thresholds are detectable but the field in general is rapidly progressing.[214-217] Much remains to be done to understand the scales that transitions operate on, and what are the effects on the biota consistent with general ecological |

| | |
|---|---|
| | interpretations of thresholds.[214] Some progress has been made on the theoretical aspects of threshold transitions[217] but empirical work is only beginning. Current work is exploring what the impacts might be of large events, such as the breakup of ice-shelves, the absence of fast ice in the ocean and melt events in terrestrial areas.[216,217] Positive thresholds may be encountered when coastal glaciers and ice shelves have been lost or retreated making new areas available for the establishment of new ecosystems. Negative thresholds may be passed when ice shelves disintegrate and unique under ice shelf assemblages are lost (see Q.48). A major factor likely to produce threshold changes in terrestrial assemblages is water availability. Recent work has shown changes in moss communities in East Antarctica and in ecosystems in the Dry Valleys.[203,216,217] Research over decades, using cloche systems or under soil heating, has also demonstrated that the transition from a frozen to a liquid environment has large effects on terrestrial ecosystems (see Q.50). Yet in all cases large or extreme events, and events with large impacts, have not been clearly differentiated from threshold transitions. |
| 50. What are the synergistic effects of multiple stressors and environmental change drivers on Antarctic and Southern Ocean biota? | There have been significant efforts in identifying the effects of multiple stressors.[218, 219,220,221,222,223] These have been mainly focused on the combined effects of temperature and acidification and have generally demonstrated larger effects from predicted warming than from acidification. Significant research has been done on phytoplankton and a range of marine invertebrates. Research on macroalgae showed synergistic positive effects of warming and acidification on growth in two species of *Desmarestia*.[222] However, progress towards robust evaluations of the effects of multiple stressors is limited as temperature, acidification, salinity, turbidity, sedimentation, oxygen and physical disturbance from ice are all recognized as environmental stressors and few studies, if any, have investigated more than two factors at a time in Antarctic systems. Little is known about the impact of important stressors such as the combined impacts of climate change and fishing, though there is growing awareness that such change may be important. The impacts of multiple stressors in terrestrial systems are also poorly known. Interactions between climate change and disease may have been responsible for significant changes to populations of a cushion plant on sub-Antarctic Macquarie Island.[224] A large-scale study of springtails indicates that invasive species, including in the Antarctic region, have greater tolerance to warming than their indigenous counterparts.[225] |
| 51. How will organism and ecosystems respond to a changing soundscape in the Southern Ocean? | Research on how marine species endemic to Antarctica respond to anthropogenic noise is sparse.[226,227] How anthropogenic noise affects species at the population level or how effects vary depending on the life-stage of the organism in question are poorly understood. |

| | |
|---|---|
| | The characteristics of the anthropogenic noise that Antarctic marine life is exposed to, how exposure varies over space and time, and what the environmental factors are that determine its effects, are all yet to be thoroughly investigated in the region. Identification of "sound-sensitive" Antarctic species, potential "sound hotspots" in Antarctica and cumulative effects are beginning to emerge, although this research is at its early stages.<br><br>**Crosscuts Human Presence**<br>See above. |
| 52. How will next-generation contaminants affect Antarctic and Southern Ocean biota and ecosystems? | This is an area of ongoing research and many studies continue to detect a variety of pollutants in the Antarctic covering both traditional and emerging pollutants.[228] However, most studies are short-term or one-time with little long-term monitoring to detect trends. Numerous studies on Antarctic species have found relationships between exposure to contaminants and effect responses on several levels from cellular processes, such as hormone regulation and oxidative stress, to demographic parameters, such as mortality and fecundity.[229] In recent years, attention has been paid to investigating physiological and behavioral stress responses; such as endocrine and vitamin disruption, oxidative stress, parental care and foraging efficiency; in association with contaminant exposure in Antarctic seabirds and their prey.[230,231] Global climate change may influence anthropogenic pollution as it is released from thawing permafrost in Antarctica.[232] Plastic and microplastic pollution have emerged as an unexpected contaminant for the region, with seabirds being most at risk in the Southern Ocean[233] and many studies are starting to find microplastic pollution in the Antarctic region.[234,235,236] See Q.53. |
| 53. What is the exposure and response of Antarctic organisms and ecosystems to atmospheric contaminants (e.g. black carbon, mercury, sulphur, etc.), and are the sources and distributions of these contaminants changing? | Atmospheric monitoring of Persistent Organic Pollutants (POPs) in Antarctica remains scarce. Ultra-low concentrations of atmospheric POPs have been found in coastal areas of the Ross Sea, Antarctica.[237,238,239] The occurrence of POPs in Antarctica is mainly attributed to long-range atmospheric transport from northern usage areas. It has been suggested that local contamination and volatilization from ice were potential sources for POPs in the atmosphere.[238] A variety of POPs have also been detected in East Antarctic air samples, though long-term monitoring is largely absent.[239] Lichens are recognized as an important biomarker of pollutants as well as having significant potential for tracking climate change.[240]. Studies have begun to examine contaminants such as black carbon, sulphur and zinc and other metals.[241] See Q.52. |

| | |
|---|---|
| | **Crosscuts Antarctic Atmosphere and Human Presence**<br>See above. |
| 54. How will the sources and mechanisms of dispersal of propagules into and around the Antarctic and Southern Ocean change in the future? | Dispersal pathways have been studied[176], but quantification of propagule pathways and sources, and the relative contributions of natural versus anthropogenic pathways remain undetermined. For terrestrial systems, the nature and extent of propagule pressure continues to be documented via interceptions at stations[242,243] but these efforts are not well coordinated across the region, and little modelling is available to distinguish the probability of natural versus anthropogenic propagule transfer. |
| 55. How will invasive species and range shifts of indigenous species change Antarctic and Southern Ocean ecosystems? | In marine systems, few instances of alien species establishment have been documented[244], and possibly no new reports since 2014. For terrestrial systems, the situation is different, with new records being found for both the Antarctic Peninsula region and the sub-Antarctic.[245,246] In Antarctic marine environments recent studies have evaluated the risk of alien species establishment and expectations are that alien species will have major impacts on ecosystems, but no analyses of specific impacts have been made. Modelling investigations for alien terrestrial species establishment have also been undertaken with predictions covering the present to 2100.[247,248] Some work on plant traits has demonstrated how these are changing and will likely change sub-Antarctic systems.[249] Range shifts of indigenous species have been predicted and some predicted specific range changes, such as lithodid crabs moving into shallow sites from deep water, are described as potentially overturning assemblage structure with catastrophic effects for some species. For terrestrial systems virtually no work on expected range shifts has taken place, though some monitoring of such shifts has taken place for the Antarctic's two vascular plant species.[250] No detailed modelling of likely impacts in marine or terrestrial ecosystems has been conducted. See Q48.<br><br>**Crosscuts Human Presence**<br>See above. |
| 56. How will climate change affect the risk of spreading emerging infectious diseases in Antarctica? | Numerous virology studies in Antarctica have been carried out over the past several decades. However, the development of long-term systematic epidemiological monitoring is lacking. Thus, it remains challenging to determine how climate change will affect the risk of spreading emerging infectious diseases in Antarctica. High-throughput sequencing (HTS) approaches have been recently used in the Antarctic to study soil[251], lakes[252], and marine viral ecology[253], and several viral families have been detected and characterized.[254] |

| | |
|---|---|
| | Antarctic ecosystems are dominated by microorganisms, and viruses play important roles in Antarctic aquatic systems and food webs (both marine and freshwater environments).[255] Recent studies reveal the introduction, persistence, and evolution of emerging RNA viruses of importance for human and/or animal health in Antarctica.[256] With their high mutation rates and unique dynamics, RNA viruses have a great capability for evolution and can infect aquatic animals (invertebrates, fishes, seabirds, and marine mammals). Future warming, which will cause changes in sea ice, will influence viruses and their microbial hosts through changes in the timing, magnitude, and composition of phytoplankton blooms.[257] Seabirds, flying and potentially migrating (i.e. skuas, petrels) but also diving and more sedentary (i.e. penguins), play a key role in the epidemiology of avian viruses.[258,259] Climate change will influence the abundance and distribution (affecting their breeding and foraging habitats) of vectors, but also their migration routes, which may influence the risk of spreading emerging infectious diseases in Antarctica.[258,259]<br><br>**Crosscuts Human Presence**<br>See above. |
| 57. How will increases in the ice-free Antarctic intertidal zone impact biodiversity and the likelihood of biological invasions? | Currently no intertidal areas are ice free in winter on the Antarctic continent. Lower latitude intertidal areas are often highly species rich. Many species identified attached to ships travelling to Antarctica inhabit intertidal or shallow subtidal zones.[244,260,261] No specific studies have evaluated how increased ice-free intertidal areas will affect Antarctic biodiversity, but the issue has been raised as important in recent publications. |
| 58. How will climate change affect existing and future Southern Ocean fisheries, especially krill stocks? | The past, current and expected future effects of climate change on krill and fish populations have been investigated for years.[191,262] In the Peninsula region, krill ranges are moving southwards leading to northerly declines in abundance. What the situation is elsewhere, however, remains poorly known because of the absence of repeated systematic surveys. Recent studies focus on how climate change will affect fisheries in the Southern Ocean through its impact on sea ice and physical access to fishing grounds, and thus on the stock of this most abundant keystone species of Antarctic marine food webs and also on the krill-dependent predators.[263,264] Decreasing sea ice due to climate change will lead to more areas being accessible and potentially subject to higher exploitation rates in the future, and the potential interaction between fishery and top predators may be intensified as seals and/or penguins are constrained to smaller or more fragmented ice habitats within areas where fisheries may focus future efforts.[265] Krill may play a role in global food security in the longer term.[264] Therefore, in the context of global change, increasing pressures from fisheries on krill stocks are expected. A contraction of the |

| | |
|---|---|
| | available krill spawning habitat under the business-as-usual emission scenarios (up to 80%) raises serious concerns about the potential threats to the Antarctic marine food-web and the fate krill fisheries might face during this century.[266] Current management of the krill fishery sets conservative catch limits however, it does not yet account for trends in stock size or distribution.[191,267]<br><br>**Crosscuts Human Presence**<br>See above. |
| 59. How will linkages between marine and terrestrial systems change in the future? | Increases in precipitation and glacial discharge to the ocean are anticipated to impact the marine ecosystem in terms of particle loading (turbidity), biogeochemical cycling and the stability of the water column. Field research-informed modeling studies are beginning to shed light on these processes.[268] Observations from coastal King George Island ecosystems including marine benthic communities[210] and zooplankton assemblage dominated by krill suggest that marine organisms are highly sensitive to glacial water inputs.[269] There are also suggestions that brines from Taylor Valley and the Whillians ice stream inputs into Ross Sea may fuel marine productivity – though these are more speculative and not included. Glacier retreat under climate change will offer new ice-free areas for Antarctic benthic communities.[270,271] Loss/retreat of ice shelves and coastal glaciers will make new ice-free areas available for the establishment of top-predator breeding sites. They will import substantial amounts of nutrients from the oceans to the Antarctic coast, and guano/nutrient runoff from the coast will increase the availability of nutrients in the nearshore marine environment supporting phytoplankton blooms and benthic communities (as observed in sub-Antarctic islands).[272] Linkages bringing in resources from the sea onto land include marine predators greatly increasing nutrients in terrestrial environments.[273] How these effects will change in the future depends on factors that affect wider marine ecosystems and hence predator food supplies. Predicting the future for these is still poorly developed. Studies in fiords on the Antarctic Peninsula have shown them to be highly diverse and abundant biodiversity hotspots[274] where high biodiversity is linked to weak meltwater influences, low sedimentation disturbance, and high and varied food inputs. Arctic fiords have been seen to move from this state to one of very low biodiversity when climate change induced increases in freshwater input and sedimentation have inundated assemblages.[275] It is thought that the Antarctic Peninsula fiords are at an earlier stage of environmental alteration and are likely to become more like their Arctic counterparts as runoff increases. Furthermore, there appear to be thresholds in biodiversity that are mediated by sedimentation in Antarctica.[210,275] |

| | |
|---|---|
| 60. What are the impacts of changing seasonality and transitional events on Antarctic and Southern Ocean marine ecology, biogeochemistry, and energy flow? | The impacts of changing seasonality and large-scale transitions (e.g. glacier melt) are areas of interest, and progress is evidenced by literature in the recent years. Key amongst the studies are reports of shifts in the timing of sea ice formation and melt which has numerous cascading impacts in the marine ecosystem.[276] Ice-melt and collapse-related events have also been studied revealing impacts on productivity and biogeochemistry. The Amundson Sea ecosystem was modeled for the first time and the importance of iron biogeochemistry was highlighted.[277] Likewise, in the Weddell Sea Larsen ice shelf collapse region polynya formation provided new zones of enhanced primary production.[278] A recent paper discusses the impacts of melting on the fjord system and biogeochemistry/carbon production.[279]<br><br>**Crosscuts Southern Ocean (new)**<br>The responses of species to sea ice directly influences the vertical structure of zooplankton during the winter-spring transition.[280,281] The strength of summertime carbonate saturation depends on seasonal changes of sea ice, water column stratification and primary production. Antarctic ecosystem structure is highly responsive to small perturbations and large-scale climate or weather events creating physical changes may trigger cascading ecological responses.[217,282] |
| 61. How will increased marine resource harvesting impact Southern Ocean biogeochemical cycles? | Several recent studies aimed to model the impact of current warming on the distribution of Antarctic krill over the last century showing a contraction southward, and on projected changes of its habitat (e.g. spawning) by the end of the 21st century.[266] The changing distribution of Antarctic krill is perturbing the krill-centered food-web and may affect biogeochemical cycling.[190] Increasing pressures from fisheries on krill stocks, which are known to ingest for instance lithogenic and biogenic iron and act as an iron reservoir in Southern Ocean surface waters, will therefore affect Southern Ocean biogeochemical cycles. A recent study determined the potential impacts of fisheries-induced changes in zooplankton mortality on marine biogeochemistry which predict an impact of similar size as warming-induced changes in marine biogeochemistry.[283]<br><br>**Crosscuts Human Presence**<br>See above. |
| 62. How will deep sea ecosystems respond to modifications of deep- | The Deep ocean contains many species. It is oxygenated by the global overturning circulation that drives all major currents on Earth. This circulation has been shown to have |

| | |
|---|---|
| water formation, and how will deep sea species interact with shallow water ecosystems as the environment changes? | decreased by 15% since the mid-20th century and to be on a general decreasing trend because of weakening deep water thermohaline formation at the poles.[284] There is general global concern for deep sea ecosystems because of this reduction in global circulation. There have been past periods when global oceans were stratified, and the deep ocean had large areas of low oxygen.[285] Areas of low oxygenation in the deep sea have increased in number in the last 50 years.<br><br>One mechanism assisting the movement of deep-water species onto the continental shelf in Antarctica is the intrusion of circumpolar deep water onto the continental shelf that is climate warming driven.[286] This should assist the colonization of shallower sites by deeper living species, including lithodid crabs (Q.48 and Q.55). There are no studies to date that have quantified the strength of links between Antarctic shallow and deep-water ecosystems and therefore, no predictions of how these linkages will change in future. However, the similarity between Antarctic shallow and deep-water ecosystem structure is greater than at lower latitudes, and this is thought to be an effect of glacial cycles moving species in and out of deeper habitats.[287] |
| 63. How can changes in the form and frequency of extreme events be used to improve biological understanding and forecasting? | Extreme events have facilitated biological understanding since the Scan. The grounding of a large iceberg off Ross Island - and the cascading impacts on ocean circulation and sea ice concentration allowed studies of Adelie Penguin foraging efficiency to be evaluated in which typical phenotypic plastic responses were suppressed.[288] In another event, where warm winds resulted in snow and ice melting, cascading impacts were observed in both terrestrial and marine ecosystems over an extended time frame. Coupled biological-hydrologic and oceanographic observations will improve understanding of responses to change.[217,289] Observation of responses in the terrestrial McMurdo Dry Valley ecosystems provided demonstrated thar response time scales can vary, even within the same ecosystem.[216] Lastly, a recent extreme event - Brunt ice shelf collapse in the Weddell Sea - provided an opportunity to study associated biological impacts, which at present, appear to have eliminated the habitat for a large emperor penguin colony[290,291], a scenario already observed in East Antarctica, King George V Land with the calving of Mertz Glacier ice tongue.[292]<br><br>**Crosscuts Antarctic Atmosphere**<br>Foehn winds (warm downslope winds on the lee side of mountains) are extreme episodic events that have a wide range of impacts in Antarctica, including dominating the climate of the McMurdo Dry Valleys,[293] preconditioning the Larsen Ice Shelf for disintegration[278] and |

| | |
|---|---|
| | favoring summer melting on the eastern side of the Ross Ice Shelf.[294] These spatially persistent phenomena have a wide range of biological impacts. |
| 64. How can temporal and spatial "omic-level" analyses of Antarctic and Southern Ocean biodiversity inform ecological forecasting? | The extent to which this question has been addressed varies widely among taxa. For some groups, little has been done except to highlight the potential of the approach.[213] For others, some progress has been made[295], though it remains limited. Significant advances have been made through microbial metagenomics approaches adopted by various groups to understand and forecast microbiota community responses.[172,296,297,298,299] |
| 65. What will key marine species tell us about trophic interactions and their oceanographic drivers such as future shifts in frontal dynamics and stratification? | Studies are primarily in ecosystem oceanography (before the Antarctic Science Horizon Scan), e.g. aiming to assess the role of mesoscale physical/ocean dynamics and processes on the formation and occurrence of biological hotspots.[300] Investigating biological responses to environmental changes and identifying some species (and their long-term monitoring) as bioindicators of environmental changes, is a common approach. However, while the study of the spatial distribution of key marine species hotspots, such as seabirds, provides information on oceanographic features (e.g. frontal dynamics and stratification) and their future changes and shifts, this approach remains limited. However, top-predators, especially marine mammals, have been used for several decades as oceanographic platforms, and several studies have pointed out the interest in biologging/animal-borne sensors to collect data to improve ocean observing systems.[301,302] |
| 66. How successful will Southern Ocean Marine Protected Areas be in meeting their protection objectives, and how will they affect ecosystem processes and resource extraction? | Over the last decade, there have been several proposals for Marine Protected Areas (MPAs) within the Southern Ocean under the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR).[303] Two MPAs have been designated near the South Orkney Islands (in 2009) and in the Ross Sea (2016), but trade-offs in the CCAMLR-MPA process raise some major issues that will impact potential effectiveness.[304,305] Some Parties to CCAMLR have interpreted the term 'rational use' in the Convention text as '…the unrestricted right to fish…' and, most recently, the term has been evoked in opposition to the establishment of MPAs in Antarctica.[306] The international negotiations in this area have been investigated, with emphasis on the complexity of international diplomacy in CCAMLR.[307] |
| 67. What *ex situ* conservation measures, such as genetic repositories, are required for the Antarctic and Southern Ocean? | One of the first initiatives regarding genetic repositories was established in 2017 at the University of Waikato – The Antarctic Genetic Archive in which DNA samples (particularly from specially protected areas) can be deposited and shared.[308] Additional biodiversity measures that have seen development recently is due to the activities of SCAR's expert |

| | |
|---|---|
| | group in Antarctic biodiversity informatics, in which members have established Antarctic biodiversity Information Facility and the Microbial Antarctic Resource System.<br><br>**Crosscuts Human Presence**<br>Genetic variation in fish stocks has been studied with a recognition that commercial fishing might make some stocks more prone to higher levels of variation. Studies of genetic characteristics are used to assess adaptive potential and inform conservation management. What deserves further attention is how Antarctic biological materials are collected, stored and analyzed. There is a lack of clarity about access and benefit sharing, especially when such genetic repositories are likely to attract commercial and political value.[309] If *ex-situ* conservation measures are required, then questions need to be posed about reporting and sharing. |
| 68. How effective are Antarctic and Southern Ocean conservation measures for preserving evolutionary potential? | Little is known about whether current conservation measures will deliver effective conservation of Antarctic ecosystems and biodiversity into the future, as little attention has been given to abundance and range dynamics and to evolutionary potential. The latter is especially concerning given recent studies demonstrating the significance of Antarctic marine fauna in terms of diversification rates compared with those elsewhere.[310,311] Given the pace of change in the Polar Regions, this issue is high priority. Nonetheless, substantial work has been done on investigating the variety of ocean environments that require marine area protection.[312,313] In terrestrial systems, much has been done to assess the effectiveness of the Antarctic Specially Protected Area (ASPA) network. The work has assessed coverage of the Antarctic Conservation Biogeographic Regions[314] and biodiversity generally. [315] Threats to protected areas have also been investigated.[316] See Q.66.<br><br>**Crosscuts Human Presence**<br>Although the designation of protected areas in Antarctica and the Southern Ocean remains the topic of much investigation, including about the diplomacy required to establish them[317] very little discussion of future resilience of the protected area system because of changing organismal and ecosystem characteristics has taken place. Rather the focus tends to be on international diplomacy and the overall state of the protected area system. Other aspects of conservation such as the use of Specially Protected Species measures are not commonly discussed. |

Table S10. Summary of qualitative (subjective) expert assessments of progress in answering “Antarctic Life on the Precipice” questions rated as: 1 - no or little progress, 2 - moderate progress, 3 - major progress and 4 - answered. When a question crosscuts other clusters an additional perspective(s) on progress is provided. (New) – indicates a question that was not originally identified as cross-cutting in the Scan. For detailed commentary on progress and supporting references see Table S9.

| **Antarctic Science Horizon Scan Question**[1,2] | **Qualitative (Subjective) Rating (1-4)** |
|---|---|
| 43. What is the genomic basis of adaptation in Antarctic and Southern Ocean organisms and communities? | **1**<br>Research is in the beginning phases of discovery considering the diversity of Antarctic and Southern Ocean life. |
| 44. How fast are mutation rates and how extensive is gene flow in the Antarctic and the Southern Ocean? | **2**<br>Mainly unknown especially for mutation rates and more studies are needed on gene flow. |
| 45. How have ecosystems in the Antarctic and the Southern Ocean responded to warmer climate conditions in the past? | **1**<br>There is progress regarding the last Mya (glacial cycles of warming and cooling) with identification of refugia [both marine and terrestrial habitats]. Knowledge is starting to be developed for some marine and terrestrial systems, but ecosystem responses remain largely unknown.<br><br>**Crosscuts Antarctic Atmosphere: 1**<br>See above.<br><br>**Crosscuts Southern Ocean**<br>See above. |
| 46. How has life evolved in the Antarctic in response to dramatic events in the Earth’s history? | **1-3**<br>1, 2 or 3 depending on the adaptation and event. Significant adaptations are known in relation to cooling (antifreeze, hemoglobin loss etc.) and in other areas [e.g., refugia] good progress has been made. |

| | |
|---|---|
| | **Dynamic Earth**<br>See above. |
| 47. How do subglacial systems inform models for the development of life on Earth and elsewhere? | **1-2**<br>In the early stages of discovery, much work remains to be done to address this question.<br><br>**Crosscuts Eyes in the Sky**<br>See above. |
| 48. Which ecosystems and food webs are most vulnerable in the Antarctic and Southern Ocean, and which organisms are most likely to go extinct? | **2-3**<br>There is progress on this question in many areas, but it is variable between different ecosystems. |
| 49. How will threshold transitions vary over different spatial and temporal scales, and how will they impact ecosystem functioning under future environmental conditions? | **1-2**<br>There is little information on how ecosystem function will be impacted by future threshold transitions, and even thresholds remain largely unknown. |
| 50. What are the synergistic effects of multiple stressors and environmental change drivers on Antarctic and Southern Ocean biota? | **1**<br>There has been little research on the effects of multiple stressors on Antarctic terrestrial ecosystems. |
| 51. How will organism and ecosystems respond to a changing soundscape in the Southern Ocean? | **2**<br>Most information on this question is derived from studies in other regions of the world's oceans. Much work remains to be done specific to the Antarctic region soundscape, organisms and ecosystems.<br><br>**Crosscuts Human Presence: 2**<br>See above |
| 52. How will next-generation contaminants affect Antarctic and Southern Ocean biota and ecosystems? | **2** |

| | |
|---|---|
| | Progress on this question is dependent on the contaminant as there are several chemicals recently detected in the Antarctic air, precipitation, ice, snow, marine sediment, soils and organisms. Most studies are short-term; thus, the series are not yet sufficiently long to draw unambiguous inferences concerning trends and long-term effects on biota/ecosystems. Many studies are starting to find microplastic pollution in the Antarctic region. |
| 53. What is the exposure and response of Antarctic organisms and ecosystems to atmospheric contaminants (e.g. black carbon, mercury, sulphur, etc.), and are the sources and distributions of these contaminants changing? | **2**<br>Atmospheric monitoring of Persistent Organic Pollutants (POPs) in Antarctica remains limited and little is known about exposure and/or response for a broad range of contaminants for Antarctic organisms<br><br>**Crosscuts Antarctic Atmosphere: 2**<br>See above.<br><br>**Crosscuts Human Presence: 2**<br>From a social-science perspective, aspects of this question that require additional work include the implications of a changing climate for long-range contaminant transport patterns to Antarctica as well as locally generated contamination. |
| 54. How will the sources and mechanisms of dispersal of propagules into and around the Antarctic and Southern Ocean change in the future? | **2**<br>Dispersal pathways have been studied, but quantification of propagule pathways and sources, and the relative contributions of natural versus anthropogenic pathways remains poorly known. |
| 55. How will invasive species and range shifts of indigenous species change Antarctic and Southern Ocean ecosystems? | **2**<br>In marine systems, few instances of alien species establishment have been documented. For terrestrial systems, the situation is different, with new records being found for both the Antarctic Peninsula region and the sub-Antarctic. Resultant ecological impacts remain largely unknown. |

| | |
|---|---|
| | **Crosscuts Human Presence**<br>See above. |
| 56. How will climate change affect the risk of spreading emerging infectious diseases in Antarctica? | **1**<br>There is no long-term systematic epidemiological monitoring, thus it is challenging to determine the impacts of climate change.<br><br>**Crosscuts Human Presence: 2**<br>As above, further research is needed in terms of monitoring and tracking of the spread of infectious diseases in Antarctica as a precondition for understanding how this risk might be affected by climate change. |
| 57. How will increases in the ice-free Antarctic intertidal zone impact biodiversity and the likelihood of biological invasions? | **1**<br>No specific studies have evaluated how increased ice-free intertidal areas will affect Antarctic biodiversity, but the issue has been raised as important in recent publications. |
| 58. How will climate change affect existing and future Southern Ocean fisheries, especially krill stocks? | **1**<br>There are ongoing studies using data which are fraught with problems in terms of being able to accurately predict what the current status is of krill populations and what will happen to them.<br><br>**Crosscuts Human Presence: 1**<br>While it is known that warming in polar waters disrupts the life cycle of krill and affects the metabolism of various Southern Ocean fish species, the ramifications for fisheries management are unknown. |
| 59. How will linkages between marine and terrestrial systems change in the future? | **1**<br>Modest work has begun to study these linkages in Antarctica (currently this is an active area of study in the Arctic and sub-Antarctic), but predicting the future for marine-terrestrial linkages is still poorly investigated. |

| | |
|---|---|
| 60. What are the impacts of changing seasonality and transitional events on Antarctic and Southern Ocean marine ecology, biogeochemistry, and energy flow? | **2**<br>There is evidence for impact from changing seasonality and large-scale transitions. |
| 61. How will increased marine resource harvesting impact Southern Ocean biogeochemical cycles? | **1**<br>Some progress [linked to climate change] but understanding of the interaction with fisheries is limited. Several recent model studies suggest a contraction southward in distributions of krill and changes to habitats.<br><br>**Crosscuts Human Presence: 1**<br>There is the potential for increased fishing pressures from states not currently involved in Southern Ocean fisheries. |
| 62. How will deep sea ecosystems respond to modifications of deep-water formation, and how will deep sea species interact with shallow water ecosystems as the environment changes? | **1**<br>Some initial efforts, but little progress. No studies to date have quantified the strength of links between Antarctic shallow and deep-water ecosystems, and therefore no predictions can be made of how these links will change in the future. |
| 63. How can changes in the form and frequency of extreme events be used to improve biological understanding and forecasting? | **1-2**<br>There have been a few studies of extreme events such as biological and ecological changes associated with ice shelf collapse.<br><br>**Crosscuts Antarctic Atmosphere: 2**<br>Foehn winds (warm downslope winds on the lee side of mountains) are extreme episodic events that have a wide range of impacts in Antarctica. |
| 64. How can temporal and spatial "omic-level" analyses of Antarctic and Southern Ocean biodiversity inform ecological forecasting? | **2**<br>The extent to which this question has been addressed varies widely among taxa. |

| | |
|---|---|
| 65. What will key marine species tell us about trophic interactions and their oceanographic drivers such as future shifts in frontal dynamics and stratification? | **1-2**<br>There has been some work on identifying key marine species and population shifts as bioindicators of change. |
| 66. How successful will Southern Ocean Marine Protected Areas be in meeting their protection objectives, and how will they affect ecosystem processes and resource extraction? | **1**<br>Answers to this question are yet to be determined and, in most instances, resources have not been made available for long-term monitoring projects needed to assess designation effectiveness in reaching conservation goals.<br><br>**Crosscuts Human Presence: 2**<br>There is a growing body of literature on marine protected areas in general, and the Ross Sea Marine Protected Area in particular, but it is too early to answer this question. |
| 67. What *ex situ* conservation measures, such as genetic repositories, are required for the Antarctic and Southern Ocean? | **1**<br>One of the first initiatives regarding genetic repositories was established in 2017 in New Zealand.<br><br>**Crosscuts Human Presence: 1-2**<br>There is a need for the standardization of protocols for organisms, including collection, storage and analysis and procedures for making these collections and the data produced widely available. |
| 68. How effective are Antarctic and Southern Ocean conservation measures for preserving evolutionary potential? | **1**<br>Little is known about the effectiveness of conservation measures in the region for preserving evolutionary potential.<br><br>**Cross cuts Human Presence: 1**<br>See above. |

Table S11. Expert (subjective) assessments of progress toward answering “Near-Earth Space and Beyond - Eyes on the Sky” questions supported by peer-reviewed literature citations. Comments by experts from crosscutting clusters are identified as ‘Crosscuts [name of cluster]’. The references cited are exemplars and not intended to be an exhaustive literature review.

| **Antarctic Science Horizon Scan Question**[1,2] | **Conclusions** |
|---|---|
| 69. What happened in the first second after the universe began? | The early universe has been investigated in two news ways from Antarctica. The gravitational lensing will tie the masses of cosmic constituents to fluctuations of the Cosmic Microwave Background radiations (CMB).[318] The Sunyaev-Zel'dovich effect informs about the momentum of these constituents. |
| 70. What is the nature of the dark universe and how is it affecting us? | The search for dark matter has not progressed as quickly as expected ten years ago and remains elusive. However, with advances in neutrino detections (e.g., IceCube Neutrino Observatory) and gravitational waves (Laser Interferometer Gravitational-Wave Observatory), a new era of “multi messenger” astronomy will revolutionize the field.[319,320,321,322,323] |
| 71. What are the differences in the inter-hemispheric conjugacy between the ionosphere and that in the lower, middle and upper atmospheres, and what causes those differences? | The hemispheric differences in solar illumination, land-mass, and tropospheric forcing generate inter-hemispheric differences.[324,325,326] These differences are seen in ionospheric convection patterns, and magnetospheric wave energy. In addition, a major difference between the Arctic and Antarctic polar atmospheres is the existence of the strong and persistent Antarctic polar vortex, which is thought to be caused by lower southern hemispheric temperatures over the Antarctic landmass as well as reduced overall planetary wave activity, as compared to a more dynamic Arctic polar vortex. |
| 72. How does space weather influence the polar ionosphere and what are the wider implications for the global atmosphere? | The term space weather generally refers to conditions on the Sun, in the solar wind, and within Earth's magnetosphere, ionosphere and upper atmosphere that can influence the performance and reliability of space-borne and ground-based technological systems.[327,328,329,330] Particle precipitation modifies the atmospheric heating and conductivity of the polar ionosphere, which can disrupt radio and Global Positioning Satellite (GPS) signals, shut down electrical systems, and expose people to radiation. The polar ionosphere is subject to the convergence of energy flux driven |

| | |
|---|---|
| | from below by the lower atmosphere, and from above by solar energization, kinetic and electromagnetic energy input driven by interactions between the solar wind and the terrestrial magnetic field, e.g., space weather. A consequence of these interactions is a highly structured polar ionosphere featuring a rich spectrum of plasma density irregularities, some on the order of hundreds of kilometers in scale size which are almost always present. This is an attribute of the polar ionosphere that is unique to terrestrial ionospheres at other latitudes. Plasma density irregularities constitute conductivity gradients which govern kinetic and electromagnetic energy input from the magnetosphere, thereby regulating the influence of space weather on the polar region. A highly structured polar ionosphere is a by-product of complex and dynamics cross-scale coupling processes that are not well understood or characterized. This lack of knowledge hinders our overall comprehension of how energy is propagated from the sun and solar wind through the coupled magnetosphere-ionosphere-thermosphere system and into the lower-atmosphere.<br><br>**Crosscuts Antarctic Atmosphere**<br>See above. |
| 73. How do the generation, propagation, variability and climatology of atmospheric waves affect atmospheric processes over Antarctica and the Southern Ocean? | The Antarctic peninsula and surrounding ocean are recognized as a hotspot of atmospheric gravity wave activity.[331] Furthermore, the winter Antarctic polar vortex is a known generator of synoptic gravity waves.[332] The localized, regional, and global impacts of this region are not yet known.<br><br>**Crosscuts Antarctic Atmosphere**<br>Where air blows over mountainous terrain waves are usually generated. These can propagate vertically and break into the stratosphere. The resulting mixing of the temperature can lead to the formation of polar stratospheric clouds.[333] The most active region of mountain wave formation in high southern latitudes is the Antarctic Peninsula due to its orientation at right angles to the prevailing westerly winds. |

Table S12. Summary of qualitative (subjective) expert assessments of progress in answering “Near-Earth Space and Beyond - Eyes on The Sky” questions rated as: 1 - no or little progress, 2 - moderate progress, 3 - major progress and 4 - answered. When a question crosscuts other clusters an additional perspective(s) on progress is provided. (New) – indicates a question that was not originally identified as cross-cutting in the Scan. For detailed commentary on progress and supporting references see Table S11.

| **Antarctic Science Horizon Scan Question**[1,2] | **Qualitative (Subjective) Rating (1-4)** |
|---|---|
| 69. What happened in the first second after the universe began? | **2**<br>Progress is focused on understanding the initial conditions of structure formation and establishing the content of the universe. |
| 70. What is the nature of the dark universe and how is it affecting us? | **1**<br>Remains elusive. Progress has been made in high energy detections, but much work remains to be done. |
| 71. What are the differences in the inter-hemispheric conjugacy between the ionosphere and that in the lower, middle and upper atmospheres, and what causes those differences? | **1**<br>Remains elusive. Progress has been made in the operation of [hemispheric] conjugate sites, but remote instrumentation logistical support is challenging. |
| 72. How does space weather influence the polar ionosphere and what are the wider implications for the global atmosphere? | **1**<br>Remains elusive. Progress has been made in the operation of site-specific instruments at manned stations, but remote instrumentation logistical support is challenging.<br><br>**Crosscuts Antarctic Atmosphere**<br>See above. |
| 73. How do the generation, propagation, variability and climatology of atmospheric waves affect atmospheric processes over Antarctica and the Southern Ocean? | **1**<br>Remains elusive. Progress has been made in the operation of site-specific instrumentation, but logistical support across the broader continent is challenging. |

| | |
|---|---|
| | **Crosscuts Antarctic Atmosphere: 2**<br>See above. |

Table S13. Expert (subjective) assessments of progress toward answering “Human Presence in Antarctica” questions supported by peer-reviewed literature citations. Comments by experts from crosscutting clusters are identified as ‘Crosscuts [name of cluster]’. The references cited are exemplars and not intended to be an exhaustive literature review.

| **Antarctic Science Horizon Scan Question**[1,2] | **Conclusions** |
|---|---|
| 74. How can natural and human-induced environmental changes be distinguished, and how will this knowledge affect Antarctic governance? | Some work has been done on distinguishing between natural variability and anthropogenic climate change in the Antarctic, but few studies have looked at the implications and lessons for Antarctic governance. There is a need to think critically about distinctions between human and natural systems (categorically and in relation to environmental change) and how these systems are co-produced or co-entangled. From a data perspective, progress on the question is limited though it has been raised several times.[334] Limited work has been undertaken on the relationship between bodies of knowledge, with a focus on climate change research, and the Antarctic as an object of and for governance.[335] In addition, work examining national political attitudes on climate change and the role these attitudes play in Antarctic climate change research and governance concludes that, at present, perspectives on climate change are a dividing rather than unifying force.[336]<br><br>**Crosscuts Southern Ocean**<br>Some progress made in detection/attribution in the Southern Ocean.<br><br>**Cross Cuts Dynamic Earth**<br>See above |
| 75. What will be the impacts of large-scale, direct human modification of the Antarctic environment? | This remains an important and, so far, largely unanswered question. While Environmental Impact Assessments (EIAs) for the establishment of permanent infrastructure (such as runways, stations, refuges, helicopter landing pads, etc.) in Antarctica require a detailed analysis of the environmental consequences resulting from the erection of permanent structures. Some EIAs include thorough and science-based assessments of environmental impacts of construction activities and new infrastructure. Some foundational conceptual work in the social sciences has been undertaken on how the human “footprint” in the Antarctic can be defined. “Human modifications” to the Antarctic environment have been |

| | |
|---|---|
| | quantified.[337] Other conceptual pieces look at how human impacts as well as wilderness (values) in Antarctica can be mapped.[338,339,340] With the potential for larger-scale, targeted modifications of the Antarctic environment being discussed, e.g. through geo-engineering solutions to artificially buttress ice shelves[341,342], more dedicated research on the impacts of such modifications – in and beyond the Antarctic – is needed.<br><br>**Crosscuts Antarctic Life**<br>See above. |
| 76. How will external pressures and changes in the geopolitical configurations of power affect Antarctic governance and science? | The most developed body of literature in this area examines the way polar governance is being shaped by international geopolitical shifts. It is now well established that Antarctica co-exists in a network of legal and political regimes and obligations and that science and politics inform each other. While research on the potential implications of global resource pressures – imagined and real – have been around since the 1980s, critical perspectives on the danger of the waning of traditional moral framings of the Antarctic as a continent for science are being increasingly shadowed by geo-economic narratives and pressures are now emerging.[343,344] This stimulates discussions around marine protected areas, biodiversity in areas beyond national jurisdiction, and a targeted regime on bioprospecting. From a geopolitical perspective, this research has focused on the changing geopolitical configurations of power via two primary registers. The first has been to focus on global players, such as China, and consider the implications of Chinese investment in Antarctic infrastructure and involvement in Antarctic Treaty System governance. as well as the broadening and deepening of larger 'Asian' interest and involvement in the Antarctic.[345,346] Opinion is split between those who think China's is largely content with the geopolitical *status quo* (believing that the ATS's structure is well-suited to a non-claimant state such as China) as opposed to those who believe that China will push its own interests and wishes more assertively.[347] The second strand considers whether there is a danger that Antarctic exceptionalism (e.g. Antarctica as a zone of peace and co-operation) might be compromised in the future by great power rivalries, recent development in international politics such as the annexation of Crimea by Russia and impositions of sanctions by others, and ongoing resource-related pressures. |
| 77. How will the use of Antarctica for peaceful purposes and science be maintained as barriers to access change? | While, the importance of science as a "symbolic political capital"[348] has been examined, the relationship between changing barriers to access, gender, science, and non-violence is an area that might develop further. Normative discussions of values and practices exist, including reflections on how values, such as peace, are embedded in global legal norm. An assessment of compliance and goodwill in the Antarctic has been undertaken[349], but the |

| | |
|---|---|
| | focus is on historical assessment rather than potential future developments in the light of changes in who can access Antarctica and when and how. |
| 78. How will regulatory mechanisms evolve to keep pace with Antarctic tourism? | This question has attracted considerable scholarship over the last couple of decades and involves an understanding of how Antarctic tourism is likely to develop in the future. A steady flow of papers has emerged on the topic of Antarctic tourism regulation and management,[350, 351,352,353] but other than some speculative excursions[354], work linking research into tourism futures and effective regulatory mechanisms has been relatively limited.[355] If there are challenges facing regulatory mechanisms then the key variables have been identified: external regulation and self-regulation of industry; the level of commitment and reflexivity of operators; the diversification and growth of markets; the spatial extent of tourism activities; tourist and operator behaviour; operator networking and cohesion; and the role of, and potential, for accidents even disaster. However, Q.78 might be too normative (assuming that regulatory mechanisms need to evolve to keep pace with tourism developments) to be of interest for scholars to pursue, and might also be too complex and speculative a topic to have been successfully brought to completion (and publication) within the relatively small window of time since the Horizon Scan questions were formulated. A critical review of the emerging literature on Antarctic tourism developments[356] and growing markets for Antarctic tourism, such as China[357,358], as well as Antarctic tourism policy options may result in further progress in addressing this question. |
| 79. What is the current and potential value of Antarctic ecosystem services? | Ecosystem services in relation to the Antarctic, as well as to oceans, are understudied.[359,360] There was a proposal by the Netherlands to the Antarctic Treaty Consultative Meeting in 2011 (Information Paper 95), which asks the Parties to consider the assessment of options to require payments for Antarctica's ecosystem services.[361] However, so far only one study attempted to map Antarctic ecosystem services, which is an ambitious undertaking. This study focused on the Weddell Sea[362] and represents a first stab at identifying how Antarctic ecosystem services could be categorized and recorded. This study calls for further research to verify the steps taken and expand their work.[362] |
| 80. How will humans, diseases and pathogens change, impact and adapt to the extreme Antarctic environment? | Ongoing climate change combined with the cumulative human activity in the form of fishing, science and tourism is raising concerns that the polar environment is ever more exposed to foreign objects and substances including seeds, viruses and pathogen agents.[363] Antarctica's extreme climate and environment does not appear to be a enough of a barrier to alien species and diseases impacting upon continental Antarctica. Accidental introduction of alien species is also acknowledged to be ever present. Pathogens, such as |

| | |
|---|---|
| | enteric bacteria, have been identified as present in Antarctic wildlife such as seals and birds, and recent research notes the presence of reverse zoonosis involving transmission from human communities to seabirds. Calls for improved biosecurity measures in Antarctica are now commonplace, as it is recognised that alien species, diseases and pathogens are proving resilient.<br><br>**Crosscuts Antarctic Life**<br>Regarding diseases and pathogens, recent studies reveal that with their high mutation rates and unique dynamics, RNA viruses have a great capability of evolution (see review from Cristina 2019 and Q.56), which may exacerbate impact on native Antarctic wildlife. |

Table S14. Summary of qualitative (subjective) expert assessments of progress in answering "Human Presence in Antarctica" questions rated as: 1 - no or little progress, 2 - moderate progress, 3 - major progress and 4 - answered. When a question crosscuts other clusters an additional perspective(s) on progress is provided. (New) – indicates a question that was not originally identified as cross-cutting in the Scan. For detailed commentary on progress and supporting references see Table S13.

| Antarctic Science Horizon Scan Question[1,2] | Qualitative (Subjective) Rating (1-4) |
|---|---|
| 74. How can natural and human-induced environmental changes be distinguished, and how will this knowledge affect Antarctic governance? | **1-2**<br>Some work on distinguishing natural variability from anthropogenic climate change in the Antarctic, but few studies of the implications for Antarctic governance. A need remains to consider the distinction between human and natural-induced changes and whether these changes are co-produced or co-entangled.<br><br>**Crosscuts All Clusters**<br>See above. |
| 75. What will be the impacts of large-scale, direct human modification of the Antarctic environment? | **1**<br>Current research focus is on understanding the impacts of small-scale and/or unintentional and undirected modification of the Antarctic environment. The potential of large-scale modification of the Antarctic environment has been discussed but its impact has not been assessed.<br><br>**Crosscuts Antarctic Life: 2**<br>See above. |
| 76. How will external pressures and changes in the geopolitical configurations of power affect Antarctic governance and science? | **2**<br>There is literature examining the way in which polar governance is positioned within the wider context of, and is being shaped by, international geopolitics, and other regimes with overlapping or complementary jurisdiction. |

| | |
|---|---|
| 77. How will the use of Antarctica for peaceful purposes and science be maintained as barriers to access change? | **2**<br>Some philosophical work and geopolitics research addresses aspects of this question but more targeted work is needed. |
| 78. How will regulatory mechanisms evolve to keep pace with Antarctic tourism? | **3**<br>Antarctic tourism regulation is a topic that has attracted considerable attention and here is a growing body of work. |
| 79. What is the current and potential value of Antarctic ecosystem services? | **1**<br>Additional work is warranted as few studies have been undertaken. |
| 80. How will humans, diseases and pathogens change, impact and adapt to the extreme Antarctic environment? | **1-2**<br>Most of the work on this question concerns human adaptation to the extreme Antarctic environment. Some work has been done on pathogens in the Antarctic environment, but the question of how human diseases and pathogens change the Antarctic are yet to be answered.<br><br>**Crosscuts Antarctic Life: 1-2**<br>Limited ongoing work – see above. |

Table S15. Summary of indications of the uptake, delivery and impact of the Scan and ARC projects' outputs. Targeted audiences are categorized by the organization and/or activity. Methods, Citations and Resources are not intended to be exhaustive but rather exemplars of the most important citations/report excerpts supporting the conclusions.

| Organization/Activity | Conclusions | Methods, Citations and Resources |
|---|---|---|
| Scientific Literature Citations | Collectively, Scan and ARC publications have been cited some 200 times, spanning all disciplines with almost half being in the life sciences.[1,2,364] Citations are largely in the peer-reviewed literature (80%), but also dissertations and theses (13%), book chapters (9%), policy papers (3%) and national strategic plans (1%). Many citations (28%) noted that they were addressing priorities identified by the Scan.[365,366,367,368] Others (14%) point to the importance of the polar regions in the global Earth System, especially in the context of climate change. A few (4%) used the Scan to point to the paucity of data in the Antarctic in various fields and two specifically note the Scan in national science plans (e.g. National Academies of Sciences, 2015 and the joint United States/United Kingdom Thwaites Glacier project).[369,370] Similarly, a recent National Antarctic Research Plan for South Africa mentioned the goal of meeting key challenges identified by the Scan.[371] Several horizon scans outside of the Antarctic region referenced the Kennicutt et al. papers as an exemplar model. The Nature Comment by Kennicutt et al. 2014[1] has been cited 16 to 33 times a year since the Scan, suggesting that | Google scholar was used to search for Scan publications. PDFs of the references which cited the publications were then downloaded. The PDFs were imported into NVIVO Version 11.4.3 and qualitatively coded according to the type of literature (e.g., peer-reviewed article, book chapter, dissertation, national strategic plan, etc.), the discipline, and the nature of the citation (e.g., the new study referenced their work in the context of addressing a Scan priority; the reference citing the Scan as an information source for the importance of the polar regions; non-Antarctic horizon scans citing the Scan as exemplary). The information on the number of citations per year was also obtained via Google Scholar. |

| | | |
|---|---|---|
| | the Scan continues to have visibility and impact in the science community. The Scan organizers and the SCAR community have promoted the Scan beyond the Antarctic community, with more than 30 citations by SCAR-affiliated scientists. | |
| Antarctic Treaty System (ATS)[372] | Antarctic Treaty Consultative Meetings (ATCMs)[373]<br><br>SCAR[374] has continually brought forward information about the Scan to the Antarctic Treaty System (ATS, Antarctic Treaty Consultative Meetings [ATCMs],[373] the Committee on Environmental Protection (CEP)[375] and the Science Committee of the Convention for the Conservation of Antarctic Marine Living Resources [SC-CCAMLR])[376].<br><br>Scan outcomes were presented at the ATCMs in 2015 and 2016. Several key documents with Scan linkages have formed the basis for discussions at ATCMs since 2014. | **ATCM XXXVII (Bulgaria, 2015)**.<br>Final report para 334: SCAR presented IP 20 Outcomes of the **1st SCAR Antarctic and Southern Ocean Science Horizon Scan**, which advised Parties on the results from the project aiming to identify the most important scientific questions in and about the Antarctic that should be addressed over the next two decades and beyond. It informed the Parties that more than 70 of the world's leading Antarctic scientists, policy makers and visionaries identified the 80 highest priority questions in six broad areas. SCAR noted further that, to answer these questions, it would be necessary to: provide long-term sustained and stable research funding; ensure access to Antarctica throughout the year; apply emerging technologies; strengthen protection of the region; grow international cooperation; and improve communication among all interested parties.<br><br>**ATCM XXXIX (Santiago, 2016).**<br>Final report paras. 23 and 201: SCAR highlighted several examples of its activities including participation in the Antarctic Roadmap Challenges project in 2015. This initiative, led by COMNAP, represented the second step of the **SCAR Antarctic and** |

| | | |
|---|---|---|
| | | **Southern Ocean Science Horizon Scan.** Both initiatives are the topic of the SCAR Science Lecture at this year's ATCM (BP 3). (…)<br>COMNAP presented IP 51 COMNAP Antarctic Roadmap Challenges (ARC) Project Outcomes, which provided a summary of the critical technologies, infrastructure and access requirements in order to support future Antarctic research, such as that identified in the **SCAR Horizon Scan project. The ARC** project is a community effort that will require international collaboration to deliver. Full results of the project are published and can be downloaded from the COMNAP website.<br><br>**ATCM XL (Beijing, 2017).**<br>WP 1 (United Kingdom): The UK's Antarctic science priorities, as outlined above, also took into account the outcomes of **the Scientific Committee on Antarctic Research (SCAR) Antarctic and Southern Ocean Science Horizon Scan**, which had identified 80 priority science questions in 2014. By presenting the priority issues and challenges for the UK Antarctic science program, the UK invites other Parties who have identified similar scientific priorities, and with whom the UK is not already collaborating, to engage with the UK National Antarctic Program to identify any opportunities for new cooperation.<br>Discussions relating to ATCM XL/WP 1 reported in Final report ATCM XL paras. 312-317. |

| | | |
|---|---|---|
| | | Final report para. 274: The United States presented IP 13 U.K./U.S. Research Initiative on Thwaites: The Future of Thwaites Glacier and its Contribution to Sea-level Rise, prepared jointly with the United Kingdom. The paper reported on a joint NSF-NERC scientific program established with the objective of substantially improving both decadal and longer-term (century-to-multi- century) projections of ice loss and sea-level rise originating from Thwaites Glacier. The United States noted that considerable uncertainty remained in projections of global sea-level rise, and that reducing this uncertainty was an international priority that had been underlined in the **SCAR “Horizon Scan 2020”** and by the National Academies of Sciences, Engineering, and Medicine. The United States welcomed further international collaboration with other Parties in relation to this research area.<br><br>**ATCM XLII (Prague, 2019)**<br><br>WP 32 (Australia): Participants also acknowledged the range of other processes relevant to the Parties’ discussions on Antarctic science priorities and challenges, including the CEP’s work to identify and promote the science needed to better understand and address the environmental challenges facing Antarctica, (which were endorsed by the CEP and reflected in the CEP 5-year work plan), the **SCAR Antarctic and Southern Ocean Science Horizon Scan, and the related COMNAP Antarctic Roadmap Challenge project.** |

| | | |
|---|---|---|
| | The Committee on Environmental Protection (CEP)[375] | **2013**<br>(21) SCAR presented IP 4 The Scientific Committee on Antarctic Research (SCAR) Annual Report for 2012/13. In 2012 SCAR approved five new Scientific Research Projects: a) State of the Antarctic Ecosystem; b) Antarctic Thresholds – Ecosystem Resilience and Adaptation; c) Antarctic Climate Change in the 21st Century; d) Past Antarctic Ice Sheet Dynamics; and e) Solid Earth Response and Cryosphere Evolution. SCAR also introduced IP 19 **1st SCAR Antarctic and Southern Ocean Science Horizon Scan**, on an activity which would assemble the SCAR community and leading Antarctic experts to identify the most important scientific questions to be addressed over the next two decades. Further information was available in BP 20 The Scientific Committee on Antarctic Research (SCAR) Selected Science Highlights for 2012/13 (SCAR).<br><br>**2014**<br>(34) SCAR presented IP 13 The Scientific Committee on Antarctic Research (SCAR) Annual Report 2013/14 and highlighted several examples of its activities. SCAR also provided an **annual update to the Antarctic Climate Change and the Environment Report. SCAR had held a Science Horizon Scan in New Zealand in April 2014**, following the crowdsourcing of over 850 unique questions and the nomination of almost 500 scientists by the SCAR community. The selected 70 participants had identified a list of the 80 most important scientific questions that |

| | | |
|---|---|---|
| | | should be addressed by research in Antarctica and the Southern Ocean beyond the next 20 years…<br><br>**2015**<br>(51) SCAR presented IP 19 The Scientific Committee on Antarctic Research (SCAR) Annual Report 2014/15 and referred to BP 4 The Scientific Committee on Antarctic Research (SCAR) Selected Science Highlights for 2014/15. It highlighted several examples of its activities including…, the **completion of the SCAR Science Horizon Scan** (IP 20) and resulting publications in the journals Antarctic Science and Nature…<br><br>(278) SCAR presented **IP 20 Outcomes of the 1st SCAR Antarctic and Southern Ocean Science Horizon Scan**. The Horizon Scan had focused on the most compelling and important scientific questions, both in and from Antarctica and the Southern Ocean, to be addressed over the next two decades and beyond. It identified 80 high-priority scientific questions divided into six areas. These included: 1) defining the global reach of the Antarctic atmosphere and Southern Ocean; 2) understanding how, where and why ice sheets lose mass; 3) revealing Antarctica's history; 4) learning how Antarctic life evolved and survived; 5) observing space and the Universe; and 6) recognizing and mitigating human influences.<br><br>(279) **The Committee congratulated SCAR for undertaking the Horizon Scan** and for |

| | | |
|---|---|---|
| | | the report on key outcomes. It noted that one of the priorities identified related to the recognition of mitigation of human impacts and **looked forward to drawing on the results of research prioritized in the Horizon Scan for its future work**.<br><br>**2016**<br>(35) SCAR presented IP 20 The Scientific Committee on Antarctic Research (SCAR) Annual Report 2015/16 …**SCAR highlighted several examples of its activities including participation in the Antarctic Roadmap Challenges project in 2015.** This initiative, led by COMNAP, represented the second step of the first SCAR Antarctic and Southern Ocean Science Horizon Scan. **Both initiatives are the topic of the SCAR Science Lecture at this year's ATCM (BP 3 rev. 1)**…<br><br>**2017**<br>(257) Portugal presented IP 24 Future Challenges in Southern Ocean Ecology Research**: another outcome of the 1st SCAR Horizon Scan**, jointly prepared with Belgium, Brazil, France, Germany, the Netherlands, SCAR, the United Kingdom, and the United States. The paper reported on an output of the **SCAR Antarctic and Southern Ocean Science Horizon Scan**. It noted that the work presented reflected contributions from many Antarctic scientists and policy makers. It focused on high-interest research areas related specifically to Southern Ocean life and ecology that, although not all retained as the |

| | | |
|---|---|---|
| | | top priorities among the addressed scientific domains, were of considerable relevance to the biology and ecology of the Southern Ocean. It highlighted that Southern Ocean ecological research would require long-term commitment by Parties to conduct international and interdisciplinary research, aided by the development of technology (in cooperation with organizations such as COMNAP and SCAR)… |
| | The Convention on the Conservation of Antarctic Marine Living Resources[377] | **2013 SC-CAMLR**[376]<br>10.2 The SCAR Observer to SC-CAMLR, Prof. M. Hindell, presented the annual report of SCAR activities of interest to CCAMLR (SC-CAMLR-XXXII/BG/08). **In particular, he noted: "… 1st SCAR Antarctic and Southern Ocean Science Horizon Scan to which the Chair of the Scientific Committee had been invited to participate**…".<br><br>**2014 SC-CAMLR**<br>10.6 Prof. Hindell presented the annual report of SCAR activities of interest to CCAMLR (SC-CAMLR-XXXIII/BG/17). In particular, he noted: "…(iii) the **first SCAR Antarctic and Southern Ocean Science Horizon Scan** identified impacts of human activities on animals and fish population as a focus for future research…"<br><br>**2014 CCAMLR**<br>Opening address by the Lieutenant Governor of Tasmania, His Excellency the Honourable Chief Justice Alan Blow Medal of the Order of Australia: "…As I understand it, **the SCAR** |

| | | |
|---|---|---|
| | | **Science Horizon Scan** was the first time that the international Antarctic community has formulated a collective vision on priority issues that need our increased attention. From a long list of candidate questions the group refined priorities to 80 key questions which were grouped across six broad themes.<br><br>Some of those themes are quite obvious and not unexpected – improved understanding of the Antarctic atmosphere and Southern Ocean ecosystem, and relationships to global environmental processes including climate change. Others are probably not as well-known and include complex areas such as ice dynamics, geological history, the evolution of life in the Antarctic, and how it survives, and, **of direct relevance to CCAMLR**, recognizing and mitigating human impact.<br><br>The scan noted several other items of particular interest. These included the number of countries actively involved in Antarctic affairs, a gradual shrinking of resources available to support Antarctic activities for many countries and a call for increased international collaboration in the Antarctic across a wide range of areas."<br><br>Agenda item: Climate change<br>5.91 **The Scientific Committee Chair also noted a paper that was recently published in the journal Nature entitled 'Polar research: six priorities for Antarctic science'** that was highlighted by the Lieutenant Governor in his opening address. |

| | | |
|---|---|---|
| | | The paper identified the most compelling scientific questions that Antarctic researchers should aspire to answer in two decades and was developed during the SCAR Horizon Scan meeting from 20 to 23 April 2014 in Queenstown, New Zealand, in which the Chair participated. The Scientific Committee Chair highlighted one of the questions adopted by the Horizon Scan: How will climate change affect existing and future Southern Ocean fisheries, especially krill stocks? **The Chair underscored that the answer to this question is of critical importance to all of CCAMLR**. The Commission noted, consistent with SC-CAMLR-XXXIII (paragraph 8.4), that development of a feedback management strategy for the krill fishery offers the opportunity to adapt to the impacts of climate change.<br><br>**2015 – WG-EMM**<br>2.213 The Working Group recognized that in the future of CEMP development there will be **a need to make better use of existing CEMP data, data from other sources and initiatives outside of CCAMLR such as the Scientific Committee on Antarctic Research (SCAR) Horizon Scan,** Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) and SOOS in order to develop a better system-level understanding through improved population and ecosystem models. The Working Group considered that this could be achieved by holding a workshop in the near future to consider these issues and noted that there |

| | | |
|---|---|---|
| | | have been many methodological developments and additional data sources since a previous CEMP review workshop in 2003. It may be possible to fund such a workshop through a proposal to the CEMP Special Fund in 2016.<br><br>**2015 - SC-CAMLR**<br>10.5 Prof. M. Hindell (SCAR Observer) presented the annual report of SCAR activities of interest to CCAMLR (SC-CAMLR-XXXIV/BG17 Rev 1.). He noted: "(…(iv) several existing synergies are already present between SCAR and CCAMLR, such SOOS, ACCE, **and the Antarctic and Southern Ocean Science Horizon Scan."** |
| Scientific Committee on Antarctic Research (SCAR)[374] | SCAR's structural review in 2015 advocates that its disciplinary groups have a role in promoting science linked to Scan questions and that it should shape the agenda for the group's discussions. This review and its recommendations informed SCAR's strategic plan 2017-22 which states that SCAR will use the key questions arising from the Scan "to guide research priorities and research direction over the next six years and beyond.<br><br>A word search of 'Horizon', 'Roadmap' and 'ARC' in SCAR biennial Delegates meeting reports from 2014 to 2018 detected 27 instances of usage of these terms. | Antarctic Science Horizon Scan[378]<br><br>SCAR Structural Review[379]<br><br>SCAR Strategic Plan 2017-2022[380]<br><br>SCAR groups have designed international workshops around Scan questions.[381,382]<br><br>Two key documents presenting the outcomes of the Scan and ARC have been downloaded from the SCAR website 300 and 416 times respectively, indicating interest and usage (ATCM XXXVIII IP 020, and ATCM LX WP 15).<br><br>There have been recent Humanities and Social Sciences developments within the Scientific Committee on Antarctic Research. |

| | | |
|---|---|---|
| | | Action Groups (AG) established under the umbrella of the SCAR Standing Committee on the Humanities and Social Sciences explicitly refer to Scan questions. The Action Group on Resilience and the Future of Science-based Decision-making for Antarctica (PoLSciNex AG) has “identified some specific topics or areas of interests where examination of the policy-law-science nexus would be fruitful for both social sciences and natural sciences scholarship. Examples are: (a) marine protected areas (MPAs) in the Southern Ocean (Q.61, Q.66); (b) Antarctic Specially Protected Areas (ASPA) and Specially Managed Areas (ASMAs) (Q.68, Q.74); (c) invasive species in the Antarctic (Q.55); (d) biological prospecting in the Antarctic (Q.43, Q.44); (e) environmental liability in the Antarctic (Q.74); (f) environmental impact assessment in the Antarctic (Q.53, Q.74); (g) large-scale scientific establishments and logistical facilities in the Antarctic (Q.75); (h) marine scientific research in the Southern Ocean (Q.12-Q.23); (i) “commercial” activities in the Antarctic, including Antarctic tourism (Q.78); etc. (especially with regard to, but the mismatch between the pace of changes occurring in Antarctica and the slow motion of putting in place international/national strategic plans and actions urges for a more rigorous prioritization (fewer questions and more targeted, to be more effective?), and for structured milestone plans?. Similarly, the AG on Intrinsic Value in Antarctica (AGIVA), which aims “to develop a broad cross-cultural |

| | | |
|---|---|---|
| | | understanding of the intrinsic value of Antarctica in order that the intention of the Madrid Protocol to provide protection to this value can be better understood. Intrinsic value is a complex philosophical problem which requires experience and expertise", has links to Q.79. Other research that was stimulated by the Scan involves an assessment of the past, present and future elements of human impacts in the Antarctic to develop robust integrative frameworks that consider humanities and social-sciences knowledge in scientific understandings of human impacts. |
| Council of Managers of National Antarctic Programs (COMNAP)[383] | The ARC outcomes contributed to a restructure of the COMNAP Expert Groups, refocusing the "Advancing Critical Technologies", "Science Facilitation" and "Marine Platforms" groups to respond to the ARC findings.<br><br>A word search for "Horizon Scan", "SCAR HS", "ARC" and "Antarctic Roadmap Challenges" of COMNAP Annual General Meeting (AGM) Reports from 2014 to 2018 detected 65 instances of usage of these terms. | Antarctic Roadmap Challenges Project[384] |
| Other examples of "Impact, Uptake and Delivery" | In the days immediately following the Scan retreat, the International Science Media Network, through its New Zealand website, shared "Scanning the Antarctic Horizon" which was subsequently picked up by the print, television and radio media. In the context of formal education, at least one higher learning institute incorporated a Scan focus. | Some of these media activities and presentations are archived on the SCAR website.[385]<br><br>The Tinker Foundation[386] provided financial support for staging the Scan and ARC and highlighted the outcomes via its on-line media. |

| | | |
|---|---|---|
| | SCAR has presented research results to the United Nations Framework Convention on Climate Change (UNFCCC) conferences on several occasions, aligned with key themes of the Scan (e.g. in 2019 SCAR addressed the theme of the role of the Southern Ocean in the Global Climate System). | |

Table S16. Antarctica is unique, managed via an international treaty setting the region aside as a scientific preserve and establishes freedom of scientific investigation. There are territorial claims, open ocean, a vast array of endemic and migratory species, complex food webs and no indigenous peoples. This table provides a brief description of the stakeholders, organizations (governmental and non-governmental), end-users and constituencies.

| Stakeholder/Organization/ Activity | Mission/Goals | Role in Antarctica/ Membership |
|---|---|---|
| Antarctic Treaty System (ATS)[372] (inter-governmental) | The Antarctic Treaty was signed in Washington, DC, USA (1959). The total number of Parties to the Treaty is fifty-four (2019). | The overarching international governance structure. Antarctic Treaty Parties include 29 consultative members and 25 countries that have acceded to the Treaty (2019).[387] |
| Antarctic Treaty Consultative Meetings (ATCMs)[373] (inter-governmental) | The formal meeting of Parties under the Antarctic Treaty. | Every year Consultative Parties meet "for the purpose of exchanging information, consulting together on matters of common interest pertaining to Antarctica, and formulating and considering and recommending to their Governments measures in furtherance of the principles and objectives of the Treaty" (Art. IX). |
| Antarctic Treaty Parties | There were 12 original signatories to the Treaty and an additional 42 (2019) countries that have acceded to the Treaty since 1959. Those Parties that are entitled to participate in the Consultative Meetings (Antarctic Treaty Consultative Parties) are those that have demonstrated their interest in Antarctica by "conducting substantial research activity there". Currently (2019) there are 29 Consultative Parties. The other 25 Non-Consultative Parties are invited to attend the Consultative Meetings but | Antarctic Treaty Consultative Parties are those countries that are active in Antarctica, both in the funding and conduct of Antarctic science as well as in implementing the regulations and principles of the Antarctic Treaty into domestic law and legislation. |

| | | |
|---|---|---|
| | do not participate in decision-making.[387] | |
| The Committee on Environmental Protection (CEP)[375]<br>(inter-governmental) | Established through the Protocol on Protection of the Environment to the Antarctic Treaty, and as such part of the ATS. The Committee's functions are "to provide advice and formulate recommendations to the Parties in connection with the implementation of this Protocol, including the operation of its Annexes, for consideration at Antarctic Treaty Consultative Meetings." | The Committee consists of representatives of the 40 (2019) Parties to the Environment Protocol and normally meets once a year in conjunction with the ATCM. CEP meetings are also attended by various observers. |
| The Convention on the Conservation of Antarctic Marine Living Resources[377]<br>(inter-governmental), | A part of the ATS. The Convention on the Conservation of Antarctic Marine Living Resources is an international agreement (1980).It is a multilateral response to concerns that unregulated increases in krill catches in the Southern Ocean could be detrimental for Antarctic marine ecosystems particularly for seabirds, seals, whales and fish that depend on krill for food. There are 25 Members and 11 Acceding States (2019) and It convenes a Scientific Committee.[376,388] | The CAMLR Convention applies to all Antarctic populations of all living resources found south of the Antarctic Convergence (the Convention Area). Apart from whales and seals, which are the subject of other conventions – namely, the International Convention for the Regulation of Whaling and the Convention for the Conservation of Antarctic Seals.[389,390] |
| Scientific Committee on Antarctic Research (SCAR)[374]<br>(non-governmental) | The Scientific Committee on Antarctic Research (SCAR) is an inter-disciplinary committee of the International Science Council (ISC, 1958). SCAR is charged with | SCAR has 43 national and 9 International Science Council Unions members.[391] SCAR provides objective and independent scientific advice to the ATS, CEP, CCAMLR, and ATCMs; and other organizations such as the United Nations Framework Convention on Climate Change (UNFCCC) and |

| | | |
|---|---|---|
| | initiating, developing and coordinating high quality international scientific research in the Antarctic region (including the Southern Ocean), and on the role of the Antarctic region in the Earth system. SCAR is recognized as observer to ATCMs and the CEP through the provisions of the Antarctic Treaty and Protocol on Environmental Protection. | Intergovernmental Panel on Climate Change (IPCC) on issues of science and conservation affecting the management of Antarctica and the Southern Ocean and on the role of the Antarctic region in the Earth system. |
| Council of Managers of National Antarctic Programs (COMNAP)[383]<br>(inter-governmental) | COMNAP is the international association (1988) which brings together its Members, who are the National Antarctic Programs. National Antarctic Programs are those organizations that have responsibility for delivering and supporting scientific research in the Antarctic Treaty Area. COMNAP has 30 National Antarctic Program Members (2019).[392] COMNAP is an observer to ATCMs and the CEP. | COMNAP's purpose is to "develop and promote best practice in managing the support of scientific research in Antarctica"<br><br>Each Member program is represented by the Manager of that National Antarctic Program and/or the Deputy Manager of that program. NAPs often perform the dual role of managing all aspects of scientific support and funding national scientific projects and programs. |
| National Antarctic Programs (national-governmental) | Each Party the Antarctic Treaty normally establishes a National Antarctic Program, which has national responsibility for managing the support of scientific research on behalf of its government. Establishing National Antarctic Programs is not mandatory but all those countries which have permanent research stations in Antarctica or carry out | National Antarctic Programs collectively have the greatest first-hand experience of living and working in the Antarctic and provide the support for the science conducted in Antarctica and are responsible for carrying through many of the decisions and agreements from the ATCMs. |

| | | |
|---|---|---|
| | scientific research otherwise, generally do so. | |
| A range of non-governmental organizations. | Examples (not exhaustive):<br><br>• Antarctic Southern Ocean Coalition (ASOC)[393]<br>• International Association of Antarctic Tour Operators (IAATO)[394] | Advocates for various issues and/or stakeholders.<br><br>Examples:<br>ASOC works on a wide range of Antarctic environmental issues.<br><br>IAATO - A member organization (1991) “to advocate and promote the practice of safe and environmentally responsible private-sector travel to the Antarctic”. |
| Media organizations, social media and the Public | In some instances; communicators and consumers of research outcomes, audiences, and commentators (opinion pieces, blogs, etc.). | The public includes the constituencies of the organizations that fund science in Antarctica. |

Supplementary References


1. 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. Nature 512, 23-25.
2. 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. Antarctic Science 27, 3–18.
3. Yuan, X., Kaplan, M.R. and Cane, M.A. (2018). The Interconnected Global Climate System - A Review of Tropical - Polar Teleconnections. Journal of Climate 31, 5765-5792.
4. Parish, T. R., and Bromwich, D.H. (1998). A case study of Antarctic katabatic wind interaction with large-scale forcing. Monthly Weather Review 126, 199-209.
5. Papritz, L., Pfahl, S., Sodemann, H., and Wernli, H. (2015). A climatology of cold air outbreaks and their impact on air–sea heat fluxes in the high-latitude South Pacific. Journal of Climate 28, 342-364.
6. 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. Journal of Climate 32, 3131–3151.
7. Abram, N.J., Mulvaney, R., Vimeux, F., Phipps, S.J., Turner, J. and England, M.H. (2014) Evolution of the Southern Annular Mode during the past millennium. Nature Climate Change, 4, 564-569.
8. Stenni, B., Curran, M.A.J., Abram, N.J., Orsi, A., Goursaud, S., Masson-Delmotte, V., Neukom, R., Goosse, H., Divine, D., Ommen, T. van, et al. (2017). Antarctic climate variability on regional and continental scales over the last 2000 years. Climate of the Past 13, 1609-1634.
9. 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.
10. 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.
11. Fan, T., Deser, C. and Schneider, D.P. (2014). Recent Antarctic sea ice trends in the context of Southern Ocean surface climate variations since 1950. Geophysical Research Letters 41, 2419-2426.
12. Smith, K.L., and Polvani, L.M. (2017). Spatial patterns of recent Antarctic surface temperature trends and the importance of natural variability: lessons from multiple reconstructions and the CMIP5 models. Climate Dynamics 48, 2653-2670.
13. Zhang, L., Delworth, T.L., Cooke, W., and Yang, X. (2019). Natural variability of Southern Ocean convection as a driver of observed climate trends. Nature Climate Change 9, 59-65.
14. 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. Nature Geoscience 9, 549.
15. 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. Journal of Climate Science 28, 2862-886.

16. Morrison, A.K., Griffies, S.M., Winton, M., Anderson, W.G., Sarmiento, J.L., Morrison, A.K., Griffies, S.M., Winton, M., Anderson, W.G., and Sarmiento, J.L. (2016). Mechanisms of Southern Ocean Heat Uptake and Transport in a Global Eddying Climate Model. Journal of Climate 29, 2059-2075.
17. 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. Nature Communications 9, 3625.
18. Hines, K. M., Bromwich, D.H., Wang, S.-H., Silber, I., Verlinde, J., and Lubin, D. (2019). Microphysics of summer clouds in central west Antarctica simulated by Polar WRF and AMPS. Atmospheric Chemistry and Physics, acp-2018-1251, revised.
19. Kay, J.E., Wall, C., Yettella, V., Medeiros, B., Hannay, C., Caldwell, P., and Bitz, C. (2015). Global Climate Impacts of Fixing the Southern Ocean Shortwave Radiation Bias in the Community Earth System Model (CESM). Journal of Climate, 29, 4617-4636.
20. Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) Field Campaign Report, https://www.osti.gov/biblio/1524775
21. Nowicki, S.M.J., Payne, T., 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. Geosciences Model Development 9, 4521–4545.
22. Asay-Davis, X.S., Cornford, S.L., Durand, G., Galton-Fenzi, B.K., Gladstone, R.M., Gudmundsson, G.H., Hattermann, T., Holland, D.M., Holland, D., Holland, P.R., et al. (2016). Experimental design for three interrelated marine ice sheet and ocean model intercomparison projects: MISMIP v. 3 (MISMIP +), ISOMIP v. 2 (ISOMIP +) and MISOMIP v. 1 (MISOMIP1). Geoscientific Model Development 9, 2471–2497.
23. DeConto, R.M., and Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. Nature 531, 591–597.
24. 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. Scientific Reports 8, 11323.
25. Golledge, N.R., 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.
26. 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.
27. Levy, R., Harwood, D., Florindo, F., Sangiorgi, F., Tripati, R., Eynatten, H. von, Gasson, E., Kuhn, G., Tripati, A., DeConto, R., et al. (2016). Antarctic ice sheet sensitivity to atmospheric CO2 variations in the early to mid-Miocene. Proceedings of the National Academies of Science of the United States 113, 3453-3458.
28. International Ocean Discovery Program, https://www.iodp.org/
29. International Partnership in Ice Core Sciences (IPICS), SCAR, https://www.scar.org/science/ipics/ipics/
30. Beyond EPICA Oldest Ice, https://www.beyondepica.eu/
31. Antpas – Antarctic Permafrost, Periglacial Environments and Soils, https://www.antpas.org/
32. Solomon, S., Ivy, D.J., Kinnison, D., Mills, M.J., Neely, R.R., and Schmidt, A. (2016). Emergence of healing in the Antarctic ozone layer. Science 353, 269-274.

33. Bandoro, J., Solomon, S., Donohoe A., Thompson, D.W.J., and Santer, B.D. (2014). Influences of the Antarctic Ozone Hole on Southern Hemispheric Summer Climate Change. Journal of Climate, 27, 6245-6264.
34. Grytsai, A., Klekociuk, A., Milinevsky, G., Evtushevsky, O., and Stone, K. (2017). Evolution of the eastward shift in the quasi-stationary minimum of the Antarctic total ozone column. Atmospheric Chemistry and Physics, 17, 1741-1758.
35. The 2018 Antarctic Ozone Hole Season, https://atmosphere.copernicus.eu/2018-antarctic-ozone-hole-season
36. Ball, W.T., Alsing, J., Mortlock, D.J., Staehelin, J., Haigh, J.D., Peter, T., Tummon, F., Stübi, R., Stenke, A., Anderson, J., et al. (2018). Evidence for a continuous decline in lower stratospheric ozone offsetting ozone layer recovery. Atmospheric Chemistry and Physics 18, 1379-1394.
37. 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.
38. 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. Nature Communications 10, 13.
39. Moreau S, Vidussi F, Ferreyra G, Mostajir B. (2016). Ecological impacts of ultraviolet-B radiation in marine ecosystems. In Stressors in the Marine Environment, ed. M Solan, NM Whitely, pp. 261-268. (Oxford: Oxford University Press).
40. 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. Photochemical & Photobiological Sciences 18, 681-716.
41. Gutt J, Bertler N, Bracegirdle TJ, Buschmann A, Comiso J., et al. (2015) The Southern Ocean ecosystem under multiple climate change stresses—an integrated circumpolar assessment. Global Change Biology 21,1434-53.
42. Bao, T., Zhu, R., Wang, P., Ye, W., Dawei, M., and Xu, H. (2018). Potential effects of ultraviolet radiation reduction on tundra nitrous oxide and methane fluxes in maritime Antarctica. Scientific Reports 8, 3716.
43. Robinson, S.A., and Erickson, D.J. 3rd. (2015). Not just about sunburn–the ozone hole's profound effect on climate has significant implications for Southern Hemisphere ecosystems. Global Change Biology 21, 515-27.
44. Robinson, S.A., King D.H., Bramley-Alves J., Waterman M.J., Ashcroft M.B., et al. (2018). Rapid change in East Antarctic terrestrial vegetation in response to regional drying. Nature Climate Change 8, 79-84.
45. 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.
46. Landschützer, P., Gruber, N., Haumann, F.A., Rödenbeck, C., Bakker, D.C.E., Heuven, S. van, Hoppema, M., Metzl, N., Sweeney, C., Takahashi, T., et al. (2015). The reinvigoration of the Southern Ocean carbon sink. Science 349, 1221-1224.
47. Roemmich, D., Church, J., Gilson, J., Monselesan, D., Sutton, P., and Wijffels, S. (2015). Unabated planetary warming and its ocean structure since 2006. Nature Climate Change 5, 240-245.

48. Shi, J.-R., Xie, S.-P., Talley, L.D., Shi, J.-R., Xie, S.-P., and Talley, L.D. (2018). Evolving Relative Importance of the Southern Ocean and North Atlantic in Anthropogenic Ocean Heat Uptake. Journal of Climate, 31, 7459-7479.
49. 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. Science Advances 3, e160426.
50. 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. Journal of Geophysical Research: Oceans 124, 1778-1794.
51. Snow, K., Rintoul, S.R., Sloyan, B., and Hogg, A. (2018). Decrease in density and volume of Adélie Land Bottom Water induced by iceberg calving. Geophysical Research Letters, 45, 2380-2387.
52. DeVries, T., Holzer, M., and Primeau, F. (2017). Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. Nature 542, 215-218.
53. Rintoul, S. R. (2018). The global influence of localized dynamics in the Southern Ocean. Nature, 558, 209-218.
54. Thompson, A. F., and Naveira Garabato, A. C. (2014). Equilibration of the Antarctic Circumpolar Current by standing meanders. Journal of Physical Oceanography 44, 1811–1828.
55. 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. Nature Communications 8, 172; corrigendum 9, 209 (2018).
56. 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. Nature Geoscience 9, 596-601.
57. 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.
58. 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. Nature Communications 9, 1789.
59. Wilson, E.A., Riser, S.C., Campbell, E.C., Wong, A.P.S., Wilson, E.A., Riser, S.C., Campbell, E.C., and Wong, A.P.S. (2019). Winter Upper-Ocean Stability and Ice–Ocean Feedbacks in the Sea Ice–Covered Southern Ocean. Journal of Physical Oceanography 49, 1099–1117.
60. Goosse, H., Kay, J.E., Armour, K.C., Bodas-Salcedo, A., Chepfer, H., Docquier, D., Jonko, A., Kushner, P.J., Lecomte, O., Massonnet, F., et al. (2018). Quantifying climate feedbacks in polar regions. Nature Communications 9, 1919.
61. Meehl, G.A., Arblaster, J.M., Chung, C.T.Y., Holland, M.M., DuVivier, A., Thompson, L., et al. (2019). Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. Nature Communications 10, 14.
62. 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 Modelling, 104, 99-110.
63. Kohyama, T., and Hartmann, D.L. (2016). Antarctic Sea Ice Response to Weather and Climate Modes of Variability. Journal of Climate 29.721-741.

64. Zhang, L., Delworth, T.L., Cooke, W., and Yang, X. (2019). Natural variability of Southern Ocean convection as a driver of observed climate trends. Nature Climate Change 9, 59.
65. 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. Proceedings of the National Academy of Sciences of the United States of America 116, 14414–14423.
66. Climate Change Initiative, European Space Agency, http://cci.esa.int/
67. 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.
68. 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.
69. Montiel, F., and Squire, V.A. (2017). Modelling wave-induced sea ice break-up in the marginal ice zone. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 473(2206), 20170258.
70. Squire, V.A. (2018). A fresh look at how ocean waves and sea ice interact. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering 376(2129), 20170342.
71. Stopa, J.E., Sutherland, P., and Ardhuin, F. (2018). Strong and highly variable push of ocean waves on Southern Ocean sea ice. Proceedings of the National Academy of Sciences of the United States of America 115, 5861-5865.
72. 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. Nature Geoscience 9, 596-601.
73. Smith, D.M., Dunstone, N.J., Scaife, A.A., Fiedler, E.K., Copsey, D., and Hardiman, S.C. (2017). Atmospheric Response to Arctic and Antarctic Sea Ice: The Importance of Ocean–Atmosphere Coupling and the Background State. Journal of Climate 30, 4547-4964.
74. England, M., Polvani, L., and Sun, L. (2018). Contrasting the Antarctic and Arctic Atmospheric Responses to Projected Sea Ice Loss in the Late Twenty-First Century. Journal of Climate 31, 6353-6370.
75. 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.
76. Francis, D., Eayrs, C., Cuesta, J., and Holland, D. (2019). Polar Cyclones at the Origin of the Reoccurrence of the Maud Rise Polynya in Austral Winter 2017. Journal of Geophysical Research: Atmospheres 124, 5251-5267.
77. Schlosser, E., Haumann, F.A., and Raphael, M.N. (2018). Atmospheric influences on the anomalous 2016 Antarctic sea ice decay. The Cryosphere 12, 1103-1119.
78. 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. Geophysical Research Letters 44, 9008-9019.
79. Turner, J., Phillips, T., Marshall, G.J., Hosking, J.S., Pope, J.O., Bracegirdle, T.J., and Deb, P. (2017). Unprecedented springtime retreat of Antarctic sea ice in 2016. Geophysical Research Letters 44, 6868-6875.
80. 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. Nature Communications 8, 15799.

81. 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. Geophysical Research Letters 45, 1472-1480.
82. Siegfried, M.R., Medley, B., Larson, K.M., Fricker, H.A., and Tulaczyk, S. (2017). Snow accumulation variability on a West Antarctic ice stream observed with GPS reflectometry, 2007–2017. Geophysical Research Letters 44, 7808-7816.
83. Brook, E.J., and Buizert, C. (2018). Antarctic and global climate history viewed from ice cores. Nature 558, 200.
84. Chalk, T.B., Hain, M.P., Foster, G.L., Rohling, E.J., Sexton, P.F., Badger, M.P.S., Cherry, S.G., Hasenfratz, A.P., Haug, G.H., Jaccard, S.L., et al. (2017). Causes of ice age intensification across the Mid-Pleistocene Transition. Proceedings of the National Academy of Science of the United States of America 114, 13114.
85. Ferrari, R., Jansen, M.F., Adkins, J.F., Burke, A., Stewart, A.L., and Thompson, A.F. (2014). Antarctic sea ice control on ocean circulation in present and glacial climates. Proceedings of the National Academy of Sciences of the United States of America 111, 8753-8758.
86. Hasenfratz, A.P., Jaccard, S.L., Martínez-García, A., Sigman, D.M., Hodell, D.A., Vance, D., Bernasconi, S.M., Kleiven, H. F., Haumann, F.A., and Haug, G.H. (2019). The residence time of Southern Ocean surface waters and the 100,000-year ice age cycle. Science 363, 1080-1084.
87. Pollard, D., Chang, W., Haran, M., Applegate, P., and DeConto, R. (2016). Large ensemble modeling of last deglacial retreat of the West Antarctic Ice Sheet: Comparison of simple and advanced statistical techniques. Geosciences Model Development, 9, 1697-1723.
88. 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. Geophysical Research Letters 46, 3359-3367.
89. Gruber, N., Landschützer, P., and Lovenduski, N.S. (2019). The Variable Southern Ocean Carbon Sink. Annual Review of Marine Science 11, 159-186
90. Gray, A.R., Johnson, K.S., Bushinsky, S.M., Riser, S.C., Russell, J.L., Talley, L.D., Wanninkhof, R., Williams, N.L., and Sarmiento, J.L. (2018). Autonomous Biogeochemical Floats Detect Significant Carbon Dioxide Outgassing in the High-Latitude Southern Ocean. Geophysical Research Letters 45, 9049-9057.
91. Boyd, P.W. (2019). Physiology and iron modulate diverse responses of diatoms to a warming Southern Ocean. Nature Climate Change 9, 148-152.
92. Hauck, J., Volker, C., Wolf-Gladrow, D.A., Laufkotter, C., Vogt, M., Aumont, O., Bopp, L., Buitenhuis, E.T., Doney, S.C., Dunne, J., et al. (2015). On the Southern Ocean CO2 uptake and the role of the biological carbon pump in the 21st century. Global Biogeochemical Cycles 29, 1451-1470.
93. Xu, K., Fu, F.X., and Hutchins, D.A. (2014). Comparative responses of two dominant Antarctic phytoplankton taxa to interactions between ocean acidification, warming, irradiance, and iron availability. Limnology and Oceanography 59, 1919-1931.
94. Ericson, J.A., Hellessey, N., Kawaguchi, S., Nicol, S., Nichols, P.D., Hoem, N., and Virtue, P. (2018). Adult Antarctic krill proves resilient in a simulated high $CO_2$ ocean. Communications Biology 1, 190.
95. Gardner, J., Manno, C., Bakker, D.C.E., Peck, V.L., and Tarling, G.A. (2017). Southern Ocean pteropods at risk from ocean warming and acidification. Marine Biology 165, 8.

96. Peck, V.L., Oakes, R.L., Harper, E.M., Manno, C., and Tarling, G.A. (2018). Pteropods counter mechanical damage and dissolution through extensive shell repair. Nature Communications 9, 264.
97. Peck, L. (2018). Antarctic marine biodiversity: adaptations, environments and responses to change. In Oceanography and Marine Biology: An Annual Review, ed. S.J. Hawkins, A.J. Evans, A.C. Dale, L.B. Firth, and I.P. Smith, pp. 105–236 (Taylor and Francis).
98. Banwell, A.F., Willis, I.C., Macdonald, G.J., Goodsell, B., and MacAyeal, D.R. (2019). Direct measurements of ice-shelf flexure caused by surface meltwater ponding and drainage. Nature Comms 10, 730.
99. Henley, S.F., Schofield, O.M., Hendry, K.R., Schloss, I.R., Steinberg, D.K., Moffat, C., Peck, L.S., Costa, D.P., Bakker, D.C.E., Hughes, C., et al. (2019). Variability and change in the west Antarctic Peninsula marine system: Research priorities and opportunities. Progress in Oceanography 173, 208-237.
100. Haid, V., Iovino, D., and Masina, S. (2017). Impacts of freshwater changes on Antarctic sea ice in an eddy-permitting sea-ice–ocean model. The Cryosphere 11, 1387-1402.
101. NASA Operation IceBridge, https://icebridge.gsfc.nasa.gov
102. Morlighem, M., Williams, C.N., Rignot, E., An, L., Arndt, J.E., Bamber, J.L., Catania, G., Chauché, N., Dowdeswell, J.A., Dorschel, B. et al. 2017. BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multibeam echo sounding combined with mass conservation. Geophysical Research Letters, 44,11-51.
103. Durand, G., Gagliardini, O., Favier, L., Zwinger, T., and Le Meur, E. (2011). Impact of bedrock description on modeling ice sheet dynamics. Geophysical Research Letters, 38.
104. Greenbaum, J.S., Blankenship, D.D., Young, D.A., Richter, T.G., Roberts, J.L., Aitken, A.R.A., Legresy, B., Schroeder, D.M., Warner, R.C., Ommen, T.D. van, et al. (2015). Ocean access to a cavity beneath Totten Glacier in East Antarctica. Nature Geoscience 8, 294.
105. Falcini, F.A.M., Rippin, D.M., Krabbendam, M., and Selby, K.A. (2018). Quantifying bed roughness beneath contemporary and palaeo-ice streams. Journal of Glaciology 64, 822-834.
106. Jeofry, H., Ross, N., Brocq, A.L., Graham, A.G.C., Li, J., Gogineni, P., Morlighem, M., Jordan, T., and Siegert, M.J. (2018). Hard rock landforms generate 130 km ice shelf channels through water focusing in basal corrugations. Nature Communications 9, 4576.
107. Schroeder, D. M., Blankenship, D. D., Young, D. A., Witus, A. E., and Anderson, J. B. (2014). Airborne radar sounding evidence for deformable sediments and outcropping bedrock beneath Thwaites Glacier, West Antarctica. Geophysical Research Letters, 41(20), 7200-7208.
108. Arthern, R. J., Hindmarsh, R. C., and Williams, C. R. (2015). Flow speed within the Antarctic ice sheet and its controls inferred from satellite observations. Journal of Geophysical Research: Earth Surface, 120(7), 1171-1188.
109. Gillet-Chaulet, F., Durand, G., Gagliardini, O., Mosbeux, C., Mouginot, J., Rémy, F., and Ritz, C. (2016). Assimilation of surface velocities acquired between 1996 and 2010 to constrain the form of the basal friction law under Pine Island Glacier. Geophysical Research Letters, 43(19), 10-311.
110. Pattyn, F., Schoof, C., Perichon, L., Hindmarsh, R.C.A., Bueler, E., Fleurian, B. de, Durand, G., Gagliardini, O., Gladstone, R., Goldberg, D., et al. (2012). Results of the Marine Ice Sheet Model Intercomparison Project, MISMIP. The Cryosphere 6, 573–588.
111. ice2sea MISMIP3D: Marine Ice Sheet Model Intercomparison Project for planview models (3D), http://homepages.ulb.ac.be/~fpattyn/mismip3d/

112. Ice Sheet System Model, NASA, https://issm.jpl.nasa.gov/
113. Elmer/Ice, http://elmerice.elmerfem.org/
114. BISICLES, https://commons.lbl.gov/display/bisicles?atl_token=bb21509b202635ed8078fe4f24c80cfbaef3247f
115. Martin, D.F., Cornford, S.L., and Payne, A.J. (2019). Millennial-Scale Vulnerability of the Antarctic Ice Sheet to Regional Ice Shelf Collapse. Geophysical Research Letters 46, 1467-1475.
116. 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.
117. Gillet-Chaulet, F., Durand, G., Gagliardini, O., Mosbeux, C., Mouginot, J., Rémy, F., and Ritz, C. (2016). Assimilation of surface velocities acquired between 1996 and 2010 to constrain the form of the basal friction law under Pine Island Glacier. Geophysical Research Letters 43, 10,311-10,321.
118. Marine Ice Sheet-Ocean Model Intercomparison Project (MISOMIP), http://www.climate-cryosphere.org/activities/targeted/misomip
119. ISMIP6 - Ice Sheet Model Intercomparison Project for CMIP6, WCRP, https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/cmip6-endorsed-mips-article/1049-modelling-cmip6-ismip
120. Fricker, H.A., Siegfried, MR., Carter, S. P., and Scambos, T.A. (2016). A decade of progress in observing and modelling Antarctic subglacial water systems. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 374(2059), 20140294.
121. Siegert, M.J., Ross, N., and Le Brocq, A.M. (2016). Recent advances in understanding Antarctic subglacial lakes and hydrology. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 374(2059), 20140306.
122. Siegfried, M.R., Fricker, H.A., Carter, S.P., and Tulaczyk, S. (2016). Episodic ice velocity fluctuations triggered by a subglacial flood in West Antarctica. Geophysical Research Letters, 43(6), 2640-2648.
123. Young, D.A., Schroeder, D.M., Blankenship, D.D., Kempf, S.D., and Quartini, E. (2016). The distribution of basal water between Antarctic subglacial lakes from radar sounding. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 374(2059), 20140297.
124. Key, K., and Siegfried, M.R. (2017). The feasibility of imaging subglacial hydrology beneath ice streams with ground-based electromagnetics. Journal of Glaciology 63(241): 755-771.
125. 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. Geological Society, London, Special Publications 461, 197-213.
126. 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. Geophysical Research Letters, 44(22), 11-417.
127. Report on Taking the Temperature of the Antarctic Continent (TACtical) Workshop 21-23 March 2018, Hobart, Tasmania, Australia; https://www.scar.org/scar-news/serce-news/report-tact-2018/

128. Liefferinge, B.V., Pattyn, F., Cavitte, M. G., Karlsson, N. B., Young, D. A., Sutter, J., and Eisen, O. (2018). Promising Oldest Ice sites in East Antarctica based on thermodynamical modelling. The Cryosphere, 12, 2773-2787.
129. Whitehouse, P.L., Gomez, N., King, M.A., and Wiens, D.A. (2019). Solid Earth change and the evolution of the Antarctic Ice Sheet. Nature Communications 10, 503.
130. 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(7573), 421.
131. Pattyn, F., Ritz, C., Hanna, E., Asay-Davis, X., DeConto, R., Durand, G., Favier, L., Fettweis, X., Goelzer, H., Golledge, N.R., et al. (2018). The Greenland and Antarctic ice sheets under 1.5 °C global warming. Nature Climate Change 8, 1053-1061.
132. 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. Geophysical Research Letters, 44, 6191-6199.
133. Arthern, R.J., and Williams, C.R. (2017). The sensitivity of West Antarctica to the submarine melting feedback. Geophysical Research Letters 44, 2352-2359
134. Trusel, L.D., Frey, K.E., Das, S.B., Karnauskas, K.B., Munneke, P.K., Van Meijgaard, E., and Van Den Broeke, M.R. (2015). Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios. Nature Geoscience 8, 927.
135. 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.
136. Nitsche, F.O., Porter, D., Williams, G., Cougnon, E.A., Fraser, A.D., Correia, R., and Guerrero, R. (2017). Bathymetric control of warm ocean water access along the East Antarctic Margin. Geophysical Research Letters 44, 8936-8944.
137. Dutrieux, P., Rydt, J.D., Jenkins, A., Holland, P.R., Ha, H.K., Lee, S.H., Steig, E.J., Ding, Q., Abrahamsen, E.P., and Schröder, M. (2014). Strong Sensitivity of Pine Island Ice-Shelf Melting to Climatic Variability. Science 343, 174-178.
138. 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. Nature Geoscience 11, 121.
139. Jenkins, A., Shoosmith, D., Dutrieux, P., Jacobs, S., Kim, T.W., Lee, S.H., Ha, H.K., and Stammerjohn, S. (2018). West Antarctic Ice Sheet retreat in the Amundsen Sea driven by decadal oceanic variability. Nature Geoscience 11, 733-738.
140. Garabato, A.C.N., Frajka-Williams, E.E., Spingys, C.P., Legg, S., Polzin, K.L., Forryan, A., Abrahamsen, E.P., Buckingham, C.E., Griffies, S.M., McPhail, S.D., et al. (2019). Rapid mixing and exchange of deep-ocean waters in an abyssal boundary current. Proceedings of the National Academy of Sciences of the United States of America 116, 13233-13238.
141. International Thwaites Glacier Collaboration, https://www.bas.ac.uk/project/international-thwaites-glacier-collaboration/
142. Rintoul, S.R., Silvano, A., Pena-Molino, B., Wijk, E. van, Rosenberg, M., Greenbaum, J.S., and Blankenship, D.D. (2016). Ocean heat drives rapid basal melt of the Totten Ice Shelf. Science Advances 2, e1601610.
143. Rignot, E., Mouginot, J., Scheuchl, B., Broeke, M. van den, Wessem, M.J. van, and Morlighem, M. (2019). Four decades of Antarctic Ice Sheet mass balance from 1979-2017. Proceedings of the National Academies of Science of the United States 116, 1095-1103.

144. Golledge, N.R., Menviel, L., Carter, L., Fogwill, C.J., England, M.H., Cortese, G., and Levy, R.H. (2014). Antarctic contribution to meltwater pulse 1A from reduced Southern Ocean overturning. Nature Communications, 5, 5107.
145. Ice Sheet Mass Balance Inter-Comparison Exercise (IMBIE), http://imbie.org/about-the-project/
146. Smith, A.M., Woodward, J., Ross, N., Bentley, M.J., Hodgson, D.A., Siegert, M.J. and King, E.C. (2018). Evidence for the long-term sedimentary environment in an Antarctic subglacial lake. Earth and Planetary Science Letters 504: 139-151.
147. Spector, P., Stone, J., Pollard, D., Hillebrand, T., Lewis, C., and Gombiner, J. (2018). Antarctic sites for subglacial drilling to test for past ice-sheet collapse, The Cryosphere 12: 2741-2757.
148. Fastdrill, https://websites.pmc.ucsc.edu/~tulaczyk/fastdrill.htm
149. Rapid Access Ice Drill, http://www.rapidaccessicedrill.org/
150. 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, In supplement to: Golynsky, A.V. et al. (2018). New magnetic anomaly map of the Antarctic. Geophysical Research Letters 45, 6437-6449.
151. An, M., Wiens, D.A. Zhao, Y., Feng, M., Nyblade, A., Kanao, M. Li, Y. Maggi, A. and Lévêque, J.J. (2015). Temperature, lithosphere-asthenosphere boundary, and heat flux beneath the Antarctic Plate inferred from seismic velocities, Journal of Geophysical Research - Solid Earth 120, 8720-8742.
152. 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. Geophysical Research Letters 44, 5436-5446.
153. Goodge, J.W. (2018). Crustal heat production and estimate of terrestrial heat flow in central East Antarctica, with implications for thermal input to the East Antarctic ice sheet. The Cryosphere 12, 491–504.
154. An informative blog related to Q.36: https://blogs.egu.eu/divisions/cr/2018/03/23/image-of-the-week-geothermal-heat-flux-in-antarctica-do-we-really-know-anything/
155. POLENET, The Polar Observing Network, http://polenet.org/
156. ROSETTA-Ice at ESR, https://rosetta.esr.org/
157. 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. Geophysical Journal International 214, 811–824.
158. Vries, M. van W. de, Bingham, R.G., and Hein, A.S. (2018). A new volcanic province: an inventory of subglacial volcanoes in West Antarctica. Geological Society, London, Special Publications 461, 231–248.
159. Lough, A.C., Wiens, D.A., Barcheck, C.G., Anandakrishnan, S., Aster, R.C., Blankenship, D.D., Huerta, A.D., Nyblade, A., Young, D.A., and Wilson, T.J. (2013). Seismic detection of an active subglacial magmatic complex in Marie Byrd Land, Antarctica. Nature Geoscience 6, 1031.
160. Antarctic Volcanism (Antvolc), SCAR, https://www.scar.org/science/antvolc/antvolc/
161. An informative blog related to Q.38: http://www.antarcticglaciers.org/glacial-geology/antarctic-ice-sheet/subglacial-volcanoes/
162. Frisia, S., Weyrich, L.S., Hellstrom, J., Borsato, A., Golledge, N.R., Anesio, A.M., Bajo, P., Drysdale, R.N., Augustinus, P.C., Rivard, C. and Cooper, A. (2017). The influence of

Antarctic subglacial volcanism on the global iron cycle during the Last Glacial Maximum. Nature Communications 8, 15425.
163. 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. Journal of Geophysical Research: Earth Surface 124, 812-829.
164. Paxman, G.J.G., Jamieson, S.S.R., Ferraccioli, F., Bentley, M.J., Ross, N., Armadillo, E., Gasson, E.G.W., Leitchenkov, G., and DeConto, R.M. (2018). Bedrock Erosion Surfaces Record Former East Antarctic Ice Sheet Extent. Geophysical Research Letters 45, 4114-4123.
165. Sugden, D.E., and Jamieson, S.S.R. (2018). The pre-glacial landscape of Antarctica. Scottish Geographical 134, 203-223.
166. Austermann, J., Mitrovica, J.X., Huybers, P., and Rovere, A. (2017). Detection of a dynamic topography signal in last interglacial sea-level records. Science Advances 3, e1700457.
167. Fraser, C.I., Terauds, A., Smellie, J., Convey, P., and Chown, S.L. (2014). Geothermal activity helps life survive glacial cycles. Proceedings of the National Academy of Sciences of the United States of America 111, 5634-5639.
168. Mock, T., Otillar, R.P., Strauss, J., McMullan, M., Paajanen, P., Schmutz, J., Salamov, A., Sanges, R., Toseland, A., Ward, B.J., et al. (2017). Evolutionary genomics of the cold-adapted diatom *Fragilariopsis cylindrus*. Nature 541, 536-540.
169. 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. Nature Ecology and Evolution 3, 469-478.
170. Shin, S.C., Ahn, D.H., Kim, S.J., Pyo, C.W., Lee, H., Kim, M.K., Lee, J., Lee, J.E., Detrich, H.W., Postlethwait, J.H., et al. (2014). The genome sequence of the Antarctic bullhead notothen reveals evolutionary adaptations to a cold environment. Genome Biology 15, 468.
171. 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. Nature Communications 5, 4611.
172. Ji, M., Greening, C., Vanwonterghem, I., Carere, C.R., Bay, S.K., Steen, J.A., Montgomery, K., Lines, T., Beardall, J., van Dorst, J., et al. (2017). Atmospheric trace gases support primary production in Antarctic desert surface soil. Nature 552, 400-403.
173. Diaz, A., Gérard. K., Gonzalez-Wevar, C., Maturana, C., Féral, J.-P., David, B., Saucède, T., and Poulin, E. (2018). Genetic structure and demographic inference of the regular sea urchin *Sterechinus neumayeri* (Meissner, 1900) in the Southern Ocean: The role of the last glaciation. PLoS One 13, e0197611.
174. Frugone, M.J., Lowther, A., Noll, D., Ramos, B., Pistorius, P., Dantas, G.P.M., Petry, M.V., Bonadonna, F., Steinfurth, A., Polanowski, A., Raya Rey, A., Lois, N.A., Pütz, K., Trathan, P., Wienecke, B., Poulin, E., and Vianna, J.A. (2018). Contrasting phylogeographic pattern among *Eudyptes* penguins around the Southern Ocean. Scientific Reports 8, 17481.
175. Fraser, C.I., Morrison, A.K., McC Hogg, A., Macaya, E.C., van Sebille, E., Ryan, P.G., Padovan A., Jack, C., Valdivia, N., and Waters, J.M. (2018). Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. Nature Climate Change 8, 704-708.
176. Leiva, C., Taboada, S., Kenny, N. J., Combosch, D., Giribet, G., Jombart, T., and Riesgo, A. (2019). Population substructure and signals of divergent adaptive selection

despite admixture in the sponge *Dendrilla antarctica* from shallow waters surrounding the Antarctic Peninsula. Molecular Ecology 28, 3151-3170.
177. Cristofari, R., Bertorelle, G., Ancel, A., Benazzo, A., Le Maho, Y., Ponganis, P.J., Stenseth, N.C., Trathan, P.N., Whittington, J.D., Zanetti, E., et al. (2016). Full circumpolar migration ensures evolutionary unity in the Emperor penguin. Nature Communications 7, 11842.
178. Moon, K.L., Chown, S.L., and Fraser, C.I. (2017). Reconsidering connectivity in the sub-Antarctic. Biological Reviews 92, 2164-2181.
179. Barnes, D.K.A. and Hillenbrand, C.D. (2010). Faunal evidence for a late quaternary trans-Antarctic seaway. Global Change Biology 16, 3297-3303.
180. Chown, S.L., Clarke, A., Fraser C.I., Cary S.C., Moon, K.L. & McGeoch, M.A. (2015). The changing form of Antarctic biodiversity. Nature 522, 427-434.
181. Soler-Membrives, A., Linse, K. Miller, K.J., Arango, C.P. (2017). Genetic signature of Last Glacial Maximum regional refugia in a circum-Antarctic sea spider. Royal Society Open Science 4, 170615
182. Clarke, A., and Crame, J.A. (2010) Evolutionary dynamics at high latitudes: speciation and extinction in polar marine faunas. Philosophical Transactions of the Royal Society B 365, 3655-3666.
183. Collins, G.E., Hogg I.D., Convey P., Barnes A.D. and McDonald I.R. (2019). Spatial and temporal scales matter when assessing the species and genetic diversity of springtails (Collembola) in Antarctica. Frontiers in Ecology and Evolution 7, 76.
184. Basher, Z., and Costello, M.J. (2016). The past, present and future distribution of a deep-sea shrimp in the Southern Ocean. PeerJ – Life &Environment 4, e1713.
185. Trucchi, E., Gratton, P., Whittington, J.D., Cristofari, R., Le Maho, Y., Stenseth, N.C., and Le Bohec, C. (2014). King penguin demography since the last glaciation inferred from genome-wide data, Proceedings of the Royal Society London B, 281, 20140528.
186. Cristofari, R., Liu, X., Bonadonna, F., Cherel, Y., Pistorius, P., Le Maho, Y., Raybaud, V., Stenseth, N.C., Trucchi, E., and Le Bohec, C. (2018). Climate-driven range shifts of King Penguins in a fragmented ecosystem. Nature Climate Change 8, 245-251.
187. Younger, J.L., Emmerson, L.M., and Miller, K.J. (2016). The influence of historical climate changes on Southern Ocean marine predator populations: a comparative analysis. Global Change Biology 22, 474-493.
188. Cabrera, A.A., Schall, E., Bérubé, M., Bachmann, L., Berrow, S., Best, P.B., Clapham, P.J., Cunha, H.A., Rosa, L.D., Dias, C., et al. (2018). Strong and lasting impacts of past global warming on baleen whale and prey abundance. BioRxiv 497388.
189. Yu, Z., Beilman, D.W., and Loisel, J. (2016). Transformations of landscape and peat-forming ecosystems in response to late Holocene climate change in the western Antarctic Peninsula. Geophysical Research Letters, 43, 7186-7195.
190. 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., et al. (2019). Krill (*Euphausia superba*) distribution contracts southward during rapid regional warming. Nature Climate Change 9, 142-147.
191. Sancho, L.G., Pintado, A., Navarro, F., Ramos, M., De Pablo, M.A., Blanquer, J.M., Raggio, R., Valladares, F., and Green, T.G.A (2017). Recent warming and cooling in the Antarctic Peninsula region has rapid and large effects on lichen vegetation. Scientific Reports 7, 5689.

192. O’Brien, K.M. (2016). New Lessons from an old fish: what Antarctic icefishes may reveal about the functions of oxygen-binding proteins. Integrative and Comparative Biology 56, 531-541.
193. 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*. Frontiers in Ecology and Evolution 6, 77.
194. Dornburg, A., Federman, S., Lamb, A.D., Jones, C.D., and Near, T.J. (2017). Cradles and museums of Antarctic teleost biodiversity. Nature. Ecology and Evolution 1, 1379-1384.
195. O’Hara, T.D., Hugall, A.F., Woolley, S.N.C., Bribiesca-Contreras, G., and Bax, N.J. (2019). Contrasting processes drive ophiuroid phylodiversity across shallow and deep seafloors. Nature 565, 636-639.
196. 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.
197. 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.
198. Mikucki, J.A., Auken, E., Tulaczyk, S., Virginia, R.A., Schamper, C., Sorensen, K.I., Doran, P.T., Dugan, H., and Foley, N. (2015). Deep groundwater and potential subsurface habitats beneath an Antarctic dry valley. Nature Communications 6, 6831.
199. Dugan, H.A., Doran, P.T., Tulaczyk, S., Mikucki, J.A., Arcone, S.A., Auken, E., Schamper, C., and Virginia, R.A. (2015). Subsurface imaging reveals a confined aquifer beneath an ice-sealed Antarctic lake. Geophysical Research Letters 42, 96-103.
200. Terauds, A. and Lee, J.R. (2016) Antarctic biogeography revisited: updating the Antarctic Conservation Biogeographic Regions. Diversity and Distributions 22, 836-840.
201. Aronson, R.B., Thatje, S., Clarke, A., Peck, L.S., Blake, D.B., Wilga, C.D., and Seibel, B.A. (2007). Climate change and invasibility of the Antarctic benthos. Annual Review of Ecology, Evolution, and Systematics 38,129-154.
202. Bokhorst, S., Convey, P., Huiskes, A. and Aerts, R. (2016). *Usnea antarctica*, an important Antarctic lichen, is vulnerable to aspects of regional environmental change. Polar Biology 39, 511-521.
203. 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. Nature Climate Change 8, 879.
204. 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. Current Biology 27, 1616-1622.
205. Smith, K.E., Aronson, R.B., Thatje, S., Lovrich, G.A., Amsler, M.O., Steffel, B.V., and McClintock, J.B. (2017). Biology of the king crab *Paralomis birsteini* on the continental slope off the western Antarctic Peninsula. Polar Biology 40, 2313-2322.
206. Ashton, G., Morley, S.A., Barnes, D.K.A., Clark, M.S., Peck, L.S. (2017). Warming by 1°C drives species and assemblage level responses in Antarctica’s marine shallows. Current Biology 27, 2698-2705.
207. Gardner, J., Manno, C., Bakker, D., Peck, V.L., and Tarling, G.A. (2018). Southern Ocean pteropods at risk from ocean warming and acidification. Marine Biology 165, 8.

208. Cross, E., Harper, E,M., and Peck, L.S. (2019). Thicker shells compensate extensive dissolution in brachiopods under future ocean acidification. Environmental Science and Technology 53, 5016-5026.
209. Ingels, J., Aronson, R.B., and Smith, C.R. (2019). The scientific response to Antarctic ice-shelf loss. Nature Climate Change 8, 848-851.
210. Sahade, R., Lagger, C., Torre, L., Momo, F., Monien, P., Schloss, I., Barnes, D.K.A., Servetto, N., Tarantelli, S., Tatián, M., et al. (2015). Climate change and glacier retreat drive shifts in an Antarctic benthic ecosystem. Science Advances 1, 10.
211. Trathan, P.N., Wienecke, B., Barbarud, C., Jenouvrier, S., Kooyman, G., Le Bohec, C., Ainley, D.G., Ancel, A., Zitterbart, D.P., Chown, et al. (in press). The emperor penguin – vulnerable to projected rates of warming and sea ice loss. Biological Conservation.
212. Gutt, J., Adams, B., Bracegirdle, T., Cowan, D., Cummings, V., di Prisco, G., Gradinger, R., Isla, E., McIntyre, T., Murphy, E., et al. (2013). Antarctic Thresholds - Ecosystem Resilience and Adaptation a new SCAR-Biology Programme. Polarforschung 82, 147-150.
213. Gutt, J., Isla, E., Bertler, A.N., Bodeker, G.E., Bracegirdle, T.J., Cavanagh, R.D., Comiso, J.C., Convey, P., Cummings, V., De Conto, R., et al. (2018). Cross-disciplinarity in the advance of Antarctic ecosystem research. Marine Genomics 37, 1-17.
214. 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. Global Change Biology 19, 3749-3761.
215. Kapsenberg, L., Kelley, A.L., Shaw, E.C., Martz, T.R., and Hofmann, G.E. (2015) Near-shore Antarctic pH variability has implications for the design of ocean acidification experiments. Scientific Reports 5, 9638.
216. 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. Nature Ecology & Evolution 1, 1334.
217. Fountain, A.G., Saba, G., Adams, B., Doran, P., Fraser, W., Gooseff, M., Obryk, M., Priscu, J.C., Stammerjohn, S., and Virginia, R.A. (2016). The impact of a large-scale climate event on Antarctic ecosystem processes. BioScience 66, 848-863.
218. Clark, M.S., Nieve, L.V., Hoffman, J.L., Davies, A.L., Trivedi, U.H., Tuner, F., Ashton, G.V. and Peck, L.S. (in press). No long-term acclimation in Antarctic encrusting species: vulnerabilities in a warmer world. Nature Communications.
219. Cross, E.L., Peck, L.S., and Harper, E.M. (2015). Ocean acidification does not impact shell growth or repair of the Antarctic brachiopod *Liothyrella uva* (Broderip, 1833). Journal of Experimental Marine Biology and Ecology 462, 29-35.
220. Henley, S.F., Schofield, O.M., Hendry, K.R., Schloss, I.R., Steinberg, D.K., Moffat, C., Peck, L.S., Costa, D.P., Bakker, D.C.E., Hughes, C., et al. (2019). Variability and change in the west Antarctic Peninsula marine system: Research priorities and opportunities. Progress in Oceanography 173, 208-237.
221. Petrou, K., Kranz, S., Trimborn, S., Hassler, C.S., Blanco Ameijeiras, S., Sackett, O., Beardall, J., Davidson, A., and Ralph, P.J. (2016). Southern Ocean phytoplankton physiology in a changing climate. Journal of Plant Physiology 203, 135-150.
222. Schoenrock, K.M., Schram, J.B., Amsler, C.D., McClintock, J.B. and Angus, R.A. 2015. Climate change impacts on overstory *Desmarestia* spp. from the western Antarctic Peninsula. Marine Biology 162, 377-389.

223. Suckling, C., Clark, M.S., Richard, J., Morley, S.A., Thorne, M.A.S., Harper, E.M., and Peck, L.S. (2015). Adult acclimation to combined temperature and pH stressors significantly enhances reproductive outcomes compared to short-term exposures. Journal of Animal Ecology 84, 773-784.
224. Bergstrom, D.M., Bricher, P.K., Raymond, B., Terauds, A., Doley, D., McGeoch, M.A., Whinam, J., Glen, M., Yuan, Z., Kiefer, K., et al. (2015). Rapid collapse of a sub-Antarctic alpine ecosystem: the role of climate and pathogens. Journal of Applied Ecology 52, 774-783.
225. Janion-Scheepers, C., Phillips, L., Sgrò, C.M., Duffy, G.A., Hallas, R., and Chown, S.L. (2018). Basal resistance enhances warming tolerance of alien over indigenous species across latitude. Proceedings of the National Academy of Sciences of the United States of America 115, 145–150.
226. Haver, S.M., Klinck, H., Nieukirk, S.L., Matsumoto, H., Dziak, R.P., and Miksis-Olds, J.L. (2017). The not-so-silent world: Measuring Arctic, Equatorial, and Antarctic soundscapes in the Atlantic Ocean. Deep-Sea Research Part I: Oceanographic Research Papers 122, 95-104.
227. Van Opzeeland I., and Boebel O. (2018). Marine soundscape planning: Seeking acoustic niches for anthropogenic sound. Journal of Ecoacoustics. 2, #5GSNT8.
228. 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. Environmental Pollution 250, 953-959.
229. 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. Environmental Pollution, 237, 824-831.
230. 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. Science of the Total Environment, 505, 180-188.
231. Seco, J., Xavier, J.C., Coelho, J.P., Pereira, B., Tarling, G., Pardal, M.A., Bustamante, P., Stowasser, G., Brierley, A.S. and Pereira, M.E. (2019). Spatial variability in total and organic mercury levels in Antarctic krill *Euphausia superba* across the Scotia Sea. Environmental Pollution, 247, 332-339.
232. Potapowicz, J., Szumińska, D., Szopińska, M., Polkowska, Z. (2019). The influence of global climate change on the environmental fate of anthropogenic pollution released from the permafrost Part I. Case study of Antarctica. Science of the Total Environment, 651, 1534-1548.
233. Wilcox, C., Sebille, E.V., and Hardesty, B.D. (2015). Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proceedings of the National Academy of Sciences of the United States of America 112, 11899–11904.
234. Isobe, A., Uchiyama-Matsumoto, K., Uchida, K., and Tokai, T. (2017). Microplastics in the Southern Ocean. Marine Pollution Bulletin 114, 623–626.
235. Lacerda, A.L. d F., Rodrigues, L. dos S., Sebille, E. van, Rodrigues, F.L., Ribeiro, L., Secchi, E.R., Kessler, F., and Proietti, M.C. (2019). Plastics in sea surface waters around the Antarctic Peninsula. Scientific Reports 9.
236. 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. Science of the Total Environment 598, 220-227.

237. Wang, P., Li, Y., Zhang, Q., Yang, Q., Zhang, L., Liu, F., Fu, J., Meng, W., Wang, D., Sun, H., et al. (2017). Three-year monitoring of atmospheric PCBs and PBDEs at the Chinese Great Wall Station, West Antarctica: Levels, chiral signature, environmental behaviors and source implication. Atmospheric Environment 150, 407–416.
238. Pozo, K., Martellini, T., Corsolini, S., Harner, T., Estellano, V., Kukučka, P., Mulder, M.D., Lammel, G., and Cincinelli, A. (2017). Persistent organic pollutants (POPs) in the atmosphere of coastal areas of the Ross Sea, Antarctica: indications for long-term downward trends. Chemosphere 178, 458-465.
239. Bengtson Nash, S.M., Wild, S.J., Hawker, D.W., Cropp, R.A., Hung, H., Wania, F., Xiao, H., Bohlin-Nizzetto, P., Bignert, A., and Broomhall, S. (2017). Persistent Organic Pollutants in the East Antarctic Atmosphere: Inter-Annual Observations from 2010 to 2015 Using High-Flow-Through Passive Sampling. Environmental Science & Technology 51, 13929-13937.
240. Sancho, L.G., Pintado, A., and Green, T.G.A. (2019). Antarctic studies show lichens to be excellent biomonitors of climate change. Diversity 11, 42.
241. Casey, K.A., Kaspari, S.D., Skiles, S.M., Kreutz, K. and Handley, M.J. (2017). The spectral and chemical measurement of pollutants on snow near South Pole, Antarctica. Journal of Geophysical Research Atmospheres 122, 6592-6610.
242. Houghton, M., McQuillan, P.B., Bergstrom, D.M., Frost, L., Hoff, J. van den, and Shaw, J. (2016). Pathways of alien invertebrate transfer to the Antarctic region. Polar Biology 39, 23-33.
243. Newman, J., Poirot, C., Roper-Gee, R., Leihy, R.I., and Chown, S.L. (2018). A decade of invertebrate colonization pressure on Scott Base in the Ross Sea region. Biological Invasions 20, 2623-2633.
244. McCarthy, A., Peck, L.S., Hughes, K. and Aldridge, D.A. (2019). Antarctica: the final frontier for marine biological invasions. Global Change Biology 2019, 1-21.
245. Phillips, L., Janion-Scheepers, C., Houghton, M., Terauds, A., Potapov, M., and Chown, S.L. (2017). Range expansion of two invasive springtails on sub-Antarctic Macquarie Island. Polar Biology 40, 2137-2142.
246. Enríquez, N., Pertierra, L.R., Tejedo, P., Benayas, J., Greenslade, P., and Luciáñez, M.J. (2019). The importance of long-term surveys on species introductions in Maritime Antarctica: first detection of *Ceratophysella succinea* (Collembola: Hypogastruridae). Polar Biology 42, 1047–1051.
247. Duffy, G.A., Coetzee, B.W.T., Latombe, G., Akerman, A.H., McGeoch, M.A., and Chown, S.L. (2017). Barriers to globally invasive species are weakening across the Antarctic. Diversity and Distributions 23, 982–996.
248. Pertierra, L.R., Aragón, P., Shaw, J.D., Bergstrom, D.M., Terauds, A., and Olalla-Tárraga, M.Á. (2017). Global thermal niche models of two European grasses show high invasion risks in Antarctica. Global Change Biology 23, 2863–2873.
249. Mathakutha, R., Steyn, C., Roux, P.C. le, Blom, I.J., Chown, S.L., Daru, B.H., Ripley, B.S., Louw, A., and Greve, M. (in press). Invasive species differ in key functional traits from native and non-invasive alien plant species. Journal of Vegetation Science https://doi.org/10.1111/jvs.12772
250. Cannone, N., Guglielmin, M., Convey, P., Worland, M.R., and Longo, S.E.F. (2016). Vascular plant changes in extreme environments: effects of multiple drivers. Climatic Change 134, 651-665.

251. Adriaenssens, E.M., Kramer, R., Van Goethem, M.W., Makhalanyane, T.P., Hogg, I., and Cowan, D.A. (2017). Environmental drivers of viral community composition in Antarctic soils identified by viromics. Microbiome 5, e83.
252. Aguirre de Cárcer, D., López-Bueno, A., Alonso-Lobo, J. M., Quesada, A., and ,Alcami, A. (2016). Metagenomic analysis of lacustrine viral diversity along a latitudinal transect of the Antarctic Peninsula. FEMS Microbiology Ecology 92, fiw074.
253. Miranda, J.A., Culley, A.I., Schvarcz, C.R., and Steward, G.F. (2016). RNA viruses as major contributors to Antarctic virioplankton. Environmental Microbiology 18, 3714-3727.
254. Smeele, Z.E., Ainley, D.G., and Varsani, A. (2018). Viruses associated with Antarctic wildlife: From serology-based detection to identification of genomes using high throughput sequencing. Virus Research 243, 91-105.
255. Cavicchioli, R. and Erdmann, S. (2015). The discovery of Antarctic RNA viruses: A new game changer. Molecular Ecology 24, 4809-4811.
256. Cristina, J., (2019) Molecular biology of RNA viruses isolated in Antarctica. the ecological role of microorganisms in the Antarctic environment, In: Castro-Sowinski S. (eds) The Ecological Role of Micro-organisms in the Antarctic Environment. Springer Polar Sciences. Springer, Berlin, pp.197-217.
257. Evans, C., Brandsma, J., Pond, D.W., and Venables, H.J. (2017). Drivers of interannual variability in virioplankton abundance at the coastal western Antarctic peninsula and the potential effects of climate change. Environmental Microbiology 19, 740-755.
258. De Souza Petersen, E, de Araujo, J., Kruger, L., Seixas, M., Ometto, T. Thomazelli, L.M., Walker, D., Durigon, E.L., Petry, M.V. (2017). First detection of avian influenza virus (H4N7) in Giant Petrel monitored by geolocators in the Antarctic region. Marine Biology 164, 62.
259. Wille, M., Aban, M., Wang, J., Moore, N., Shan, S., Marshall J., González-Acuña D., Vijaykrishna, D., Butler, J., Wang, J., Hall, R.J., Williams, D.T., and Hurt, A.C. (2019). Antarctic penguins as reservoirs of diversity for avian avulaviruses. Journal of Virology 93, e00271-19.
260. Lee, J.E., and Chown, S.L. (2007). *Mytilus* on the move: transport of an invasive bivalve to the Antarctic. Marine Ecology Progress Series 339, 307-310.
261. Peck, L.S. (2018). Antarctic marine biodiversity: adaptations, environments and responses to change. Oceanography and Marine Biology - An Annual Review 56, 105-236.
262. Atkinson, A., Siegel, V., Pakhomov, E.A., Rothery, P., Loeb, V., Ross, R.M., Quetin, L.B., Schmidt, K., Fretwell, P., Murphy, E.J., Tarling, G.A., and Fleming, A.H. (2008). Oceanic circumpolar habitats of Antarctic krill. Marine Ecology Progress Series 362, 1-23.

263. Reiss, C.S., Cossio, A., Santora, J.A., Dietrich, K.S., Murray, A., Mitchell, B.G., Walsh, J., Weiss, E.L., Gimpel, C., Jones, C.D., and Watters, G.M. (2017). Overwinter habitat selection by Antarctic krill under varying sea-ice conditions: implications for top predators and fishery management. Marine Ecology Progress Series 568, 1-16.
264. Reid, K. (2018) Climate change Impacts, vulnerabilities and adaptations: Southern Ocean marine fisheries. In Impacts of climate change on fisheries and aquaculture, ed. M. Barange, T. Bahri, M.C.M. Beveridge, K.L Cochrane, S. Funge-Smith, and F. Poulain, pp. 363–373. (FAO Fisheries and Aquaculture Technical Paper 67, Rome).
265. 268. Nicol, S., and Foster, J. (2016). The fishery for Antarctic krill – its current status and management regime. In Biology and ecology of Antarctic krill, ed. V. Siegel, pp. 387–421. (Springer, Berlin

266. Piñones, A., and Fedorov, A.V. (2016). Projected changes of Antarctic krill habitat by the end of the 21st century, Geophysical Research Letters 43, 8580–8589.
267. Trathan, P.N., Warwick-Evans, V., Hinke, J.T., Young, E.F., Murphy, E.J., Carneiro, A.P.B., Dias, M.P., Kovacs, K.M., Lowther, A.D., Godø, O.R., et al. (2018). Managing fishery development in sensitive ecosystems: identifying penguin habitat use to direct management in Antarctica. Ecosphere 9, e02392.
268. Meredith, M.P., Stammerjohn, S.E., Venables, H.J., Ducklow, H.W., Martinson, D.G., Iannuzzi, R.A., Leng, M.J., van Wessem, J.M., Reijmer, C.H., and Barrand, N.E. (2017). Changing distributions of sea ice melt and meteoric water west of the Antarctic Peninsula. Deep-Sea Research Part Ii-Topical Studies in Oceanography 139, 40-57.
269. Fuentes, V., Alurralde, G., Meyer, B., Aguirre, G.E., Canepa, A., Wolfl, A.C., Hass, H.C., Williams, G.N., and Schloss, I.R. (2016). Glacial melting: an overlooked threat to Antarctic krill. Scientific Reports 6, 27234.
270. Lagger, C., Servetto, N., Torre, L., and Sahade, R. (2017). Benthic colonization in newly ice-free soft-bottom areas in an Antarctic fjord. PLoS One 12, 1e0186756.
271. Lagger, C., Nime, M., Torre, L., Servetto, N., Tatián, M., and Sahade, R. (2018). Climate change, glacier retreat and a new ice-free island offer new insights on Antarctic benthic responses. Ecography 141, 579–591.
272. Treasure, A.M., Ruzicka, J.J., Moloney, C.L., Gurney, L.J., and Ansorge, I.J. (2015) Land–sea interactions and consequences for sub-Antarctic marine food webs. Ecosystems 18, 752-768.
273. Ramirez-Fernandez, L., Trefault, N., Caru, M. and Orlando, J. (2019). Seabird and pinniped shape soil bacterial communities of their settlements in Cape Shirreff, Antarctica. PLOS One 14, e0209887.
274. Grange, L.J. and Smith, C.R. (2013). Megafaunal communities in rapidly warming fjords along the West Antarctic Peninsula: Hotspots of abundance and beta diversity. PLOS One 8, e77917.
275. Wlodarska-Kowalczuk, M. Pearson, T.H. and Kendall, M.A. (2005). Benthic response to chronic natural physical disturbance by glacial sedimentation in an Arctic fjord. Marine Ecology Progress Series 303, 31–41.
276. Constable, A.J., Melbourne-Thomas, J., Corney, S.P., Arrigo, K.R., Barbraud, C., Barnes, D.K.A., Bindoff, N.L., Boyd, P.W., Brandt, A., Costa, D.P., et al. (2014). Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. Global Change Biology 20, 3004-3025.
277. St-Laurent, P., Yager, P.L., Sherrell, R.M., Oliver, H., Dinniman, M.S., and Stammerjohn, S.E. (2019). Modeling the seasonal cycle of Iron and Carbon fluxes in the Amundsen Sea Polynya, Antarctica. Journal of Geophysical Research-Oceans 124, 1544-1565.
278. Cape, M.R., Vernet, M., Kahru, M., and Spreen, G. (2014). Polynya dynamics drive primary production in the Larsen A and B embayments following ice shelf collapse. Journal of Geophysical Research-Oceans 119, 572-594.
279. Cape, M.R., Vernet, M., Pettit, E.C., Wellner, J., Truffer, M., Akie, G., Domack, E., Leventer, A., Smith, C.R., and Huber, B.A. (2019). Circumpolar deep water impacts glacial meltwater export and coastal biogeochemical cycling along the West Antarctic Peninsula. Frontiers in Marine Science doi: 10.3389/fmars.2019.00144.
280. Wallis, J.R., Swadling, K.M., Everett, J.D., Suthers, I.M., Jones, H.J., Buchanan, P.J., Crawford, C.M., James, L.C., Johnson, R., Meiners, K.M., et al. (2016). Zooplankton abundance and biomass size spectra in the East Antarctic sea-ice zone during the winter–

spring transition. Deep Sea Research Part II: Topical Studies in Oceanography 131, 170–181.
281. Michel, L.N., Danis, B., Dubois, P., Eleaume, M., Fournier, J., Gallut, C., Jane, P., and Lepoint, G. (2019). Increased sea ice cover alters food web structure in East Antarctica. Scientific Reports 9, 8062.
282. Nielsen, U.N., Wall, D.H., Adams, B.J., Virginia, R.A., Ball, B.A., Gooseff, M.N., and McKnight, D.M. (2012). The ecology of pulse events: insights from an extreme climatic event in a polar desert ecosystem. Ecosphere 3, art17.
283. Getzlaff, J., and Oschlies, A. (2017). Pilot Study on potential impacts of fisheries-induced changes in zooplankton mortality on marine biogeochemistry. Global Biogeochemical Cycles 31, 1656–1673.
284. Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., and Saba, V. (2018). Observed fingerprint of a weakening Atlantic overturning circulation Nature 556, 191-196.
285. Jenkyns, H.C. (2010). Geochemistry of oceanic anoxic events. Geochemistry, Geophysics, Geosystems 11, Q03004.
286. Nakayama, Y., Menemenlis, D., Zhang, H., Schodlok, M., and Rignot, E. (2018). Origin of circumpolar deep water intruding onto the Amundsen and Bellingshausen Sea continental shelves. Nature Communications 9, 3403.
287. Brandt, A., De Broyer, C., Ebbe, B., Ellingsen, K. E., Gooday, A. J., Janussen, D., Kaiser, S., Linse, K., Schueller, M., Thomson, M.R.A., et al. (2012). Southern Ocean deep benthic biodiversity. In Antarctic Ecosystems: An Extreme Environment in a Changing World, ed. A.D. Rogers, N.M. Johnston, E.J. Murphy, and A. Clarke, pp. 291–334. (Oxford: Blackwell Publishing Ltd.).
288. Lescroël, A., Ballard, G., Gremillet, D., Authier, M., and Ainley, D.G. (2014). Antarctic climate change: extreme events disrupt plastic phenotypic response in Adélie penguins. PLoS One 9, e85291.
289. Andriuzzi, W.S., Adams, B.J., Barett, J.E., Virginia, R.A., and Wall, D.H. (2018) Observed trends of soil fauna in the Antarctic Dry Valleys: early signs of shifts predicted under climate change. Ecology 99, 312-321.
290. Rydt, J.D., Gudmundsson, G.H., Nagler, T., and Wuite, J. (2019). Calving cycle of the Brunt Ice Shelf, Antarctica, driven by changes in ice-shelf geometry. The Cryosphere Discussions, 1–19.
291. Fretwell, P.T., and Trathan, P.N. (2019). Emperors on thin ice: three years of breeding failure at Halley Bay. Antarctic Science 31, 133-138.
292. 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.
293. Steinhoff, D. F., Bromwich, D.H., Speirs, J.C., McGowan, H.A., and Monaghan A.J. (2014) Austral summer foehn winds over the McMurdo Dry Valleys of Antarctica from Polar WRF. Quarterly Journal of the Royal Meteorological Society 140, 1825-1837.
294. Zou, X., Bromwich, D.H., Nicolas, J.P., Montenegro, A. and Wang, S.-H. (2019) West Antarctic surface melt event of January 2016 facilitated by foehn warming. Quarterly Journal of the Royal Meteorological Society 145, 687-704.
295. Kobelkova, A., Goto, S.G., Peyton, J.T., Ikeno, T., Lee, R.E., and Denlinger, D.L. (2015). Continuous activity and no cycling of clock genes in the Antarctic midge during the polar summer. Journal of Insect Physiology 81, 90–96.

296. Hamm, J.N., Erdmann, S., Eloe-Fadrosh, E.A., Angeloni, A., Zhong, L., Brownlee, C., Williams, T.J., Barton, K., Carswell, S., Smith, M.A., et al. (2019). Unexpected host dependency of Antarctic Nanohaloarchaeota. Proceedings of the National Academy of Sciences of the United States of America 116, 14661–14670.
297. Chou, L., Kenig, F., Murray, A.E., Fritsen, C.H., and Doran, P.T. (2018). Effects of legacy metabolites from previous ecosystems on the environmental metabolomics of the brine of Lake Vida, East Antarctica. Organic Geochemistry 122, 161–170.
298. Tschitschko, B., Erdmann, S., DeMaere, M.Z., Roux, S., Panwar, P., Allen, M.A., Williams, T.J., Brazendale, S., Hancock, A.M., Eloe-Fadrosh, E.A., et al. (2018). Genomic variation and biogeography of Antarctic haloarchaea. Microbiome 6, 113.
299. Niederberger, T.D., Bottos, E.M., Sohm, J.A., Gunderson, T., Parker, A., Coyne, K.J., Capone, D.G., Carpenter, E.J., and Cary, S.C. (2019). Rapid microbial dynamics in response to an induced wetting event in Antarctic dry valley soils. Frontiers in Microbiology 10, doi: doi.org/10.3389/fmicb.2019.00621.
300. Santora, J.A., Veit, R.R., Reiss, C.S., Schroeder, I.D., Mangel, M. (2017). Ecosystem oceanography of seabird hotspots: environmental determinants and relationship with Antarctic krill within an important fishing ground. Ecosystems 20, 885-903.
301. Roquet, F., Boehme, L., Block, B., Charrassin, J.-B., Costa, D., Guinet, C., Harcourt, R.G., Hindell, M.A., Hückstädt, L.A., McMahon, C.R., et al. (2017). Ocean observations using tagged animals. Oceanography 30, 139.
302. Reisinger, R.R., Raymond, B., Hindell, M.A., Bester, M.N., Crawford, R.J.M., Davies, D., de Bruyn, P.J.N., Dilley, B.J., Kirkman, S.P., Makhado, A.B., et al. (2018). Habitat modelling of tracking data from multiple marine predators identifies important areas in the Southern Indian Ocean. Diversity and Distributions 24, 535-550.
303. Smith, D., McGee, J., and Jabour, J. (2016). Marine protected areas: a spark for contestation over ‘rational use’ of Antarctic marine living resources in the Southern Ocean? Journal Australian Journal of Maritime and Ocean Affairs 8, 180-198.
304. Brooks, C.M. (2013). Competing values on the Antarctic high seas: CCAMLR and the challenge of marine-protected areas. The Polar Journal 3, 277-300.
305. 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.
306. Jacquet, J., Blood-Patterson, E., Brooks, C., and, Ainley, D. (2016). ‘Rational use’ in Antarctic waters. Marine Policy 63, 28-34.
307. Liu, N., and Brooks, C.M. (2018). China's changing position towards marine protected areas in the Southern Ocean: Implications for future Antarctic governance. Marine Policy 94, 189-195.
308. Antarctic Genetic Archive, https://ictar.aq/antarctic-genetic-archive/
309. Puig-Marcó, R. (2014). Access and benefit sharing of Antarctica’s Biological Material. Marine Genomics 17, 73–78.
310. 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.
311. O’Hara, T.D., Hugall, A.F., Woolley, S.N.C., Bribiesca-Contreras, G., and Bax, N.J. (2019). Contrasting processes drive ophiuroid phylodiversity across shallow and deep seafloors. Nature 565, 636.

312. De Broyer, C., Koubbi, P., Griffiths, H.J., Raymond, B., D'Acoz, C.d.U., van de Putte, A., Danis, B., David, B., Grant, S.M., Gutt, J., et al. (2014). Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research, Cambridge.
313. Douglass, L.L., Turner, J., Grantham, H.S., Kaiser, S., Constable, A., Nicoll, R., Raymond, B., Post, A., Brandt, A., and Beaver, D. (2014). A hierarchical classification of benthic biodiversity and assessment of protected areas in the Southern Ocean. PLoS One 9, e100551.
314. 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 Biology 12, e1001888.
315. Wauchope, H.S., Shaw, J.D. and Terauds, A. (2019). A snapshot of biodiversity protection in Antarctica. Nature Communications 10, 946.
316. Hughes, K.A. and Convey, P. (2010). The protection of Antarctic terrestrial ecosystems from inter- and intra-continental transfer of non-indigenous species by human activities: A review of current systems and practices. Global Environmental Change 20, 96-112.
317. Brooks, C.M., and Ainley, D.G. (2017). Fishing the bottom of the Earth: the political challenges of ecosystem-based management. In Handbook on the Politics of Antarctica, ed. K. Dodds, A.D. Hemmings, P. and Roberts, pp. 422-438. (Cheltenham: Edward Elgar).
318. Staggs, S., Dunkley, J. and Page L. (2018). Recent discoveries from the cosmic microwave background: a review of recent progress. Reports on Progress in Physics 81, 044901.
319. 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. Astrophysical Journal 870, 134.
320. Burns E., Tohuvavohu, A., Bellovary J.M., Blaufuss, E., Brandt, T.J., Buson, S., Caputo, R., Cenko, S.B., Christensen, N., Conklin, J.W., D'Ammando, F., et al. (2019). Astro2020 Science White Paper, Opportunities for Multimessenger Astronomy in the 2020s. Retrieved from: https://arxiv.org/abs/1903.04461
321. Ellis, J., Hektor, A., Hütsi, G., Kannike, K., Marzola, L., Raidal, M., and Vaskonen, V. (2018). Search for dark matter effects on gravitational signals from neutron star mergers. Physics Letters B 781, 607-610.
322. Gaisser, T., and Halzen, F. (2014). IceCube. Annual Review of Nuclear Particle Science 64, 101-123.
323. The Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Baczko, A.-K., Ball, D., Baloković, M., Barrett, J., et al. (2019). First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole. Astrophysical Journal Letters 875, L6.
324. France, J.A., Randall, C.E., Lieberman, R.S., Harvey, V.L., Eckermann, S.D., Siskind, D.E., et al. (2018). Local and remote planetary wave effects on polar mesospheric clouds in the Northern Hemisphere in 2014. Journal of Geophysical Research: Atmospheres 123, 5149-5162.
325. Goldstein, J., and McComas, D.J. (2018). The Big Picture: Imaging of the Global Geospace Environment by the TWINS Mission. Reviews of Geophysics 56, 251–277.
326. 328. Kim, H., Clauer, C.R., Gerrard, A.J., Engebretson, M.J., Hartinger, M.D., Lessard, M.R., Matzka, J., Sibeck, D.G., Singer, H.J., Stolle, C., et al. (2017). Conjugate

observations of electromagnetic ion cyclotron waves associated with traveling convection vortex events. Journal of Geophysical Research and Space Physics 122, 7336–7352
327. Baker, D.N., and Lanzerotti, L.J. (2016). Resource Letter SW1: Space Weather. American Journal of Physic 84,166.
328. Lanzerotti, L.J. (2017). Space Weather: Historical and Contemporary Perspectives. Space Science Reviews 212, 1253–1270.
329. Perry, G. W. and St.-Maurice, J.P. (2018). A Polar-Cap Patch Detection Algorithm for the Advanced Modular Incoherent Scatter Radar System. Radio Science 53(10), 1225–1244.
330. Sojka, J.J. (2017). Locations Where Space Weather Energy Impacts the Atmosphere. Space Science Reviews 212, 1041–1067.
331. de Wit, R.J., Hibbins, R.E., Espy, P.J., and Hennum, E.A. (2015). Coupling in the middle atmosphere related to the 2013 major sudden stratospheric warming. Annals of Geophysics 33, 309–319.
332. Mehta, D., Gerrard, A.J., Ebihara, Y. Weatherwax, A.T., and Lanzerotti, L.J. (2017), Short-period mesospheric gravity waves and their sources at the South Pole, Atmospheric Chemistry and Physics, 17, 911–919.
333. Orr, A., Hosking, J.S., Hoffmann, L., Keeble, J., Dean, S.M., Roscoe, H.K., Abraham, N.L., Vosper, S., and Braesicke, P. (2015). Inclusion of mountain-wave-induced cooling for the formation of PSCs over the Antarctic Peninsula in a chemistry–climate model. Atmospheric Chemistry and Physics, 15, 1071-1086.
334. Chown, S.L., Brooks, C.M., Terauds, A., Bohec, C.L., Klaveren-Impagliazzo, C. van, 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 Biology 15, e2001656.
335. Stephens, T. (2018). The Antarctic Treaty System and the Anthropocene. The Polar Journal 8, 29–43.
336. Gladkova, E.N., Blanco-Wells, G., and Nahuelhual, L. (2018). Facing the climate change conundrum at the South Pole: actors’ perspectives on the implications of global warming for Chilean Antarctic governance. Polar Research 37, 1468195.
337. Brooks, S.T., Jabour, J., and Bergstrom, D.M. (2018). What is ‘footprint’ in Antarctica: proposing a set of definitions. Antarctic Science 30, 227–235.
338. Carver, S., and Tin, T. (2015). A Big Blank White Canvas? Mapping and Modelling Human Impact In Antarctica. Science and Stewardship to Protect and Sustain Wilderness Values: Tenth World Wilderness Congress Symposium 2013, 116–12.
339. Summerson, R., and Tin, T. (2018). Twenty years of protection of wilderness values in Antarctica. The Polar Journal 8, 265-288.
340. Pertierra, L. R., Hughes, K. A., Vega, G. C., and Olalla-Tárraga, M. A. (2017). High resolution spatial mapping of human footprint across Antarctica and its implications for the strategic conservation of avifauna. PLoS ONE 12, e0173649.
341. Moore, J.C., Gladstone, R., Zwinger, T., and Wolovick, M. (2018). Geoengineer polar glaciers to slow sea-level rise. Nature 555, 303–305.
342. Wolovick, M.J., and Moore, J.C. (2018). Stopping the flood: could we use targeted geoengineering to mitigate sea level rise? The Cryosphere 12, 2955–2967.
343. Chaturvedi, S. (2018). The future of Antarctica: minerals, bioprospecting, and fisheries. In The Routledge Handbook of the Polar Regions, ed. M. Nuttall, T.R. Christensen, and M. Siegert. (Abingdon, Oxon; New York, NY: Routledge).
344. Dodds, K., Hemmings, A.D., and Roberts, P. (2017). Handbook on the Politics of Antarctica. Edward Elgar Publishing.

345. Harrington, J. (2017). China, Global Ecopolitics and Antarctic Governance: Converging Paths? Journal of Chinese Political Science 22, 37–56.
346. Liu, N. (2019). The rise of China and the Antarctic Treaty System? Australian Journal of Maritime and Ocean Affairs, 1–12.
347. Brady, A.-M. (2017). China as a Polar Great Power. Cambridge University Press.
348. Elzinga, A. (2017). The continent for science. In Handbook on the Politics of Antarctica, ed. K. Dodds, A.D. Hemmings, and P. Roberts, pp. 103–124. (Edward Elgar Publishing).
349. Tamm, S. (2018). Peace vs. compliance in Antarctica: inspections and the environment. The Polar Journal 8, 333–350.
350. Jabour, J. (2014). Strategic Management and Regulation of Antarctic Tourism. Antarctic Futures, 273–286.
351. Liggett, D., and Stewart, E.J. (2017). Sailing in icy waters: Antarctic cruise tourism development, regulation and management. Cruise Ship Tourism, 484–504.
352. Student, J., Amelung, B., and Lamers, M. (2016). Towards a tipping point? Exploring the capacity to self-regulate Antarctic tourism using agent-based modelling. Journal of Sustainable Tourism 24, 412-429.
353. Verbitsky, J. (2013). Antarctic tourism management and regulation: the need for change. Polar Record 49, 278-285.
354. Liggett, D., Frame, B., Gilbert, N., and Morgan, F. (2017). Is it all going south? Four future scenarios for Antarctica. Polar Record 53, 459-478.
355. Stewart, E.J., Liggett, D., and Dawson, J. (2017). The evolution of polar tourism scholarship: research themes, networks and agendas. Polar Geography 40, 59-84.
356. Bender, N. A., Crosbie, K., and Lynch, H. J. (2016). Patterns of tourism in the Antarctic Peninsula region: A 20-year analysis. Antarctic Science 28, 194-203.
357. Keyuan, Z., and Xinchang, L. (2015). New Trends in China's Practice in Antarctic Expedition Management. The International Journal of Marine and Coastal Law 30, 533-550.
358. Luo, F., Becken, S. and Zhong, Y(2018). Changing travel patterns in China and "carbon footprint" implications for a domestic tourist destination. Tourism Management 65, 1–13.
359. Delgado, L.E., and Marín, V.H. (2015). Ecosystem services: Where on earth? Ecosystem Services 14, 24-26.
360. Grant, S.M., Hill, S.L., Trathan, P.N., and Murphy, E.J. (2013). Ecosystem services of the Southern Ocean: trade-offs in decision-making. Antarctic Science 25, 603.
361. Verbitsky, J. (2018). Ecosystem services and Antarctica: the time has come? Ecosystem Services 29, 381–394.
362. Deininger, M., Koellner, T., Brey, T., and Teschke, K. (2016). Towards mapping and assessing Antarctic marine ecosystem services – The Weddell Sea case study. Ecosystem Services 22, 174–192.
363. 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? Science of The Total Environment 654, 190–196.
364. 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 21$^{st}$century Antarctic and Southern Ocean science. Antarctic Science 28, 407-423.
365. 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.

366. Gutt, J., Isla, E., Bertler, A.N., Bodeker, G.E., Bracegirdle, T.J., Cavanagh, R.D., Comiso, J.C., Convey, P., Cummings, V., De Conto, R., et al. (2018). Cross-disciplinarity in the advance of Antarctic ecosystem research. Marine Genomics 37, 1-17.
367. McCarthy, A.H., Peck, L.S., Hughes, K.A., and Aldridge, D.C. (2019). Antarctica: The final frontier for marine biological invasions. Global Change Biology 25, 2221-2241.
368. Xavier, J.C., Brandt, A., Ropert-Coudert, Y., Badhe, R., Gutt, J., Havermans, C., Jones, C., Costa, E.S., Lochte, K., Schloss, I.R., et al. (2016). Future Challenges in Southern Ocean Ecology Research. Frontiers in Marine Science 3.
369. National Academies of Sciences, Engineering, and Medicine. (2015). A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research. Washington, DC: The National Academies Press.
370. Thwaites: The Future of Thwaites Glacier and its Contribution to Sea-level Rise, NSF, https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505320
371. Ansorge, I.J., Skelton, P., Bekker, A., De Bruyn, N., Butterworth, D., Cilliers, P., Cooper, J., Cowan, D., Dorrington, R., Fawcett, S., et al. (2017). Exploring South Africa's southern frontier: A 20-year vision for polar research through the South African National Antarctic Programme. South African Journal of Science 113, 1-7.
372. Antarctic Treaty System (ATS), https://www.ats.aq/e/ats.htm
373. Antarctic Treaty Consultative Meetings (ATCMs), https://www.ats.aq/devAS/ats_meetings.aspx?lang=e
374. Scientific Committee on Antarctic Research (SCAR), https://www.scar.org/
375. The Committee on Environmental Protection (CEP), https://www.ats.aq/e/cep.htm
376. The Convention on the Conservation of Antarctic Marine Living Resources Scientific Committee (SC-CCAMLR), https://www.ccamlr.org/en/science/scientific-committee
377. The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), https://www.ccamlr.org/en/organisation/camlr-convention
378. Antarctic Science Horizon Scan, https://www.scar.org/about-us/horizon-scan/overview/
379. SCAR Structural Review, https://scar.org/scar-library/reports-and-bulletins/scar-bulletins/2634-scar-bulletin-192/file/
380. SCAR Strategic Plan 2017-2022, https://www.scar.org/about-us/futureplans/strategic-plan/
381. SCAR Past Antarctic Ice Sheets, https://www.scar.org/science/pais/pais/
382. SCAR Antarctic Near Shore Terrestrial Observing System, https://www.scar.org/scar-library/search/science-4/physical-sciences/antos/3446-2015-antos-workshop-report/
383. Council of Managers of National Antarctic Programs (COMNAP), https://www.comnap.aq/SitePages/Home.aspx
384. COMNAP Antarctic Roadmap Challenges Project, https://www.comnap.aq/Projects/SitePages/ARC.aspx
385. Antarctic Science Horizon Scan media activities, https://www.scar.org/about-us/horizon-scan/results/
386. Tinker Foundation, https://www.tinker.org/
387. Antarctic Treaty Parties (2019), https://www.ats.aq/devAS/ats_parties.aspx?lang=e
388. The Convention on the Conservation of Antarctic Marine Living Resources membership, https://www.ccamlr.org/en/organisation/membership
389. Convention for the Regulation of Whaling, https://iwc.int/home
390. Convention for the Conservation of Antarctic Seals, https://www.ats.aq/e/ats_related.htm

391. Scientific Committee on Antarctic Research (SCAR) membership (2019), https://www.scar.org/about-us/members/detailed-information/
392. Council of Managers of National Antarctic Programs (COMNAP) membership (2019), https://www.comnap.aq/Members/SitePages/Home.aspx
393. Antarctic Southern Ocean Coalition (ASOC), https://www.asoc.org/
394. International Association of Antarctic Tour Operators (IAATO), https://iaato.org/home