Antarctic Climate Change and the Environment: A Decadal Synopsis and Recommendations for Action

Compiled by:

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The report has been compiled from the findings presented in the reports of the *Intergovernmental Panel on Climate Change* predominantly, and of the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.

The IPCC reports are cited extensively in this document and provide the foundation for the majority of this report's findings. The IPCC and IPBES reports should be consulted and are available at:

Intergovernmental Panel on Climate Change
https://www.ipcc.ch/about/

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
https://www.ipbes.net/

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Summary

Scientific evidence is abundantly clear and convincing that due to the current trajectory of human-derived emissions of CO_2 and other greenhouse gases, the atmosphere and ocean will continue to warm, the ocean will continue to acidify, atmospheric and ocean circulation patterns will be altered, the cryosphere will continue to lose ice in all forms, and sea level will rise.

While uncertainties remain about various aspects of the Earth System, what is known is beyond dispute. The trends, based on observations and confirmed by modelling, will accelerate if high rates of CO_2 and other greenhouse gas emissions continue.

The IPCC AR6 WGII Summary for Policymakers (SPM D.5.3) unambiguously emphasises this conclusion: *The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all.*

Human influence on the climate is clear, with observed changes in the climate and in greenhouse gas concentrations unequivocally attributable to human activities.

Human-induced climate change has caused extensive negative impacts, including losses to people and to nature, some of which are irreversible, such as the extinction of species.

Climate change is increasingly exacerbating the impact of other human-caused effects on nature and human well-being, and the impacts are expected to grow with increasing climate change magnitude.

Observations, modelling and global assessments describe significant changes in Antarctic physical and living systems, both marine and terrestrial.

Changes in Antarctic and Southern Ocean environments are linked to and influence climate impact drivers globally.

The most significant potential influence of Antarctica's changes will be on global mean sea level change and its influence on society and nature in all coastal regions of the globe.

Further global impacts influenced by Antarctic change include extreme climate and weather events, droughts, wildfires and floods, and ocean acidification. These impacts cause ecosystem disruption and loss of biodiversity beyond the Antarctic region.

Under current projections, and without nations meeting the Nationally Determined Contributions of the Paris Climate Agreement, the rate of global change will outpace societal, political, and economic responses that will facilitate adaptation and strengthen resilience to the impacts of climate change.

The agreements of the Antarctic Treaty System will not escape these influences. Rapidly changing Antarctic and Southern Ocean environments require similarly rapid environmental governance responses, including potential changes to agreements that have previously taken many years to reach. Impacts of climate change are also likely to challenge geopolitical relations in regions outside the Antarctic, in turn influencing relations within the Antarctic Treaty System.

Past global arrangements and isolated responses have been ineffective in addressing cross-boundary challenges that require an Earth System approach. Research conducted in the Antarctic and Southern Ocean regions, and strong policies developed from its results, are critical for the development of an integrated Earth System approach and the discernment of a path to a sustainable future for the planet.

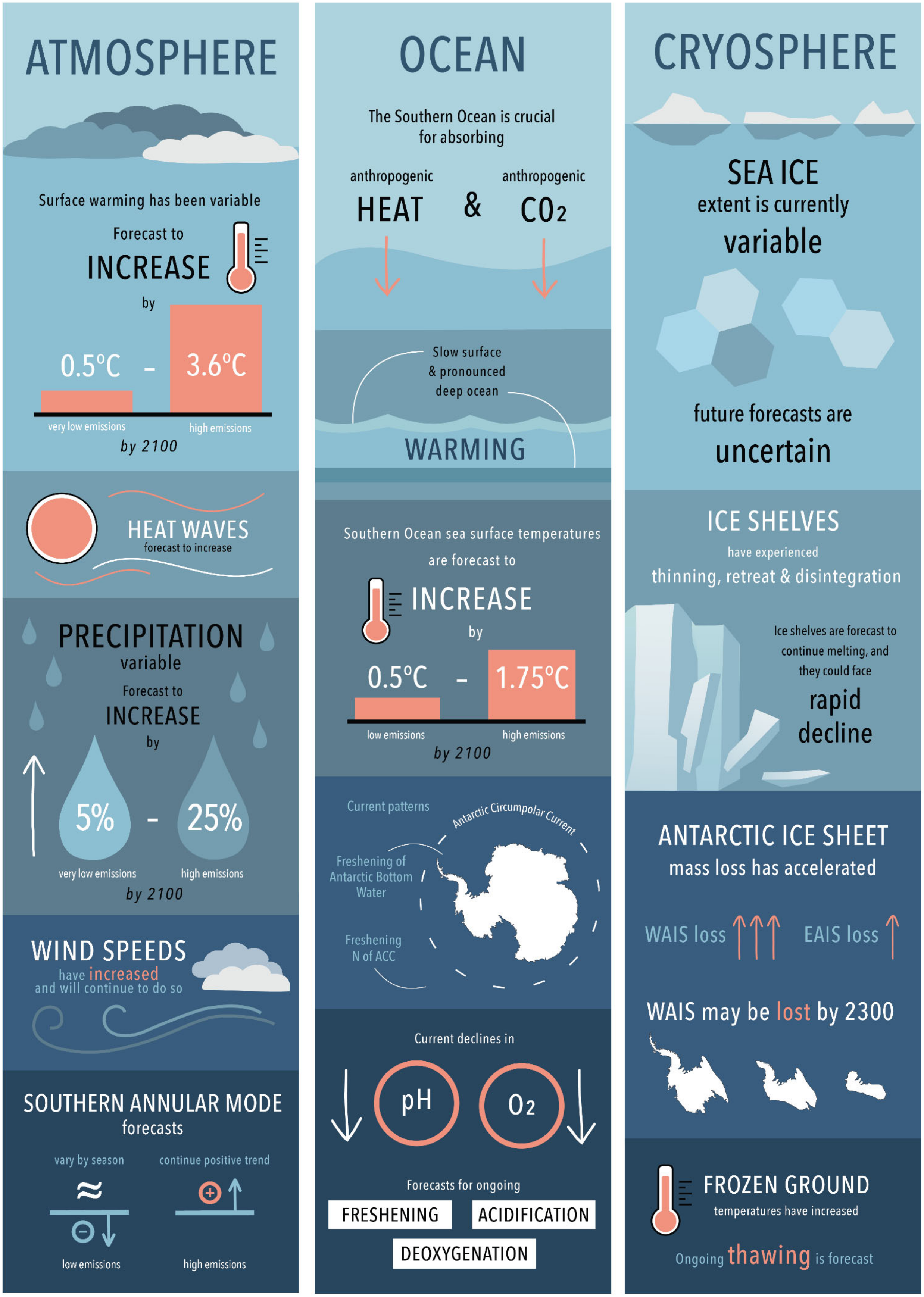
Cooperative and coordinated international responses are required to address critical research needs in Antarctica and the Southern Ocean. In turn, receptive Antarctic governance is needed to use the knowledge generated by the research to create effective policy and decisions. Enhanced investment in science will provide policymakers and planners with more comprehensive and coherent sets of information over time to help put in place timely, scalable adaptation and mitigation strategies. Investment in new science and technology that provides updated information on the likelihood of major drivers of climate risk will more than repay itself.

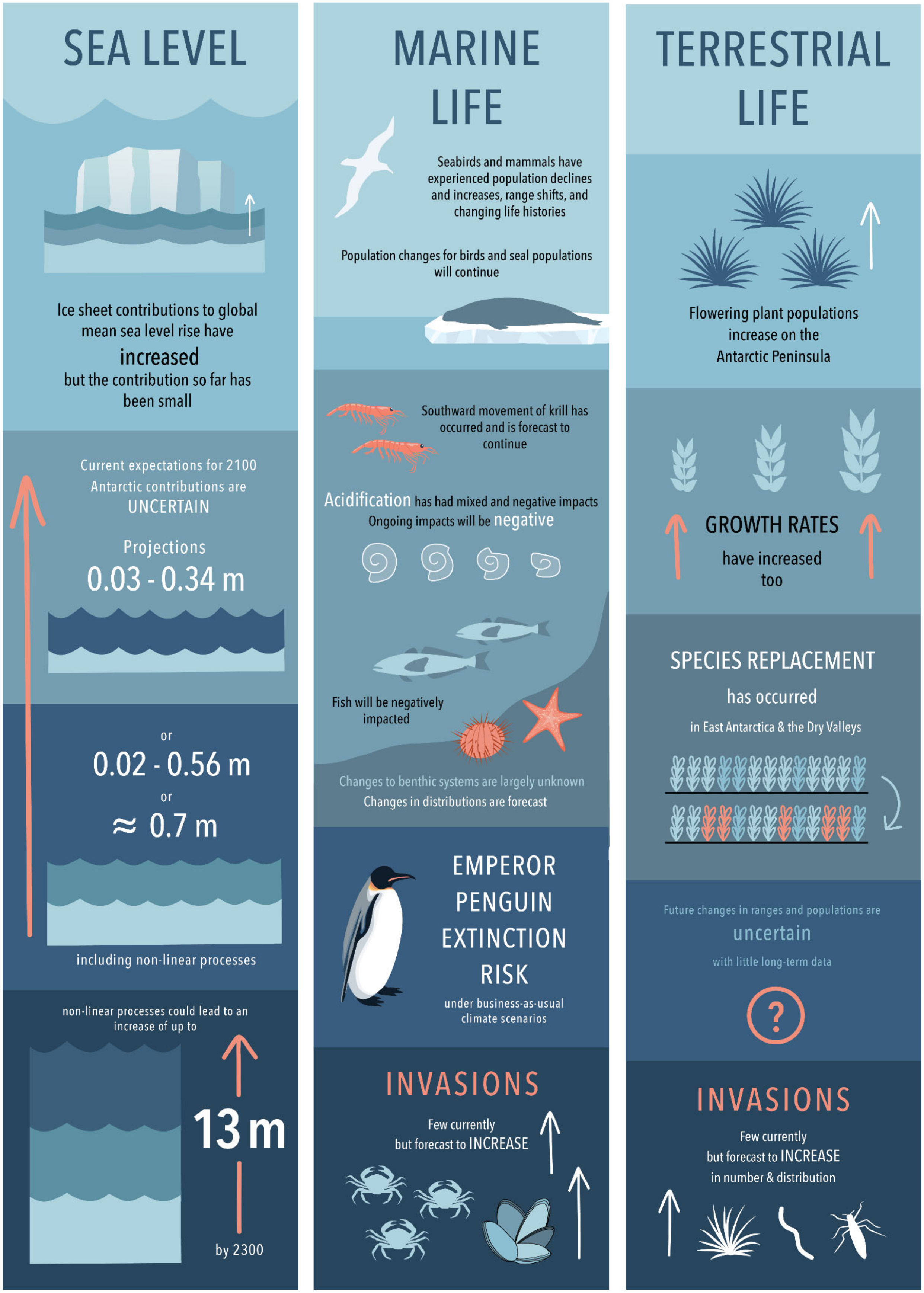
Science communication and education in partnership with other cultural and societal actors is essential to enable further appreciation of the value of Antarctica and the Southern Ocean for current and future human well-being, for biodiversity, and for the interdependence of humans and nature.

To limit further change, immediate and deep emissions reductions are required across all sectors.

Effective action is now more urgent than it has ever been.

Environmental Change Summary




SEA LEVEL
Ice sheet contributions to global mean sea level rise have
increased
but the contribution so far has been small
Current expectations for 2100 Antarctic contributions are
UNCERTAIN
Projections
0.03 - 0.34 m
or
0.02 - 0.56 m
or
≈ 0.7 m
including non-linear processes
non-linear processes could lead to an increase of up to
13 m
by 2300
MARINE LIFE
Seabirds and mammals have experienced population declines and increases, range shifts, and changing life histories
Population changes for birds and seal populations will continue
Southward movement of krill has occurred and is forecast to continue
Acidification has had mixed and negative impacts
Ongoing impacts will be negative
Fish will be negatively impacted
Changes to benthic systems are largely unknown
Changes in distributions are forecast
EMPEROR PENGUIN EXTINCTION RISK
under business-as-usual climate scenarios
INVASIONS
Few currently but forecast to INCREASE
TERRESTRIAL LIFE
Flowering plant populations increase on the Antarctic Peninsula
GROWTH RATES
have increased too
SPECIES REPLACEMENT
has occurred
in East Antarctica & the Dry Valleys
Future changes in ranges and populations are
uncertain
with little long-term data
?
INVASIONS
Few currently
but forecast to INCREASE
in number & distribution

Recommendations

Policy Recommendations

Policy recommendations are made throughout this report. Here, these recommendations are made in order of significance. They include advice for the policymakers of the Antarctic Treaty System (ATS) and advice for National Antarctic Programs (NAPs). The recommendations from this report will be conveyed specifically to the XLIV Antarctic Treaty Consultative Meeting and, as appropriate, to the 41st Meeting of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

PR 1 The Antarctic Treaty Parties (ATPs) and observers to the Treaty should communicate to governments and to civil society the urgency of, at the very least, meeting the Nationally Determined Contributions (i.e., country greenhouse gas emissions reduction targets) of the Paris Climate Agreement to ensure that Antarctic and Southern Ocean environments are preserved in a state close to that known for the past 200 years, and in so doing help ensure achievement of the Sustainable Development Goals. The ATPs and observers are also encouraged to convey to governments, to parties to other international environmental agreements, and to civil society the outcomes of climate change-related research, and the benefits of informed immediate management actions in the Antarctic region. The need for additional extensive research to resolve uncertainties about cryosphere change, its rate, and its implications is urgent. Equally pressing is the need for effective communication to international efforts to address climate change beyond Antarctica.

PR 2 The Antarctic Ice Sheet (AIS) is changing rapidly, with the anthropogenic signal starting to become apparent. The AIS is projected to contribute substantially to global mean sea level rise, but the risks of significantly larger rates and magnitudes of sea level rise from rapid ice sheet mass loss in the coming decades to centuries are not well known, particularly from vulnerable marine basins in West Antarctica and parts of East Antarctica. Reducing this uncertainty is a globally urgent research priority that will require further support from NAPs. Novel observations along sensitive marine-based sectors, and from paleoclimate archives, are urgently needed over the time scale of a decade to improve understanding of the physical processes driving the retreat, document the current evolution in detail, and comprehensively, and critically improve the skills of numerical projections.

PR 3 The consequences of sea level rise and melting ice (sea, land and shelves) around Antarctica's coastline will present significant risks to society. The need for, and outcomes from, research on sea level in the Antarctic should be communicated by the ATPs and observers: to international agreements, governments at all levels, the economic sector, and to civil society, as these entities will largely have to plan for, manage, and endure the impacts of sea level rise and its associated costs.

PR 4 The Southern Ocean is undergoing changes and these changes will continue under higher emissions scenarios. Major impacts on the cryosphere, marine ecosystems and their constituent species, and consequently on the ecosystem services they deliver, including on systems and services outside the Antarctic region, are expected. Significant changes are anticipated in areas that may be especially vulnerable to ice sheet instability and collapse once thresholds are reached. Changes to the Southern Ocean and its ecosystems will present growing management difficulties, logistics challenges and research requirements that will require special attention within the ATS. Research on these questions, including through expanded long-term monitoring, is imperative.

PR 5 Changes to the Southern Annular Mode, a major climate driver, have implications for climate means, and climate extremes which may be accompanied by extreme events, such as major fires and droughts, especially on Southern Hemisphere land masses. Research to support further understanding of these influences, and their interactions with greenhouse gas-related climate change, should be supported by NAPs. The outcomes of this work and its significance for disaster preparedness and environmental management must be communicated by the ATPs and observers to governments and to civil society.

PR 6 The ATPs have declared an obligation to implement the mitigation and adaptation actions that will reduce climate change-related and other human impacts on Antarctic marine and terrestrial environments, their ecosystems and biodiversity, and the ecosystem services they deliver. Continued support for the research required to deliver evidence-informed options for action, including through coordinated, international and transdisciplinary research efforts across Antarctica and the Southern Ocean by all ATPs; the development of an appropriately-resourced scientific workforce for the future; and well-supported long-term monitoring programs of the physical and living environment, are essential to meet this obligation. Our human future depends on the success of these actions.

PR 7 National Antarctic Programs and International Association of Antarctica Tour Operators members are encouraged to strengthen biosecurity protocols for all pathways (ships, aircraft, and people), especially to the Antarctic Peninsula. Procedures to remove weeds and to trap other pests in ports of departure to the Antarctic need to be strengthened in anticipation of growing ease of establishment of non-native species owing to climate change. Surveillance and decision-making processes for determining actions for newly arrived species, especially in the vicinity of stations and sites with high visitor numbers, should be adopted. Collaborations with SCAR and other researchers are needed to establish an image- and DNA-based diagnostic service for newly detected species, building on the Barcode of Life Data System approach.

PR 8 The ATPs and members of the Committee for Environmental Protection (CEP) are encouraged to increase the priority given to documenting terrestrial and marine biodiversity (including in lakes and streams) at the population, species, and community levels. In some cases, to enable observation of these systems before they disappear. Such an enhanced focus, further informed by long-term monitoring of change, is essential to ensure the efficacy of environmental protection and to document the benefits of environmental management.

PR 9 The loss of sea ice, fast ice and ice shelves together with the expansion of ice-free areas on the Antarctic continent and changes to temperatures and precipitation, including extreme weather events, will present new challenges for the management of areas of high human activity in the Antarctic (including where infrastructure and other NAP assets are deployed). Biodiversity will change and conditions will become more suitable for the establishment of non-native species, especially along the Antarctic Peninsula. These challenges should be urgently addressed by the ATPs and by members of the CEP.

Research Recommendations

Specific research recommendations from this report are included within each of the major chapters. The sources of the recommendations, where details may also be found, are the SCAR Horizon Scan [Kennicutt *et al*. 2019] and SCAR Scientific Research and other programs [SCAR 2022], though several modifications have been made to these recommendations in light of new research findings.

Here we make recommendations for the most significant and urgent research needed. Given the climate change focus of this report, the recommendations focus on changes in the region that have significant implications for the Earth System and for society, and on the expected impacts of climate change on the region's biodiversity.

RR 1 Further support the research required to reduce uncertainty about the future of the region and its impact on the Earth System and to identify commensurate management responses. Integrated, international and targeted long-term monitoring programs and observatories are among the most important for reducing uncertainty and for understanding the likely impacts of mitigation and adaptation responses.

RR 2 Urgently reduce uncertainty about the current and future behaviour of the Antarctic Ice Sheet. The current observation network, especially for the hydrology and conditions at the base of the ice sheet, and the temperature and bathymetry of ice shelf cavities, coastal regions and the continental shelf, is inadequate to fully anticipate change and to understand the risks of ice shelf collapse, loss of buttressing and rapid ice sheet mass loss in the coming decades. An international effort is urgently required to address this. A major exploration is required of key (unexplored) ice shelves and upstream glaciers using direct access techniques, ocean and airborne robotics, icebreaking ships, aircraft and space-borne remote sensing and other means to understand the ablation regime of the Antarctic ice sheet along the periphery; how it is has changed in the past, is currently changing and will change in the future; and how this will drive rapid ice mass loss and sea level rise from Antarctica.

RR 3 Understand how changes in atmospheric circulation drive changes in ocean currents around Antarctica and the advection of ocean heat onto the continental shelf, into the ice shelf cavities and in contact with the glaciers, and the influence of meltwater feedbacks.

RR 4 Determine what the contribution will be of the Antarctic Ice Sheet to future sea level rise and reduce uncertainties in projections of the rate and magnitude of that contribution, and effectively communicate the impacts and risks to stakeholders and users.

RR 5 Account for and develop a detailed process-based understanding of the contemporary annual-to-decadal time-scale trends in the Antarctic climate system. Knowledge of how climate change and variability in the high southern latitudes are connected to lower latitudes, including the tropical oceans and monsoon systems, and will respond to ongoing changes to the ozone hole and to other anthropogenic forcing, is critical for improved climate projections and anticipation of extreme climate events.

RR 6 Determine why the properties and volume of Antarctic Bottom Water are changing, and what the consequences are for global ocean circulation and climate.

RR 7 Establish which species, ecosystems and food webs are most vulnerable in the Southern Ocean, how they are likely to change, and which organisms are most likely to go extinct and over what period, as a consequence of climate change and local interactions such as with non-native species.

RR 8 Determine how increases in marine living resource harvesting in the context of climate change impacts will affect harvested, associated and dependent species and Southern Ocean biogeochemical cycles, in contrast with other groups.

RR 9 Establish which terrestrial ecosystems and food webs are most vulnerable, how they are likely to change, and which organisms are most likely to decline and/or to go extinct and over what time period, as a consequence of climate change and local interactions such as with non-native species.

Contents

1. Context and Approach

1.1 Context

In 2009, the Scientific Committee on Antarctic Research (SCAR) published its landmark report *Antarctic Climate Change and the Environment* (ACCE Report) [Turner *et al.* 2009], in part as a contribution to the International Polar Year 2007-2008. The report was widely taken up, including by the Antarctic Treaty Consultative Parties (ATCPs). On the basis of the report, the ATCPs convened a Meeting of Experts on Climate Change in Svolvaer, Norway in 2010. In turn that meeting resulted in the establishment of a Climate Change Response Work Programme within the Committee for Environmental Protection (CEP), and more recently a Subsidiary Group on Climate Change Response with the mandate to give effect to the priorities identified within the Work Programme [CEP 2020]. SCAR published a further update to the ACCE Report in 2014 [Turner *et al.* 2014]. SCAR has also produced annual synopses of research outcomes for the Antarctic Treaty Consultative Meetings (ATCM) since the presentation of the 2009 report.

Since the original ACCE publication and its 2014 update, the science has developed considerably. The outcomes from this science have been reviewed in several recent, synthetic international reports. These are the Intergovernmental Panel on Climate Change's (IPCC) three most recent reports: Special Report on the Ocean and Cryosphere in a Changing Climate (hereafter IPCC SROCC) [IPCC 2019], Sixth Assessment Report (AR6) from Working Group I on The Physical Science Basis (hereafter IPCC AR6 WGI) [IPCC 2021], and the Sixth Assessment Report (AR6) from Working Group II on Impacts, Adaptation and Vulnerability (hereafter IPCC AR6 WGII) [IPCC 2022a].

Two further reports are the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service's Global Assessment Report [IPBES 2019] and the less formal International Cryosphere Climate Initiative's integrated report on the State of the Cryosphere 2021 [ICCINET 2021].

Together, these reports provide the most recent consensus understanding of current global changes, including to the Antarctic and Southern Ocean regions, their attribution to anthropogenic causes, and prognoses for future change and impacts depending on greenhouse gas emissions scenarios. These scenarios were previously the Representative Concentration Pathways (RCPs) and are now the Shared Socio-Economic Pathways (SSPs) [Meinshausen *et al*. 2020]. The IPCC and IPBES reports form the substantive basis for the Antarctic and Southern Ocean synopsis compiled here. These reports, and their *Summaries for Policymakers* in particular, should be considered necessary background reading for full information on change that has already occurred, its attribution, and expectations for the future.

These comprehensive international reports are not the final word. Science does not work this way, nor does the environment. Change in the Antarctic region and growth of scientific understanding continue apace. Yet the reports are current and comprise the consensus understanding of an exceptionally large community of scientists, serving as either authors or reviewers.

The decadal synopsis of Antarctic Climate Change and the Environment provided here therefore uses these reports as its foundation, compiling most of its information from them, with explicit cross-referencing. The IPCC and IPBES reports are transparent about the scientific basis for the conclusions they reach, and they have been through substantive and meticulously documented review and revision. No need exists to do this again. The science is clear, including for those areas where uncertainty remains to be reduced to improve understanding and/or projections. It should be noted, however, that because the IPCC and IPBES reports represent a consensus view, agreed by participating national delegations, some scientists consider their conclusions too conservative.

This report does, however, also include material that is more recent than the comprehensive reports where relevant and/or where matters not dealt with in these reports must be covered. In the case of such additional or new material, reference to the source, peer-reviewed publications is made.

This report was compiled by the listed editors through the auspices of the Secretariat of SCAR. The draft was then circulated for review, following an independent process run by the SCAR Secretariat. Comments were incorporated and the document finalised by SCAR's Standing Committee on the Antarctic Treaty System.

1.2 How to use this report

Unlike the original ACCE Report [Turner *et al.* 2009], this decadal, compiled synopsis does not provide a full background on the history of the Antarctic and Southern Ocean region, the approaches used to document that history, and the ways in which both current measurements are undertaken and projections made. Nor does the report focus on the technical details of the research for each field. Much of the background in the original report [Turner *et al*. 2009] remains pertinent, despite growth in scientific understanding [e.g., details in the IPCC AR6 WGI Technical Summary], including through community efforts such as the development of a new generation of general circulation models which take additional aspects of the Earth System into consideration [Zelinka *et al.* 2020]. Moreover, technical aspects of the research are well captured by the international reports of the IPCC.

Rather, this report provides concise compiled synopses of current understanding, provides projections for change, typically out to 2100, where these have been made, explicit recommendations for actions to address change, and recommendations for additional research. In most cases, the research recommendations are drawn from the SCAR Antarctic and Southern Ocean Horizon Scan and its update [Kennicutt *et al.* 2014, 2015, 2016, 2019] or from questions identified by SCAR's Scientific Research Programs [Colleoni *et al.* 2022; SCAR 2022].

The primary aim of this report is, therefore, to provide a readily accessible, cross-referenced synoptic overview of current knowledge of and projections for climate change and its impacts in the Antarctic and Southern Ocean regions, coupled with specific recommendations on policy actions to address change in the Antarctic.

Throughout, where drawing on the IPCC and IPBES reports, the language of these reports regarding confidence, evidence and agreement is used [Mastrandrea *et al.* 2010; IPCC 2021] (**Figure 1.1**). Importantly, IPCC AR6 provides information on low likelihood, but potentially high impact outcomes [IPCC AR6 WGI 1.4.4.1; Cross Chapter Box 1.3].

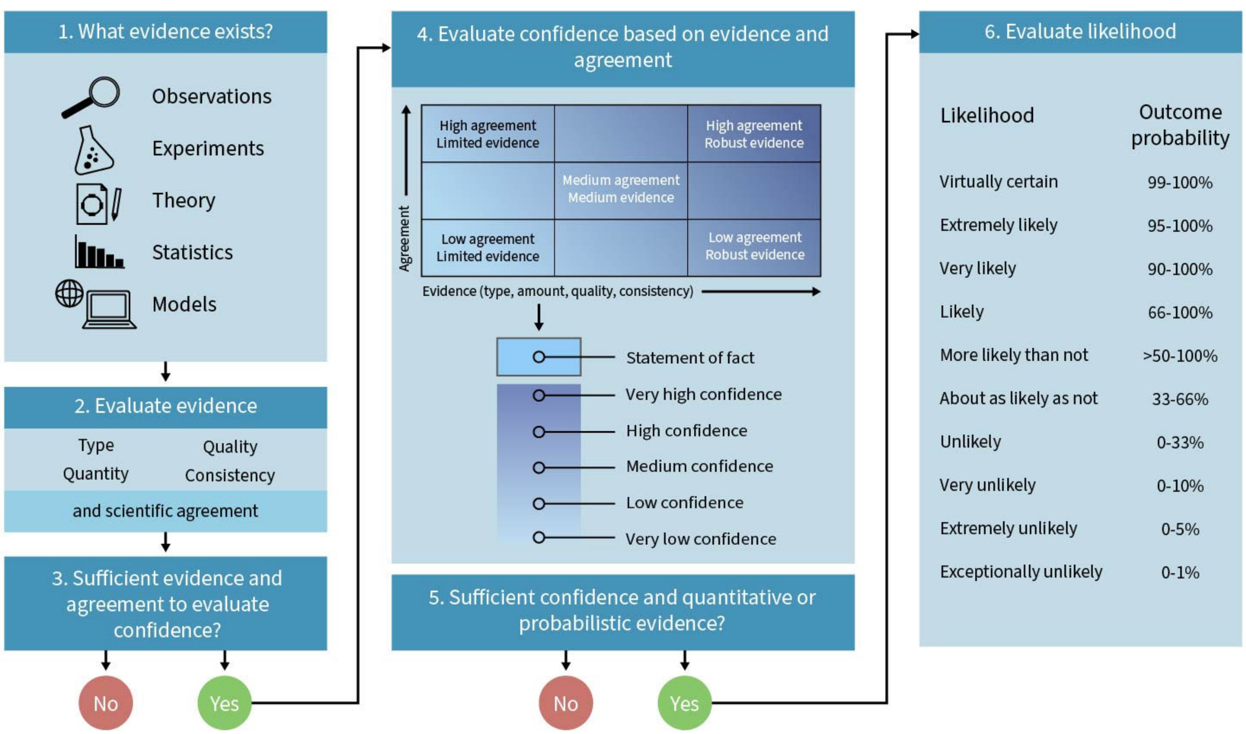


Figure 1.1 The IPCC AR6 approach for characterizing understanding and uncertainty in assessment (redrawn from IPCC AR6 WGI Box 1.1, Figure 1, with simplification).

The IPCC AR6 WGI also provides a guide to the concept of attribution – *the process of evaluating the contribution of one or more causal factors to…observed changes or events* [IPCC AR6 WGI Cross-Working Group Box: Attribution].

Where published, peer-reviewed work is reported, that work is typically mentioned in the context of these reports. Specific language regarding evidence, confidence and likelihood is not provided, however, where publications post-date the cut-off date requirements for the IPCC and IPBES reports. This is because of the absence of a fully constituted review panel approach, considering the individual papers in the context of the full body of work in an area, as per the IPCC guidelines.

The work focuses largely on the Antarctic continent and the Southern Ocean (typically the Convention on the Conservation of Antarctic Marine Living Resources Area). The sub-Antarctic islands are not given explicit attention, though they remain within SCAR's geographic area of interest. In this respect, a key obvious principle is that the Earth System, including its biodiversity, is not beholden to geopolitical agreements, though it may respond to them.

1.3 Humans as drivers of global climate and ecosystem change

The IPCC Sixth Assessment Report from Working Group I is clear.

Observed increases in well-mixed greenhouse gas (GHG) concentrations since the mid-1700s are unequivocally attributable to human activities. Human influence on the climate is also clear (**Figure 1.2**).

The *likely* range of total human-caused global surface temperature increase between 1850—1900 and 2010—2019 has been 0.8°C to 1.3°C, with well-mixed GHGs contributing a warming of 1.0°C to 2.0°C. Natural drivers and internal variability have contributed little change at all. Well-mixed GHGs have *very likely* been the main driver of tropospheric warming since 1979.

Globally averaged precipitation over land has *likely* increased since 1950, with a faster rate of increase after the 1980s (*medium confidence*). Human influence has *likely* contributed to this pattern of observed precipitation change.

The main driver of the global retreat of glaciers generally since the 1990s is *very likely* human influence. But there has been no significant trend in Antarctic sea ice area from 1979 to 2020 because of large internal variability and opposing trends in different regions.

Global mean sea level increased by 0.20 m between 1901 and 2018, and the main driver of these increases since at least 1971 is *very likely* a combination of several factors driven by human-caused changes in climate.

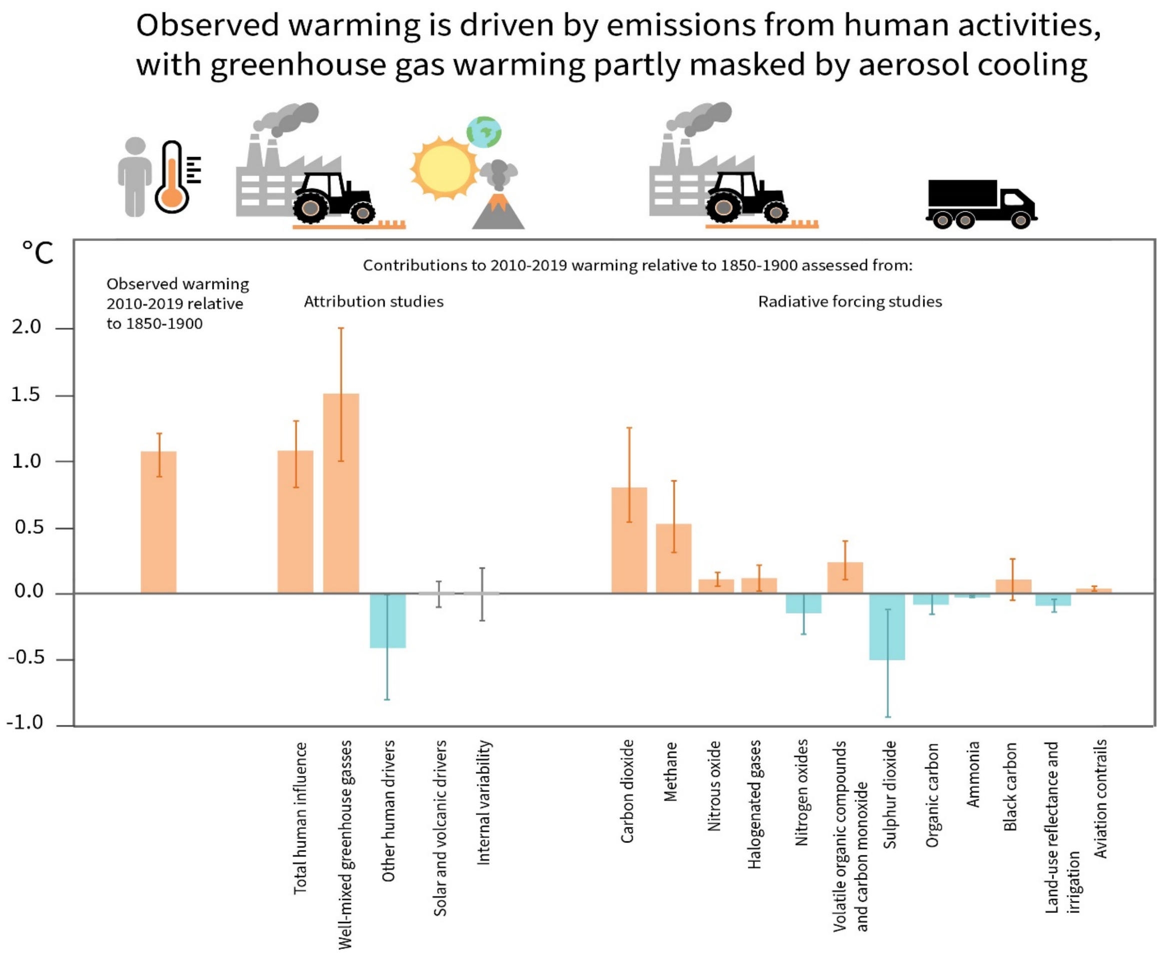


Figure 1.2 Assessed contributions to observed global warming in 2010—2019 relative to 1850—1900. Left to right the panels indicate the total observed warming, the human contribution relative to natural forcing, and the relative contributions of anthropogenic factors (redrawn from information in IPCC AR6 WGI SPM Figure SPM.2).

Patterns in observed changes in near-surface ocean salinity are *extremely likely* a consequence of human influence. Global upper ocean (0—700 m) warming since the 1970s is *virtually certain* and human influence as the main driver is *extremely likely*. Human-caused CO_2 emissions are *virtually certain* as the main driver of current global acidification of open ocean surface waters. *High confidence* exists that oxygen levels in many upper ocean regions have dropped since the mid-20th century, and human influence on this drop has *medium confidence*.

Changes in the biosphere on land since 1970 are consistent with climate change. Climate zones have shifted poleward in both hemispheres, and the growing season has on average lengthened by up to two days per decade since the 1950s in the extratropical regions of the Northern Hemisphere.

The IPCC Sixth Assessment Report from Working Group II provides comprehensive evidence that human-induced climate change, which includes more frequent and more intense extreme events, has caused extensive negative impacts, including losses to people and to biodiversity. Ecosystems and people already vulnerable for other reasons are disproportionately affected. The increase in climate and weather extremes has resulted in some irreversible impacts as natural and human system are pushed beyond their ability to adapt (*high confidence*).

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services' Global Assessment Report [IPBES 2019] makes clear that for terrestrial and freshwater ecosystems, land-use change has had the largest relative negative impact on nature since 1970. Direct exploitation, in particular overexploitation, of animals, plants, and other organisms, mainly via harvesting, logging, hunting and fishing has had the next largest effect.

For marine systems, direct exploitation of organisms (mainly fishing) has had the largest impact, followed by land-use and sea-use change.

Human actions now threaten more species with global extinction than ever before. Warming and increased frequency, severity and duration of extreme events in the near term will mean that many terrestrial, freshwater, coastal and marine ecosystems are at very high or high risks of losing biodiversity (*medium to very high confidence*, depending on the ecosystem) [IPCC AR6 WGII SPM B.3.1].

Projected global surface temperature averaged over 2081—2100 is *very likely* to be higher by 1.0°C to 1.8°C, compared to 1850—1900, under the very low GHG emissions scenario (SSP1-1.9), by 2.1°C to 3.5°C in the intermediate scenario (SSP2-4.5), and by 3.3°C to 5.7°C under the very high GHG emissions scenario (SSP5-8.5) [IPCC AR6 WGI SPM B.1.1] (see also **Figure 1.3**).

Relative to 1850—1900, global warming of 2°C would be exceeded during the 21st century under the high and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5, respectively). Global warming of 2°C would *extremely likely* be exceeded in the intermediate scenario (SSP2-4.5). Under the very low and low GHG emissions scenarios, global warming of 2°C is *extremely unlikely* to be exceeded (SSP1-1.9), or *unlikely* to be exceeded (SSP1-2.6) [IPCC AR6 WGI SPM B.1.2].

Crossing the 2°C global warming level in the mid-term period (2041—2060) is *very likely* to occur under the very high GHG emissions scenario (SSP5-8.5), *likely* to occur under the high GHG emissions scenario (SSP3-7.0), and *more likely than not* to occur in the intermediate GHG emissions scenario (SSP2-4.5).

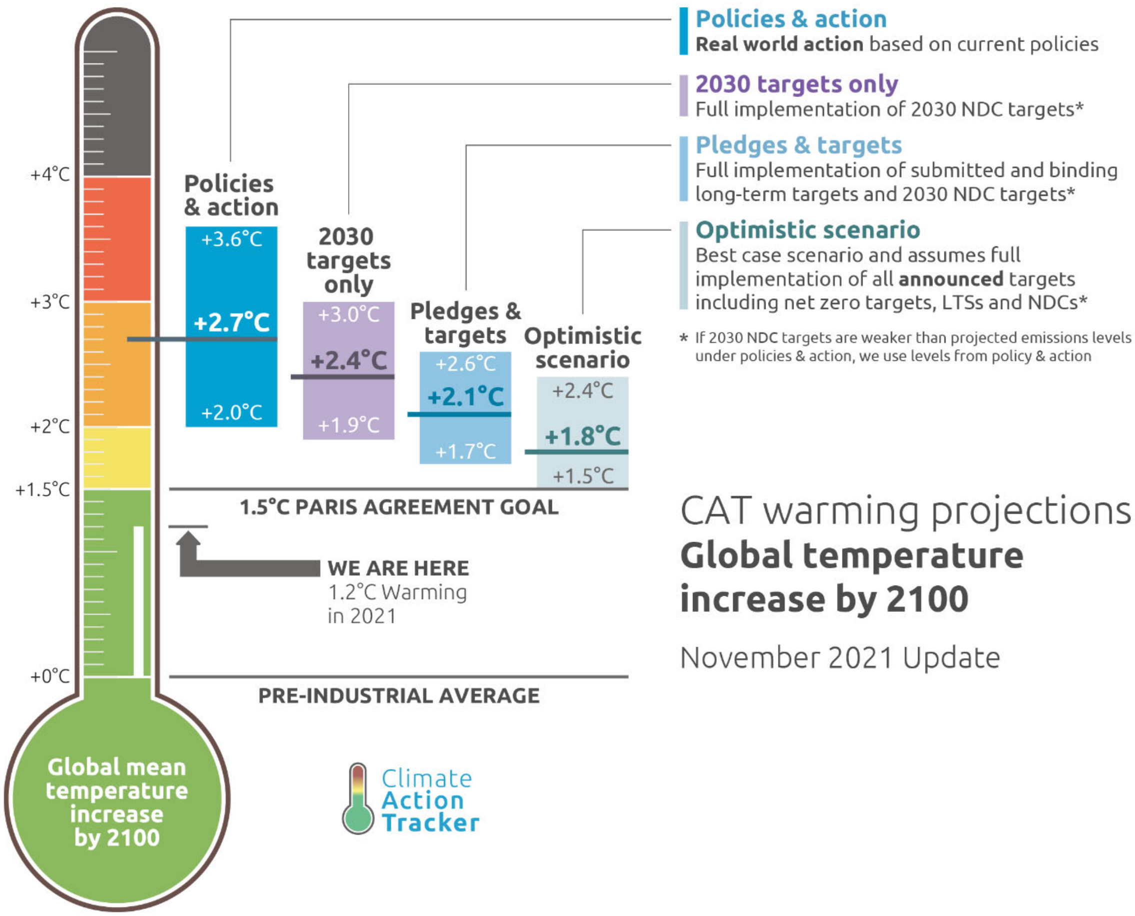


Figure 1.3 The climate action tracker thermometer (2021). The thermometer illustrates current expectations for temperature change by 2100. The CAT Thermometer. November 2021. Available at: https://climateactiontracker.org/global/cat-thermometer/ Copyright © 2021 by Climate Analytics and NewClimate Institute. All rights reserved. Note that the CAT Thermometer is regularly updated.

There is strengthened evidence that the global water cycle will continue to intensify as global temperatures rise (*high confidence*), with precipitation and surface water flows projected to become more variable over most land regions within seasons (*high confidence*) and from year to year (*medium confidence*) [IPCC AR6 WGI SPM B3.1].

Critically, climate change is a direct driver that is increasingly exacerbating the impact of other drivers on nature and human well-being, and the impacts are expected to grow with increasing climate change magnitude [IPBES 2019]. Loss of biodiversity, and damage to and transformation and degradation of ecosystems will continue to grow with every increment of global warming (*very high confidence*) [IPCC AR6 WGII SPM B4.1].

1.4 The role and importance of Antarctica and the Southern Ocean in the Earth System

Antarctica and the Southern Ocean form integral components of the Earth System.

For example, oceans have absorbed >90% of additional warming in the Earth System since 1900. Although the Southern Ocean south of 30°S encompasses about only one-third of the total ocean area, it absorbs more than two-thirds of ocean anthropogenic heat and half of the total ocean anthropogenic carbon [IPCC SROCC]. The Southern Ocean is also disproportionately important in global climate and ecological systems because it links the Atlantic, Pacific and Indian Oceans in the global circulation.

The Antarctic Ice Sheet not only provides a record of the changing Earth System, revealed through Antarctic ice cores, but responds to and influences changes in the system [IPCC SROCC]. Past changes to the AIS have had significant influences on global sea level, with the AIS containing a total contribution of approximately 58 m in sea level rise were it to melt entirely.

The Antarctic acts as a global biodiversity pump, generating species as a consequence of changing conditions over geological time, especially, but not exclusively, in marine ecosystems [Crame 2018; Rabosky *et al.* 2018; O'Hara *et al.* 2019; Baird *et al.* 2021].

Southern Ocean ecosystems are highly productive, incredibly diverse for some benthic groups, home to species with extraordinary adaptations to cold, and include some of the world's most iconic vertebrate species [Pörtner 2006; Peck 2018; Chown & Brooks 2019; Convey & Peck 2019; Hindell *et al.* 2020; Gutt *et al.* 2021]. Fishing resources are significant, especially since fishing in the Southern Ocean appears profitable even after subsidies are considered, unlike most other fisheries [Sala *et al.* 2018].

Although terrestrial biodiversity of the Antarctic continent is relatively impoverished compared with other continents, it is unusual in many respects [Chown *et al.* 2015; Convey & Peck 2019]. Unusual features include areas that may be at the limits for microbial life [Goordial *et al*. 2017; Dragone *et al.* 2021], the importance of chemosynthesis to communities [Ji *et al.* 2017; Ortiz *et al.* 2021], and, in aquatic systems, subglacial life and habitats with very high viral diversity [López-Bueno *et al.* 2009; Christner *et al.* 2014; Livingstone *et al*. 2022].

Terrestrial areas form the breeding grounds for most Southern Ocean seabirds [Harris *et al.* 2015]. The Antarctic continent also includes some of the largest wilderness areas on Earth. It incorporates extensive areas that have either never been visited by humans or have very rarely been traversed [Leihy *et al.* 2020].

Combined, these conditions make Antarctica and the Southern Ocean unique and critical in the Earth System.

1.5 The role of governance and institutions

The Shared Socio-Economic Pathways represent the expectations of climate change and its impacts given different socio-economic responses. Ultimately, what the future holds for Antarctica and the Southern Ocean, and their global influence, depends on the socio-economic pathway followed globally.

For example, a recent assessment has suggested that if the Paris Climate Agreement targets are exceeded, rapid and unstoppable sea level rise as a consequence of a changing Antarctic Ice Sheet can be expected [DeConto *et al.* 2021]. This is supported by another recent assessment suggesting that there is a SSP-dependent threshold response [Lowry *et al*. 2021].

Therefore, decisions made within international agreements, such as the Paris Climate Agreement, have significant implications for Antarctica and the Southern Ocean, as well as for other regions of the globe. Given that the nations and observers that take part in the operation of the Antarctic Treaty System (ATS) are best placed to convey the changes occurring in the region and their regional and global implications, these participants have an obligation to convey this information broadly, including to civil society, and to make every effort to influence decision-making. They are similarly obliged to convey the urgency of research about changes in the region, its implications, and the need to reduce current uncertainty, to National Antarctic Programs and to others supporting research in and about Antarctica.

Policy responses specific to the region are also essential. For example, in the Southern Ocean, the extent to which Marine Protected Areas are implemented and the way in which they and other conservation responses are managed to respond to climate change will have large influences on the region's ecosystems, biodiversity, resources and ecosystem services, including fishing resources [Hindell *et al.* 2020; Gutt *et al.* 2021; Cavanagh *et al.* 2021a,b].

In terrestrial systems, for example, the extent to which biosecurity provisions and surveillance are implemented consistently, and with regard to local variation in incursion risk, will determine the extent to which projected terrestrial ecosystem change is realised as a consequence of interactions between climate change and biological invasions [Duffy & Lee 2019; Hughes *et al.* 2020; Bergstrom 2022].

Changes in the region also extend to consequences for the infrastructure and operations supporting research in the region, with concomitant policy response requirements. This includes the potential influence of rising sea levels on coastal research infrastructure [Levy *et al.* 2020] and the impact of changing cryosphere conditions on shipping conditions and access to research stations [IPCC SROCC; IPCC AR6 WGII]

Therefore, it is clear that responses which will determine changes in Antarctica and the Southern Ocean, and their influence on the rest of the Earth System, including human society and the ecosystem services on which it depends, lie at two levels.

That is:

(i) Actions taken through United Nations instruments and their domestic implementation,

(ii) Actions taken through the Antarctic Treaty System and their domestic implementation.

The members of the ATS and the associated observers have critical roles here. These are founded on the fact that the Antarctic Treaty and associated agreements have established Antarctica as a natural reserve devoted to peace and science and seek the conservation of its marine living resources and terrestrial biodiversity. These roles of those involved in the ATS are critical for the future of the region, and are hence provided here as overarching recommendations.

1.6 Policy recommendation

The Antarctic Treaty Parties (ATPs) and observers to the Treaty should communicate to governments and to civil society the urgency of, at the very least, meeting the Nationally Determined Contributions (i.e., country greenhouse gas emissions reduction targets) of the Paris Climate Agreement to ensure that Antarctic and Southern Ocean environments are maintained in a state close to that known for the past 200 years, and in so doing help ensure achievement of the Sustainable Development Goals. The ATPs and observers are also encouraged to convey to governments, to parties to other international environmental agreements, and to civil society the outcomes of climate change-related research, and the benefits of informed immediate management actions in the Antarctic region. The need for additional extensive research to resolve uncertainties about cryosphere change, its rate, and its implications is urgent. Equally pressing is the need for effective communication to international efforts to address climate change beyond Antarctica.

1.7 Research recommendation

Further support the research required to reduce uncertainty about the future of the region and its impact on the Earth System and to identify commensurate management responses. Integrated, international and targeted long-term monitoring programs and observatories are among the most important for reducing uncertainty and for understanding the likely impacts of mitigation and adaptation responses.

2. Atmosphere

2.1 Background

Antarctic climate variability is influenced by the Southern Annular Mode (SAM) and regionally by other modes, including the El Niño Southern Oscillation (ENSO), Pacific-South American Pattern, Pacific Decadal Variability, the Indian Ocean Dipole and Zonal Wave 3 [IPCC AR6 WGI Atlas 11.1.1.1]. Thus, atmospheric teleconnections are responsible for tropical ocean and atmospheric influences on Antarctica and *vice versa* [Li *et al*. 2021] (see for example **Figure 2.1**).

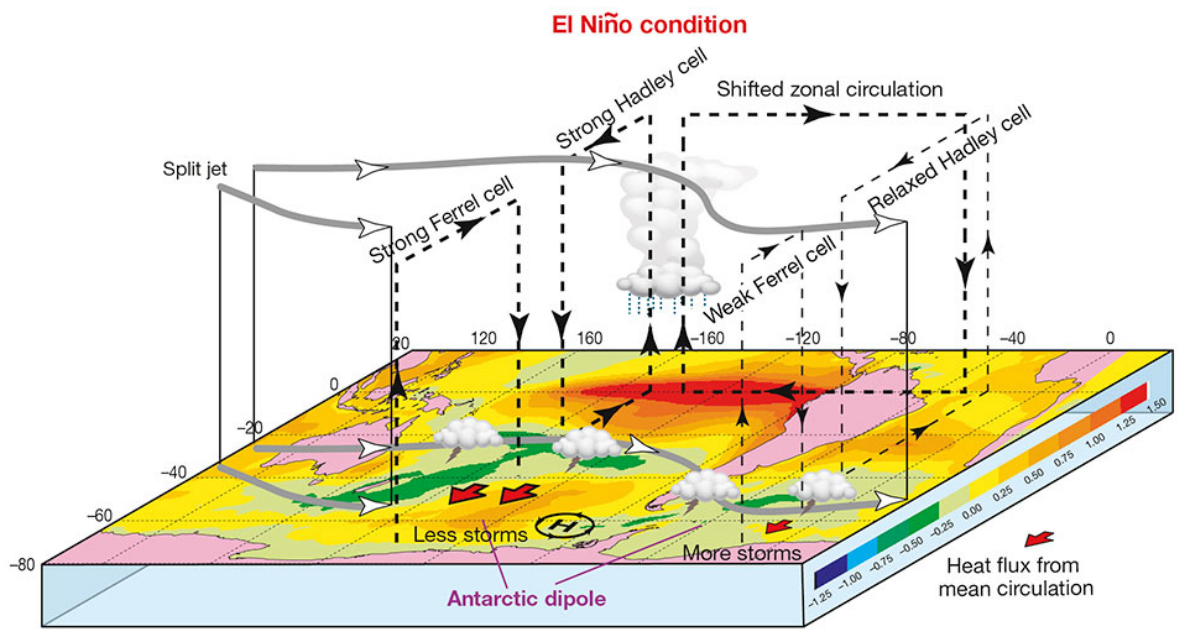


Figure 2.1 El Niño event-driven atmospheric teleconnections and the Antarctic. Remote atmospheric circulation changes are caused by warm sea-surface temperatures in the tropical Pacific Ocean accompanying the El Niño Southern Oscillation. Several mechanisms contribute to more poleward heat transport 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 (reproduced with permission from Kennicutt *et al*. 2019, original by Yuan *et al*. 2018).

Tropical forcing modulates impacts from the stratospheric ozone hole above Antarctica that propagate into the troposphere. Tropical and polar forcing governs the behaviour of the westerly winds around Antarctica affecting Southern Ocean circulation, biogeochemistry, heat and carbon sequestration, and sea ice extent. Climate change in Antarctica and the Southern Ocean is influenced by interactions between the atmosphere, ocean, sea ice and ice sheet [IPCC AR6 WGI Atlas 11.1.1.1].

The SAM is the leading mode of extratropical Southern Hemisphere variability [Marshall 2003]. It is defined as the zonal mean sea level atmospheric pressure difference between the mid latitudes (~40ºS) and Antarctica (~65ºS) [Gong & Wang 1999; Marshall 2003]. Understanding of the SAM, including its variation and change, and the causes and consequences thereof, is improving, though gaps in current understanding remain [Fogt & Marshall 2020]. Importantly, evidence indicates that recent positive SAM index values are likely unprecedented in the last millennium [Abram *et al*. 2014; Fogt & Marshall 2020].

Understanding of the global atmospheric-oceanic coupled system from model simulations and observations is also growing [e.g., Bracegirdle *et al*. 2020]. So too is knowledge of how polar modes of variability are relayed through southern mid- to low-latitudes and beyond, influencing distant global weather phenomena such as monsoon rainfall patterns and extremes such as drought and associated fire events on the southern continents [Lim *et al*. 2019; Abram *et al*. 2021; Li *et al*. 2021].

Ice cores from the Antarctic Ice Sheet (AIS) have been critical to current understanding of atmospheric gas concentrations in the past and paleoclimates [IPCC AR6 WGI 2.2.3.2].

2.2 Observed changes and impacts

2.2.1 Tropospheric and stratospheric temperatures

Global mean surface temperatures have risen over the last 50 years at a faster rate than in any other period in at least the last 2000 years (*medium confidence*), due to human influence on the climate [IPCC AR6 WGI 2.3.1.1.2, Cross section Box TS.1]. Global mean surface temperature is 1.09°C warmer (for 2011—2020) than the 1850—1900 baseline, assessed across multiple datasets. Surface warming has been more pronounced over land than over the ocean. For the period 2011—2020, global land surface air temperature (LSAT) has increased by 1.59°C (1.34—1.83) since 1850—1900 [IPCC AR6 WGI 2.3.1.1.3], compared to a 0.88°C (0.68—1.01) increase in mean annual sea surface temperature (SST).

In Antarctica, surface warming trends have shown high spatial and decadal variability, with some areas warming by more than 0.2°C per decade since 1981, while other areas have shown no significant change over the same period [IPCC AR6 WGI Figure 2.11]. Since the 1950s, near surface air temperatures *very likely* warmed significantly over the western and northern Antarctic Peninsula and in West Antarctica (e.g., Vernadsky Station warmed 0.46 ± 0.15°C per decade between 1951—2018) (*medium confidence*) [IPCC AR6 WGI Atlas 11.1.2].

The century-scale warming trend in the Antarctic Peninsula is *very likely* an emerging signal compared to natural variability, while the warming trend for Western Antarctica is at the high end of century-scale trends over the last 2000 years (*medium confidence*). Over the same period, no significant change was observed along the eastern Antarctic Peninsula [IPCC AR6 WGI Atlas 11.1.2].

In East Antarctica, stations have recorded significant warming, cooling, or no significant change in air temperature since records began [IPCC AR6 WGI Atlas 11.1.2]. In the 1979—2016 period, three coastal stations showed cooling, while at South Pole a warming trend was detected, increasing to 0.61 ± 0.34°C per decade between 1989—2018 [IPCC AR6 WGI Atlas 11.1.2], noting recent record low winter temperatures. Century-scale warming on the Queen Maud Land coast, based on ice core reconstructions, is within the range of centennial internal variability.

Record high temperatures and heatwaves have recently been observed at sites in East and West Antarctica [Bozkurt *et al.* 2018; Robinson *et al.* 2020], and the number of extreme high temperature days at stations along the Antarctic Peninsula and on the Antarctic Plateau has increased between the 1950s and 2019 [Turner *et al.* 2021].

In March 2022, Concordia Station (Dome C) recorded a temperature of -10.1°C, widely reported as 38.5°C above normal temperatures. Vostok Station recorded -17.7°C, reported as the warmest March temperature over the 65-year instrumental record at the station. Temperatures at coastal Casey Station were also higher than climatological maximum temperatures for March (33-year record) and highest on record for March 16, 2022 [Australian Bureau of Meteorology 2022] and the surrounding few days (JM Arblaster, personal communication). The Conger ice shelf, located ~300 km to the west, collapsed at the same time, after a long period of erosion. Potential links between and ultimate causes of these events have not been investigated fully, though the proximal cause of temperature increase has been attributed to poleward winds and an atmospheric river of warm, moist air that reached Antarctica from Australia. Peer-reviewed research is yet to emerge about these events which have occurred at a time when Antarctic sea ice is also at a record low [Thompson 2022; Raphael & Handcock 2022].

Since 1979, it is *very likely* that well-mixed greenhouse gases (GHGs) have been the main driver of surface warming globally, with carbon dioxide (CO_2) being the largest contributor [IPCC AR6 WGI SPM A.1.3; 2.2.8]. The current atmospheric CO_2 concentration (409.9 ± 0.4 ppm in 2019) is *very likely* higher than it has been over the last two million years (*high confidence*) [IPCC AR6 WGI 2.2.3.1; 2.2.3.4; Table 2.2] due to human influence.

Well-mixed atmospheric GHG concentrations increased substantially during the industrial era (*very high confidence*), and CO_2, methane (CH_4) and nitrous oxide (N_2O) concentrations continued to increase between 2011 and 2019 [IPCC AR6 WGI 2.2.3.4]. Atmospheric concentrations of other GHGs, such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), have also increased substantially since the 1970s, although the rate of increase of some ozone-depleting substances has slowed or halted in recent years due to international agreements on their production and consumption.

In contrast to tropospheric temperatures, the lower stratosphere (~10—30 km) has cooled by 1.41°C between 1960 and 2019, with anthropogenic emissions of ozone depleting substances, such as CFCs, being the main driver since 1979 (*extremely likely*) [IPCC AR6 WGI 2.3.1.2.2; 3.3.1.2]. Cooling in the *upper* stratosphere since 1979 was driven mainly by *both* anthropogenic increases in GHG concentration and the depletion of stratospheric ozone due to anthropogenic ozone depleting substances (*extremely likely*) [IPCC AR6 WGI 3.3.1.2]. Prior to 1960, there was no detectable change in stratospheric ozone levels [IPCC AR6 WGI 2.2.5.2]. Between 1980 and the early 1990s, global annual stratospheric ozone declined by 3.5%, with higher ozone losses observed in polar regions [IPCC AR6 WGI 2.2.5.2].

Significant stratospheric ozone loss continues to occur over Antarctica in the austral spring, although since 2000, there is evidence that the ozone hole over Antarctica is recovering [IPCC AR6 WGI 2.2.5.2]. There is insufficient coverage of surface observations to identify low altitude tropospheric ozone trends in the Southern Hemisphere and therefore determine regional patterns for the Antarctic [IPCC AR6 WGI 2.2.5.3].

Some anthropogenic activities have had a negative radiative forcing (i.e., cooling) impact for 2010—2019, relative to 1850—1900, such as aerosol emissions (esp. sulphur dioxide) and land use change. However, the net effect of both human and natural changes has been positive radiative forcing, causing warming. Natural climate influences, such as solar variability and volcanic aerosols, affect net radiative forcing. However, neither solar nor volcanic activity has been unusual in the post-industrial era relative to the last several thousand years (volcanic aerosol forcing: *medium confidence*; solar forcing: *high confidence*) [IPCC AR6 WGI 2.2].

It is *unequivocal* that human influence has warmed the global atmosphere, ocean and land [IPCC AR6 WGI SPM A.1]. Well-mixed GHGs *very likely* were the main driver of tropospheric warming since 1979 [IPCC AR6 WGI SPM A.1.3].

Although a trend towards a positive phase of the SAM since the 1970s *likely* explains a significant part of the warming of the northern Antarctic Peninsula, it has had a cooling effect on continental West Antarctica and East Antarctica. Warming in the western Antarctic Peninsula and over West Antarctica in the 1957-2016 period, and to 2020, is *likely* due to significant contributions of other factors, such as tropical Pacific forcing through Pacific Decadal Variability, El Niño-Southern Oscillation, the strength and position of the Amundsen Sea Low, and anthropogenic climate change [IPCC AR6 WGI Atlas 11.1.2].

2.2.2 Precipitation

Global land precipitation has *likely* increased since 1950 (*medium confidence*), with substantial interannual and regional variability [IPCC AR6 WGI 2.3.1.3.4]. Trends in precipitation and precipitation minus evaporation have been strongest in tropical and sub-tropical regions [IPCC AR6 WGI 2.3.1.3.4]. Both significant increases and decreases in precipitation have been observed in Antarctica and the Southern Ocean between 1980 and 2019 [IPCC AR6 WGI Figure 2.15], although confidence in high latitude and ocean precipitation trends remains limited due to a lack of *in situ* observations and limited satellite coverage south of 60°S.

In the austral summer, precipitation has generally decreased in mid-latitudes (25—45ºS) and increased at high latitudes (>45ºS) in the Southern Hemisphere [IPCC AR6 WGI 3.3.2.2]. In the austral winter, rainfall increase has been most pronounced in the southern Pacific Ocean sector of the Southern Ocean [Solman & Orlanski 2016]. Snowfall increased in the late 20th century in West Antarctica due to a deepening of the Amundsen Sea Low, which circulates relatively warm, moist air from the mid-latitudes towards the continent [IPCC AR6 WGI 8.3.1.7.2].

Limited evidence and low agreement exist for Southern Hemisphere trends in surface humidity and hydrological cycles due to poor data coverage [IPCC AR6 WGI 2.3.1.3].

2.2.3 Wind

Ocean surface winds appear to have strengthened globally between 1980 and 2000, with the largest increase in mean wind speed observed in the Southern Ocean in the austral summer (*low confidence*) [IPCC AR6 WGI 2.3.1.4.4; Figure 2.18; 9.2.1.2]. Strong westerly winds generate upwelling of cold deep waters in the Southern Ocean that are high in dissolved inorganic carbon, but have minimal anthropogenic CO_2 [Gruber *et al*. 2019]. These upwelled waters take up heat and atmospheric CO_2. Through the storage of heat and anthropogenic CO_2, the Southern Ocean has an influential role in regulating the global climate, including through the observed hiatus or slowdown of the global ocean sink in the 1990s [IPCC AR6 WGI 5.2.1.3].

Since 1950, the SAM has trended towards its positive phase during the austral summer (*high confidence*) [IPCC WGI 2.4.1.2]. This recent positive trend is *likely* unprecedented in at least the last thousand years (*medium confidence*) [IPCC WGI 2.4.1.2]. The positive austral summer SAM trend since the 1970s is *very likely* due to anthropogenic forcings from ozone depletion and GHGs. This was likely to be primarily stratospheric ozone depletion from the 1970s to the 1990s, but since 2000 its influence has been small [IPCC AR6 WGI 3.7.2]. Since 2000, ozone stabilisation and the recovery of the ozone hole over Antarctica have weakened the positive summer SAM trend (*medium confidence*) [IPCC AR6 WGI 3.7.2].

In the positive phase of the SAM, the Southern Ocean westerly winds shift poleward, reducing rainfall in southern South America, Africa, and Australia. In Antarctica, positive-phase SAM is associated with low air pressure anomalies over the continent, stronger westerly winds, deepening of the Amundsen Sea Low, and an increase in the upwelling of warm Circumpolar Deep Water (CDW), which may contribute to ice sheet melt [Fogt & Marshall 2020]. A positive-phase SAM has also been linked to increased warm and dry foehn winds on the eastern side of the Antarctic Peninsula, which were a key driver of the surface melt that led to the collapse of the Larsen B ice shelf in 2002 [IPCC SROCC 3.3.1.5.2].

Precipitation patterns over Antarctica are variable in a positive SAM, with some areas of East Antarctica and the western Antarctic Peninsula experiencing increased precipitation, and decreased precipitation observed over the Antarctic Plateau and eastern Peninsula [Marshall *et al.* 2017].

Fluctuations in the SAM have a significant effect on southern continental climates, influencing the risk of local extreme events such as droughts and fires [Abram *et al*. 2021].

2.3 Projected changes and risks

2.3.1 Temperature

Global warming trends are expected to continue or increase throughout the rest of the 21st century under most future Shared Socio-Economic Pathways (SSPs), with some regional variation.

Under a very low emissions scenario that is broadly consistent with limits to global warming of 1.5°C above pre-industrial temperatures (SSP1-1.9), annual mean surface air temperatures over Antarctica are expected to warm by 0.5°C (95% CI: 0.0—1.1) by 2081—2100, compared to 1995—2014 records [IPCC AR6 WGI Table 4.2].

Under a high emissions scenario with no additional climate policy action (SSP5-8.5), average surface temperatures in Antarctica are projected to increase by 3.6°C (95% CI: 1.7—5.6) over the same period [IPCC AR6 WGI Table 4.2].

The Arctic is projected to warm between two to four times the global average, due to the loss of sea ice and snow, the stratification of warming to the lower troposphere, and the poleward transport of atmospheric and ocean heat ('Arctic amplification') (*high confidence*) [IPCC AR6 WGI 4.6.1.1; 7.4.4.1.1]. It is *unlikely*, however, that Antarctica will warm at a faster rate than the global average in the 21st century [IPCC AR6 WGI 4.6.1.1]. This is because the Southern Ocean takes up heat, driven by the upwelling of deep waters, and transports it away from the continent, while the height of the Antarctic Ice Sheet prevents the formation of the deep atmospheric inversions that confine warming to near the surface of the Arctic [IPCC AR6 WGI 7.4.4.1.1].

The increasing uptake of atmospheric CO_2 by the Southern Ocean is, however, expected to slow and likely stop in the second half of the 21st century (2070 ± 10 years) as the ocean develops a reduced buffering capacity [IPCC SROCC 3.2.2.3].

2.3.2 Precipitation

Global land precipitation is projected to increase over the 21st century under very low (*likely* range: -0.2—4.7%; SSP1-1.9) and high (*likely* range: 0.9—12.9%; SSP5-8.5) emissions scenarios [IPCC AR6 WGI Box TS.6].

Precipitation will also *very likely* increase over Antarctica by 2100 by approximately 5%, 12%, or 25% under low (SSP1-2.6), moderate (SSP2-4.5), and high (SSP5-8.5) greenhouse gas emissions scenarios, respectively, relative to 1995—2014 [IPCC AR6 WGI Atlas 11.1.4].

The largest increase in average precipitation is projected for the coastal areas of West Antarctica and the Antarctic Peninsula [IPCC AR6 WGI Atlas 11.1.4]. Changes to precipitation over the Southern Ocean will *likely* result in increased rainfall and decreased snowfall [IPCC AR6 WGI Atlas 11.1.4]. There is, however, *low model agreement* in projected changes to the seasonality of precipitation in the Antarctic region [IPCC AR6 WGI Box 8.2, Figure 1].

Surface mass gains from increasing snowfall will partially offset surface mass loss of the AIS from melting in the near term (see Section 5 Sea Level) [IPCC AR6 WGI Atlas 11.1.4]. The rate of AIS mass loss has, however, accelerated since 2006 (*medium confidence*) [IPCC SROCC 3.3.1.1; IPCC AR6 WGI 2.3.2.4.2], and, under all Shared Socio-Economic Pathways, it is *likely* that the AIS is committed to lose mass throughout the 21st century (*medium confidence*) [IPCC AR6 WGI 9.4.2.5].

2.3.3 Wind

Predicted changes in the lower-tropospheric westerly winds over the Southern Ocean exhibit a strong scenario dependence by 2081—2100, relative to 1995—2014. Under a low emissions scenario (SSP1-2.6) there is weak model agreement in zonal mean change between 40—60°S, with a mix of increases and decreases in both summer and winter. Under a medium-high emissions scenario (SSP3-7.0) there are clear westerly increases between 55—60°S that exceed 1 m s^{-1} (*high model agreement*) in both summer and winter [IPCC AR6 WGI Figure 4.26].

Expectations for changes to the SAM differ among future climate scenarios. Under low emissions scenarios (SSP1-1.9 and SSP1-2.6), the SAM is expected to become more negative in the austral summer by 2100, relative to 1995—2014, with no change expected in winter [IPCC AR6 WGI 4.5.3.1]. Under high emissions scenarios (SSP3-7.0 and SSP5-8.5), however, there is *high confidence* that the SAM will continue to become more positive in all seasons, associated with reduced rainfall in mid-to-high latitudes in the Southern Hemisphere [IPCC AR6 WGI 4.5.3.1].

Greenhouse gas emissions and the recovery of the stratospheric ozone hole over Antarctica may have opposing effects on Southern Hemisphere mid-latitude atmospheric circulation during the 21st century [IPCC AR6 WGI 4.6.1.3]. Greenhouse gas emissions are predicted to force a strengthening and *likely* poleward shift in mid-latitude westerly jets [IPCC AR6 WGI 4.5.1.6, 4.6.1.3]. Under a low emissions scenario (SSP1-2.6), however, this shift may be countered by the effect of ozone hole recovery, contributing to non-significant change in atmospheric circulation until 2081—2100 [IPCC AR6 WGI 4.5.1.6].

The Southern Ocean is a major sink of anthropogenic CO_2. Increased winds may intensify the overturning circulation, reducing the net CO_2 sink, but increased freshwater input might cause a slowdown of the lower overturning circulation, leading to increased biological carbon storage. On centennial timescales, there is, therefore, *low confidence* in the overall effect of intensifying winds on CO_2 uptake [IPCC AR6 WGI 5.4.4.1].

2.4 Policy recommendation

Changes to the Southern Annular Mode, a major climate driver, have implications for climate means, and climate extremes which may be accompanied by extreme events, such as major fires and droughts, especially on Southern Hemisphere land masses. Research to support further understanding of these influences, and their interactions with greenhouse gas-related climate change, should be supported by National Antarctic Programs. The outcomes of this work and its significance for disaster preparedness and environmental management must be communicated by the Antarctic Treaty Parties and observers to governments and to civil society.

2.5 Research recommendations

RR 2.1 Account for and develop a detailed process-based understanding of the contemporary annual-to-decadal time-scale trends in the Antarctic climate system. Knowledge of how climate change and variability in the high southern latitudes are connected to lower latitudes, including the tropical oceans and monsoon systems, and will respond to ongoing changes to the ozone hole and to other anthropogenic forcing, is critical for improved climate projections and anticipation of extreme climate events.

RR 2.2 Improve determination of what drives change in the strength and position of westerly winds, and the consequent effects on ocean circulation, carbon uptake and global teleconnections.

RR 2.3 Determine whether the recovery of the ozone hole is proceeding as expected and reveal how its recovery will affect regional and global atmospheric circulation, climate, and ecosystems.

RR 2.4 Further reveal the controls of regional patterns of atmospheric and oceanic warming and cooling in the Antarctic and Southern Ocean.

RR 2.5 Continue to determine how coupling and feedbacks between the atmosphere and the surface (land ice, sea ice and ocean) can best be represented in weather and climate models.

RR 2.6 Improve the predictability of the Antarctic climate system on a range of spatial and temporal scales, including uncertainties of the predictions.

RR 2.7 Determine how best predictions can be downscaled and/or process studies be upscaled to enable improved parametrisation and better connections with atmosphere, ice sheet, ocean, and ecosystem studies.

RR 2.8 Continue to investigate whether climate and greenhouse gas emissions thresholds exist that indicate irreversible collapse of all or part of the marine-based sectors of the Antarctic Ice Sheet.

3. Ocean

3.1 Background

The Southern Ocean circles the globe unblocked by the major continents south of 56°S and to the coast of Antarctica. Circulation of the Southern Ocean is the result of two primary flows: the strong eastward flow of the Antarctic Circumpolar Current (ACC) and a weaker overturning circulation that carries water towards or away from the Antarctic continent [Rintoul 2018]. Thus, this circulation provides the principal connections between the world's major ocean basins (**Figure 3.1**), while also largely controlling the connection between the deep and upper layers of the global ocean circulation via its upper and lower overturning cells [IPCC AR6 WGI 3.5.4.2].

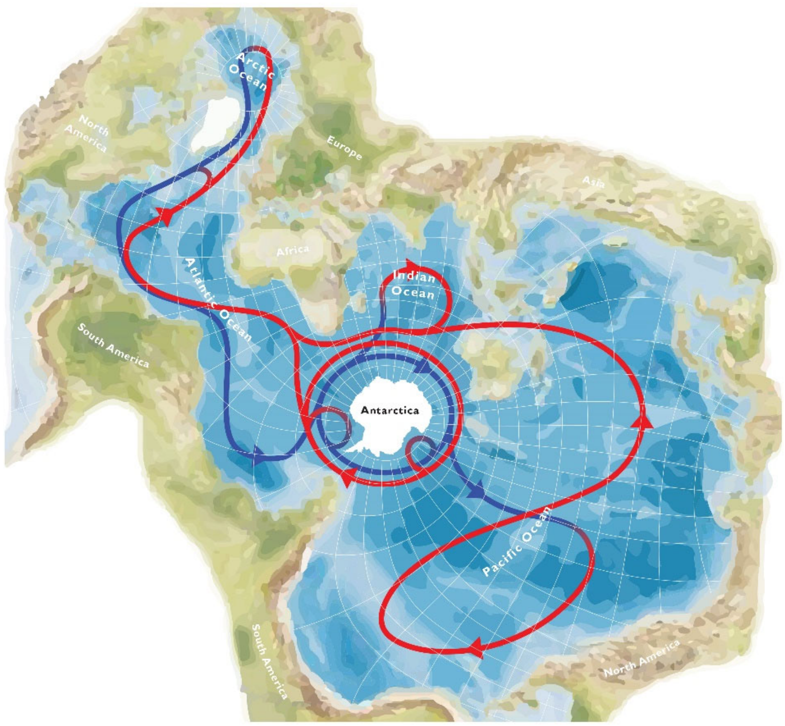


Figure 3.1 The Southern Ocean connects the global ocean. In contrast to conventional projections, this Spilhaus projection portrays the ocean fringed by land. The schematic of the global thermohaline circulation shows the connectivity of the upper-layer flow (red) and lower-layer flow (blue) (reproduced with permission from Meredith 2019).

The Southern Ocean overturning circulation plays a strong role in mediating climate change via the transfer of heat and carbon with the atmosphere [IPCC SROCC 3.2.1.2; 5.2.2.2]. It also has an impact on sea ice extent and concentration, with implications for climate via albedo. Most of the global oceans acquire their characteristics in the Southern Ocean, with ~52% of the global ocean volume making contact with the atmosphere via the Southern Ocean surface layers [De Vries & Primeau 2011].

Recent insights into the dynamics of the overturning circulation suggest the upwelling and downwelling limbs of the circulation are localised by interactions of water flow with sea-floor topography [Tamsitt *et al*. 2017]. The buoyancy added by northward transport and melt of sea ice is now recognised as essential to transforming deep water to intermediate water in the upper cell of Southern Ocean overturning [Haumann *et al*. 2016]. The strength of the Southern Ocean overturning circulation varies on decadal scales and understanding of sensitivities to changes in forcings remains incomplete [Kennicutt *et al*. 2019]. There is therefore *high confidence* that substantial climate model challenges and observational uncertainty preclude attribution of Southern Ocean circulation changes [IPCC AR6 WGI 3.5.4.2].

Much progress has, however, been made in understanding the global influence and dynamics of the Southern Ocean [IPCC AR6 WGI 3.5.4.2; 9.2.1.1; 9.2.3.2]. This work has also revealed that Southern Ocean processes have a disproportionate effect on global biogeochemical cycles, sea level, and climate [Rintoul 2018; Murphy *et al*. 2021]. These processes are connected by diverse teleconnections to low latitudes: teleconnections that encompass interactions between the ocean, cryosphere and atmosphere, but which are also the outcome of dynamics at local and regional scales, influenced by ocean bottom topography [Rintoul 2018] (**Figure 3.2**).

3.2 Observed changes and impacts

3.2.1 Temperature

Global ocean temperatures and the frequency and intensity of marine heatwaves increased throughout the 20th century due to human influence (temperature: *extremely likely*; marine heatwave frequency: *high confidence*; marine heatwave intensity: *medium confidence*) [IPCC AR6 WGI TS.2.4; Box 9.2]. Ocean warming has been most pronounced in the upper 700 m layer and in low latitudes [IPCC AR6 WGI 9.2.1.1]. Global mean sea surface temperature (SST) has warmed by 0.88°C (0.68—1.01) since 1900 (*medium confidence*) [IPCC AR6 WGI TS.2.4].

The Southern Ocean has stored a disproportionate amount of anthropogenic heat since 1870 (~75%) (*medium confidence*) [IPCC SROCC 3.2.1.2.1; IPCC AR6 WGI 9.2.2.1]. The overturning circulation takes heat added by the atmosphere, drives it north, and then into the ocean interior [Armour *et al*. 2016]. Since 1980, SSTs have warmed more slowly or even cooled in the Southern Ocean compared to the global average (*very high confidence*) due to upwelling of deeper water masses around Antarctica, upper ocean freshening from ice shelf melt, and the intensification of surface westerly winds from ozone depletion [IPCC AR6 WGI 7.4.4.1.3; 9.2.1.1].

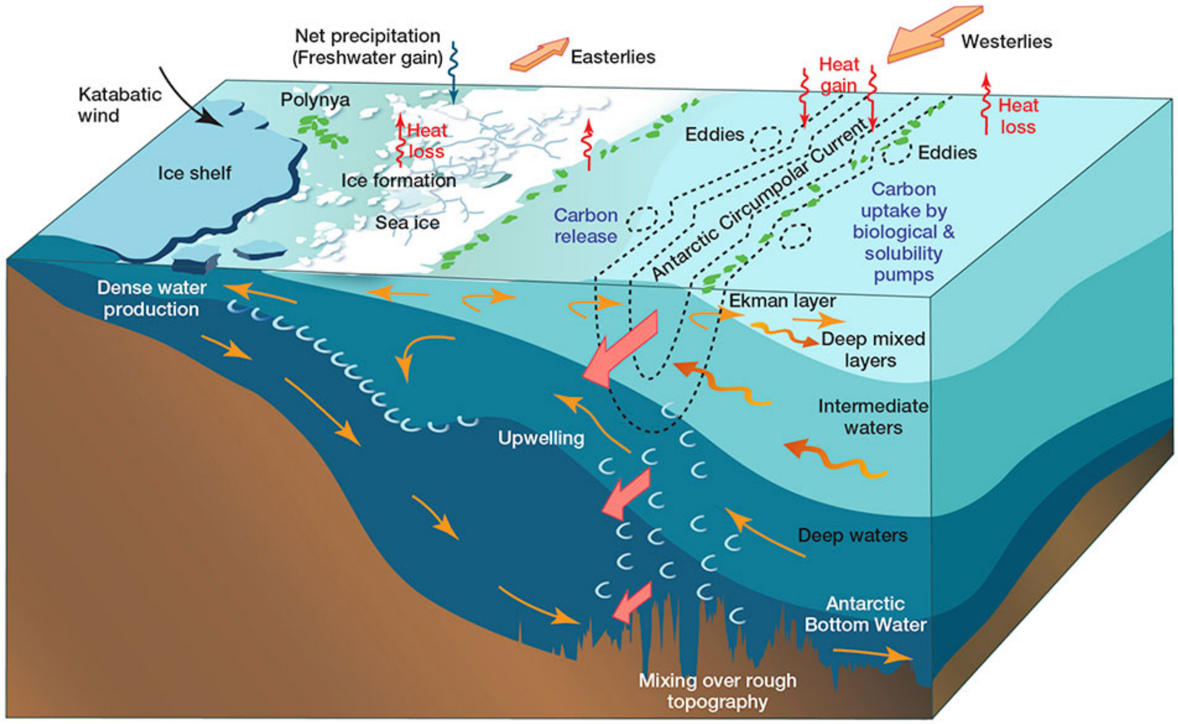


Figure 3.2 Southern Ocean dynamics. The ocean circulation is driven by wind forcing and exchange of heat and freshwater at the sea surface. The Antarctic Circumpolar Current circles the continent from west to east. Deep water flows poleward and upwells to the sea surface. Part of the upwelled water returns to lower latitudes 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 (reproduced with permission from Kennicutt *et al*. 2019).

Between 1982 and 2016, Southern Ocean surface warming was strongest to the north of the ACC (40—50ºS) [IPCC SROCC 3.2.1.2.1; IPCC AR6 WGI 9.2.1.1]. Some evidence exists of warming along the Antarctic coastal margin [Schmidtko *et al*. 2014; Bronselaer *et al.* 2020].

In contrast to surface patterns, deep ocean warming below 2 000 m has been more pronounced in the Southern Ocean than in other ocean basins due to widespread Antarctic Bottom Water (AABW) warming (*high confidence*) [IPCC AR6 WGI 9.2.2.1].

3.2.2 Ocean salinity, acidification, and dissolved oxygen

Trends in ocean salinity have been spatially variable globally (*virtually certain*) [IPCC AR6 WGI 2.3.3.2]. In the Southern Ocean, waters north of the ACC have freshened between 1950 and 2018 [IPCC SROCC 3.2.1.2.1; IPCC AR6 WGI 9.2.2.3]. Antarctic Bottom Water has freshened and decreased in density since the 1970s. This multi-decadal freshening trend has been attributed to increased supply of glacial meltwater. Climate variability has been shown to temporarily strengthen or reduce the long-term trends [Gordon *et al*. 2020; Silvano *et al*. 2020].

Ocean pH levels gradually increased over the last 50 million years (*high confidence*) [IPCC AR6 WGI 2.3.3.5]. Yet, since the 1980s, surface water pH levels have rapidly declined by 0.003—0.026 units per decade and are currently lower than at any other time in the last 26 000 years (*very high confidence*) [IPCC AR6 WGI 2.3.3.5; 5.3.2.2]. There is general consensus that the global ocean acidification trend over the last 20 years has exceeded natural variability [IPCC WGI 2.3.3.5]. Stronger acidification trends have been observed in tropical and subtropical waters than in polar regions, with limited long-term observations available for the Southern Ocean. Ocean acidification is predominately caused by the uptake of anthropogenic CO_2 from the atmosphere and the weakening of the global ocean carbon sink due to warming (*virtually certain*) [IPCC AR6 WGI 3.6.2].

Acidification trends have been strongest in the upper ocean, but declines in pH as deep as 2 000 m have been detected in the Southern Ocean (*medium confidence*) [IPCC AR6 WGI 5.3.3.1]. Declines in ocean pH reduce the saturation state of calcium carbonate ($CaCO_3$), which is the main component of the skeletons and shells of many marine species (see Section 6 Marine Life). In Antarctica, freshwater from glacial and sea ice melt and the upwelling of deep water have also resulted in a low saturation state of aragonite (a form of calcium carbonate) [IPCC AR6 WGI 5.3.2.2].

Oxygen levels in the open ocean have varied through Earth's history. After an interval of relatively cool and oxygenated oceans over the last 65 million years, the volume of oxygen-depleted open ocean waters has increased since the 1950s in association with warming SSTs (*high confidence*) [IPCC AR6 WGI 2.3.3.6]. In the upper ocean (100—600 m), total dissolved oxygen levels declined by 2% between 1970 and 2010 [IPCC AR6 WGI 5.3].

The Southern Ocean experienced the greatest absolute oxygen loss, losing 37.6 ± 0.1 Pmol between 1960 and 2010, with particularly strong decreases observed along the Antarctic coast [Schmidtko *et al.* 2017; Bronselaer *et al.* 2020]. As a percentage of global oxygen loss, the Southern Ocean had the second largest decline in oxygen content (15.8 ± 4.9% global loss) behind the North and Equatorial Pacific basins [Schmidtko *et al.* 2017].

3.2.3 Ocean circulation

No significant change has been observed in ACC transport or position over the last 20 years, despite some evidence that that the ACC has shifted poleward [IPCC AR6 WGI 2.3.3.4.2]. Due to this uncertainty, it is not possible to attribute changes in Southern Ocean circulation to anthropogenic forcing [IPCC AR6 WGI 3.5.4.2].

For the lower cell overturning circulation, there has been a slowdown of its transport consistent with an observed decrease in volume (*medium confidence*) of AABW [IPCC AR6 WGI 9.2.3.2].

Importantly, there is growing evidence that increased stratification caused by increased freshwater flux to the surface ocean can cause a shoaling and warming of the Circumpolar Deep Water (CDW), thus creating a positive feedback enhancing basal melt of the Antarctic Ice Sheet (AIS) [IPCC AR6 WGI 9.2.3.2]. Some feedback mechanisms between these ocean, atmosphere, and cryosphere climate drivers are poorly understood and not represented in current climate models [IPCC AR6 WGI 9.2.3.2].

3.3 Projected changes and risks

3.3.1 Temperature

Global mean SST is committed to rise throughout the 21st century due to human influence (*high confidence*) [IPCC AR6 WGI B.5.1, 9.2.1.1]. Global mean SST may increase by 0.86ºC (0.43—1.47) under a low emissions scenario (SSP1-2.6), and 2.89ºC (2.01—4.07) under a high emissions scenario (SSP5-8.5) by 2100, relative to a 1995—2014 reference period [IPCC AR6 WGI 9.2.1.1].

The Southern Ocean will continue to warm more slowly than the global average in the near term [IPCC AR6 WGI Fig. 9.3d].

By 2081—2100, mean Southern Ocean SST is predicted to increase by <0.5ºC under a low emissions scenario (SSP1-2.6), and <1.75ºC under a high emissions scenario (SSP5-8.5), relative to 1995—2014 [Bracegirdle *et al*. 2020]. There is, however, only *low confidence* that these warming trends will emerge by 2100, and *low agreement* among Southern Ocean temperature projections. This is due to inconsistencies between historical and near-term simulations and observations over the 20th century, as well as uncertainty around the magnitude of westerly wind changes and their effect on ocean circulation [IPCC AR6 WGI 9.2.1.1; 9.2.2.1]. Ocean warming will persist after net-zero greenhouse gas emissions targets are reached due to the slow circulation of the deep ocean (*high confidence*) [IPCC AR6 WGI 9.2.2.1].

Marine heatwaves are expected to continue to increase in intensity, duration, and frequency. Globally, marine heatwaves may become 2—15 times more frequent by 2100 under low and high emissions scenarios, although only small increases in heatwave frequency are predicted for the Southern Ocean (*medium confidence*) [IPCC AR6 WGI Box 9.2].

3.3.2 Ocean salinity, acidification, and dissolved oxygen

General circulation models indicate that relatively fresh ocean waters will become fresher into the future, while more saline waters will become increasingly saline (*medium confidence*) [IPCC AR6 WGI 9.2.2.2].

The continued melting of the Antarctic Ice Sheet will freshen the ocean surrounding Antarctica throughout the 21st century. Declines in salinity will reduce the density of AABW in the 21st century until shelf water becomes too buoyant relative to the deep layers to sink, slowing lower cell overturning circulation and increasing upper ocean stratification in the Southern Ocean (*medium confidence*) [IPCC AR6 WGI 9.2.3.2; 12.4.8].

Due to the uptake of atmospheric CO_2 by the ocean, ocean surface water pH is predicted to decline throughout the 21st century by -0.16 ± 0.002 units under a low emissions scenario (SSP1-2.6), and by -0.44 ± 0.005 units under a high emissions scenario (SSP5-8.5) [IPCC AR6 WGI 5.3.3.2; 5.3.4.1].

This acidification trend is expected to be strongest in the Southern Ocean and North Atlantic and will affect depths of over 1 km in the Southern Ocean under a medium-high emissions scenario (SSP3-7.0) [IPCC AR6 WGI Fig. 4.29].

Future expectations for undersaturation of mineral forms of calcium carbonate in the Southern Ocean vary among future climate scenarios. Under a low emissions scenario, short periods of aragonite undersaturation may occur in < 2% of the Southern Ocean by 2100. Under a high emissions scenario, however, the Southern Ocean is expected to experience aragonite undersaturation by 2030, with large areas (95%) undersaturated for at least one month of each year by the end of the century [IPCC SROCC 3.2.2.3; IPCC AR6 WGI 5.3.4.1].

Ocean waters are expected to deoxygenate further throughout the 21st century. Declines in subsurface (100—600 m) oxygen levels are projected in the *likely* range of 6.4 ± 2.9 mmol m^{-3} under a low emissions scenario (SSP1-2.6) by 2080—2099, relative to 1870—1899 levels, and 13.3 ± 5.3 mmol m^{-3} under a high emissions scenario (SSP5-8.5) [IPCC AR6 WGI 5.3.3.2].

3.3.3 Ocean circulation

Strengthening westerly winds will *very likely* force an increase of the Southern Ocean eddy field, while there is *medium confidence* that the ACC is weakly sensitive to wind change, with *limited evidence* that the ACC transport will nevertheless increase [IPCC AR6 WGI 9.2.3.2].

For the lower cell overturning circulation, confidence has strengthened that increased glacial meltwater flux will reduce the density of bottom waters over this century. The lower cell overturning circulation will, as a consequence, eventually be slowed [IPCC AR6 WGI 9.2.3.2]. Overall, observational, numerical and paleoclimate evidence provides *medium confidence* that the lower cell will continue decreasing in the 21st century as a result of increased basal melt from the AIS.

Increased freshwater input into the Southern Ocean from AIS melt may reduce overturning circulation, thereby increasing the ocean's carbon sink. Alternatively, strengthening winds may increase overturning circulation, reducing the capacity of the Southern Ocean to take up atmospheric CO_2 [IPCC AR6 WGI 5.4.4.1]. Due to the uncertainty about the contributions of these physical drivers, there is *low confidence* in the long-term effect of strengthening winds on the Southern Ocean CO_2 uptake [IPCC AR6 WGI 5.4.4.1].

Freshwater input may also increase ocean stratification and contribute to the poleward shift and warming of the CDW layer around Antarctica, which will in turn increase basal melt of the AIS through a positive feedback mechanism [IPCC AR6 WGI 9.2.3.2]. Multiple lines of evidence provide *high confidence* that changes in wind pattern, increased ice shelf melt, and eddies can facilitate access of CDW to sub-ice shelf cavities. But there is *low confidence* in the quantification, importance and the ability of present models to project changes in each of these processes There is, therefore, little consensus on future changes to CDW and thus *low confidence* in its effect on Antarctic ice shelf melt [IPCC AR6 WGI 9.4.2.3].

3.4 Policy recommendation

The Southern Ocean is undergoing changes and these changes will continue under higher emissions scenarios. Major impacts on the cryosphere, marine ecosystems and their constituent species, and consequently on the ecosystem services they deliver, including on systems and services outside the Antarctic region, are expected. Significant changes are anticipated in areas that may be especially vulnerable to ice sheet instability and collapse once thresholds are reached. Changes to the Southern Ocean and its ecosystems will present growing management difficulties, logistics challenges and research requirements that will require special attention within the Antarctic Treaty System. Research on these questions, including through expanded long-term monitoring, is imperative.

3.5 Research recommendations

RR 3.1 Understand how changes in atmospheric circulation drive changes in ocean currents around Antarctica and the advection of ocean heat onto the continental shelf, into the ice shelf cavities and in contact with the glaciers, and the influence of meltwater feedbacks.

RR 3.2 Explore how changes in the Southern Ocean result in feedbacks that accelerate or slow the pace of climate change.

RR 3.3 Determine why the properties and volume of Antarctic Bottom Water are changing, and what the consequences are for global ocean circulation and climate.

RR 3.4 Examine how changes in freshwater inputs from increased iceberg calving and ice shelf basal melting affect ocean circulation and ecosystem processes.

RR 3.5 Investigate how Southern Ocean circulation, including exchange with lower latitudes, responds to climate forcing.

RR 3.6 Quantify how climate change will affect the physical and biological capacity of the Southern Ocean for uptake of CO_2 and long-term storage of carbon.

4. Cryosphere

4.1 Background

The ocean and atmosphere interact with the Antarctic cryosphere in a multitude of ways (**Figure 4.1**). The vast Antarctic ice sheets hold close to 58 m (West Antarctic Ice Sheet (WAIS) ~5.6 m, East Antarctic Ice Sheet (EAIS ~52.3 m)) of potential global mean sea level (GMSL) rise [Morlighem *et al*. 2020]. Satellite observations indicate an acceleration of ice loss has occurred over the last 30 years, and ice sheet models indicate this acceleration in mass loss will continue in a linear fashion well-beyond the end of the century if greenhouse gas emissions continue to increase [Edwards *et al*. 2021]. One third of the Antarctic Ice Sheet (AIS) is marine-based, resting on bedrock below sea level, and most of the ice sheet margin terminates in the ocean, making it susceptible to dynamical non-linear instabilities that can cause rapid ice loss in decades to centuries [e.g., Pattyn & Morlighem 2020], such as Marine Ice Sheet Instability (MISI) and Marine Ice Cliff Instability (MICI) [IPCC AR6 WGI Box 9.4] (see Box 4.1 below). The seaward-flowing ice forms floating ice shelves. Ice shelves in contact with bathymetric highs in the seafloor or confined within embayments provide back-pressure (buttressing) that impedes the flow of upstream ice. Disintegration of ice shelves will therefore play a key role in the pace of future ice mass loss from the upstream regions of these ice shelves. Paleoclimate data and models have shown that small increases in ocean temperature have the potential to rapidly initiate destabilisation of ice shelves and melt large sections of an ice sheet that could occur within, and be irreversible on, human time scales [Golledge *et al*. 2015; Grant *et al*. 2019; DeConto *et al*. 2021].

In addition to the effects of these instabilities, the rates of Antarctic ice mass loss and GMSL rise will be affected by complex interactions among ice, ocean, atmosphere, and solid Earth processes. These interactions involve both positive and negative feedbacks that amplify and reduce the rate of GMSL rise, respectively. The formation of sea ice doubles the area of frozen water over the southern high latitudes on an annual basis and regulates the production of dense ocean water that contributes to the deep ocean circulation. The seasonal sea ice apron, together with a deep, well-mixed circum-Antarctic ocean also regulates the exchange of heat and gas between the ocean and the atmosphere, and has allowed vast amounts of CO_2 and heat from global warming to be taken up by the Southern Ocean. While this process and the presence of the ozone hole are delaying the emergence of an anthropogenic zonal surface warming signal, both models (by 2100) and paleoclimate data indicate Antarctic polar temperature amplification (2—3 times the global average) will occur in response to present atmospheric greenhouse gas (GHG) concentration [Masson-Delmotte *et al*. 2013; IPCC AR6 WGI]. This will release large amounts of glacier and ice sheet meltwater into the surface ocean disrupting deep overturning circulation of the ocean, causing global climate impacts [Knutti *et al*. 2004; Golledge *et al*. 2019]. Meltwater around the Antarctic surface causes changes in surface ocean salinity, stratification and circulation that feedback to generate further ocean-driven melting of marine-based ice sheets [Silvano *et al*. 2018; Golledge *et al*. 2019] and promote sea ice formation [Purich *et al*. 2018].

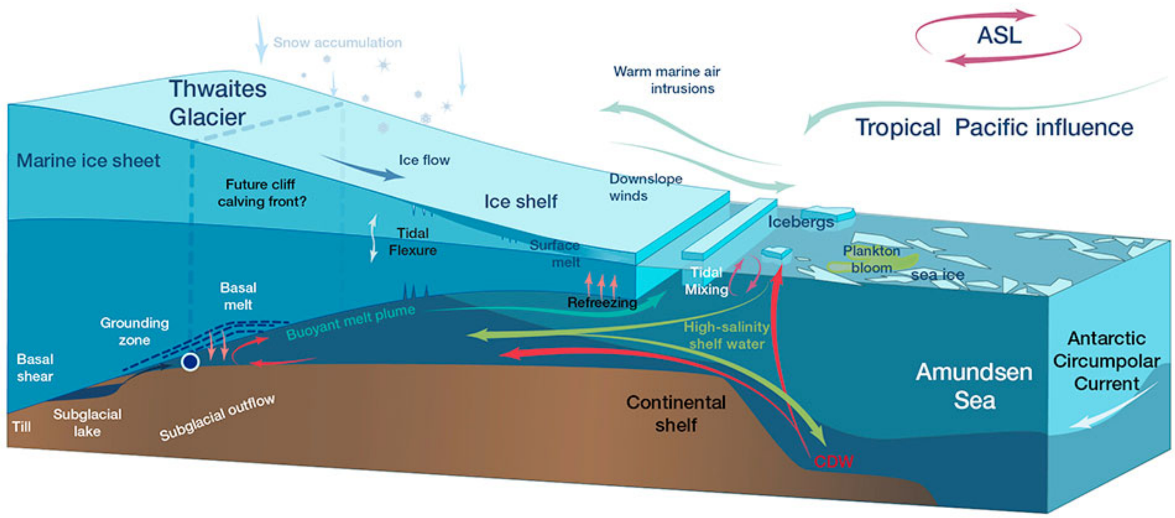


Figure 4.1 Antarctic coastal regions are influenced by various processes. The principal influences on Antarctic ice sheets and ice shelves such as snow, winds, ocean currents and calving fronts are pictured using Thwaites Glacier as an example (CDW, Circumpolar Deep Water; ASL, the Amundsen Sea Low) (reproduced with permission from Kennicutt *et al*. 2019, original by Scambos *et al*. 2017).

Subglacial hydrology under the AIS is a critical part of the Antarctic system. It modulates ice flow [Fricker *et al*. 2007] and provides an unusual habitat for life [Mikucki *et al*. 2016]. Subglacial meltwater is widespread as nearly half of the AIS is melting at its base due to geothermal heat flow and pressure melting. Meltwater is transported by a vast network of subglacial rivers and accumulates in sub-ice sheet lakes, which are abundant on the continent, with 675 now identified [Livingstone *et al*. 2022]. They are expected to decline in number with a decline in the extent of the AIS. For example, a subglacial lake beneath the Crane Glacier in the Antarctic Peninsula drained following ice shelf collapse and a steepening of the glacier [Scambos *et al*. 2011]. Nonetheless, local factors will affect how such change proceeds across the continent, leading to different projections for different areas of the continent [Livingstone *et al*. 2022]. The ice sheet also has a capacity to alter its bed as the solid Earth adjusts to ice mass loss — a process known as glacial isostatic adjustment (GIA) [Whitehouse *et al*. 2019]. Unlike most feedbacks affecting ice sheets, which amplify mass loss, GIA might help stabilise a retreating ice margin by creating subglacial pinning points on the seafloor [Kingslake *et al*. 2018].

Permafrost is an important part of the cryosphere, but is sometimes overlooked as a component of the Antarctic system. It is usually defined as ground that remains at or below 0°C for at least two consecutive years [Smith *et al*. 2022]. Less than 25% of Antarctica apparently has subglacial permafrost [Hrbáček *et al*. 2021], and ice-free ground on which permafrost occurs covers a limited area of the continent (<0.5%) [Burton-Johnson *et al*. 2016]. Permafrost underlies Antarctic soils everywhere, with three main kinds being distinguished: ice-cemented permafrost, ice-free permafrost and saline permafrost [Campbell & Claridge 2009; Verret *et al*. 2021].

Monitoring of the permafrost by assessments of active layer thawing depth and active layer thickness is being undertaken through the Circumpolar Active Layer Monitoring – South (CALM-S) program at a range of sites across Antarctica [Hrbáček *et al*. 2021].

4.2 Sea ice

4.2.1 Observed changes and impacts

Antarctic sea ice extent (SIE) has shown substantial interannual and regional variation since observations began [IPCC SROCC 3.2.1.1.1; IPCC SR1.5 3.3.8; IPCC AR6 WGI 2.3.2.1.2].

Antarctic summer SIE decreased from the early- to mid-20th century, although *low confidence* exists in observations prior to the satellite era (i.e., 1960s) [IPCC AR6 WGI 2.3.2.1.2]. Declines in winter SIE have been more regionally variable, decreasing slightly in East Antarctica and the Amundsen and Bellingshausen Seas [IPCC AR6 WGI 2.3.2.1.2; 9.3.2.1].

New evidence suggests that SIE increased slightly in the Ross Sea region over the 20th century, linked to the deepening of the Amundsen Sea Low [IPCC AR6 WGI 9.3.2.1]. Between 1979—1988 and 2010—2019, only minor changes were observed in decadal averages of summer and winter Antarctic sea ice areas (*high confidence*), yet both record-high and record-low sea ice extents were observed between 2012 and 2017 [IPCC AR6 WGI 2.3.2.1.2]. Antarctic sea ice reached its lowest extent recorded (since 1979) in February 2022 [Thompson 2022; Raphael & Handcock 2022].

Changes in Antarctic SIE are thought to be driven by the strengthening of westerly winds, near-surface ocean stratification, and ice sheet and ice shelf melt, although the relative contributions of these drivers remain uncertain due to limited observations and disagreement among models [IPCC AR6 WGI 9.3.2.1]. *Low confidence* exists in trends in Antarctic sea ice thickness due to a lack of observations, and disagreement among *in situ* observations and climate models in the Weddell Sea showing an increase and decrease in sea ice thickness over the last century, respectively [IPCC SROCC 3.2.1.1.1; IPCC AR6 WGI 9.3.2.2].

Antarctic sea ice limits the heat flux from the relatively warm ocean to the air, creating low temperature conditions on land [Turner *et al*. 2021].

4.2.2 Projected changes and risks

There is *low confidence* in Antarctic sea ice predictions for the remainder of the 21st century due to disagreement between model projections and observations, and uncertainty caused by seasonal cycles, interannual sea ice variability and the long-term increase in sea ice extent [IPCC SROCC 3.2.2.1; IPCC AR6 WGI 9.3.2]. Model improvement, including explicit simulation of Southern Ocean eddies, is required to address these uncertainties [Rackow *et al*. 2022].

4.3 Ice shelves

4.3.1 Observed changes and impacts

Some Antarctic ice shelves began to thin, retreat, and, in some instances, disintegrate, in the second half of the 20th century.

The rate of ice shelf thinning has varied in recent decades, increasing from 1100 ± 150 Gt per year in the mid-1990s, to 1570 ± 140 Gt per year in the late 2000s [IPCC AR6 WGI 9.4.2.1]. In 2018, this rate had returned to 1160 ± 150 Gt per year, reflecting decadal variability in the intrusion of warm Circumpolar Deep Water (CDW) onto the Antarctic continental shelf [IPCC AR6 WGI 9.4.2.1]. Basal melt from warm ocean waters caused the thinning of the eastern ice shelf of the Thwaites Glacier in the Amundsen Sea, where the ice shelf lost 10—33% of its volume between 1978 and 2008 [IPCC AR6 WGI 9.4.2.1]. There is *limited evidence* that wind-driven changes to the circulation of CDW between 1920 and 2018 were caused by anthropogenic forcing [IPCC AR6 WGI 9.4.2.1].

Between 1995 and 2009, the Larsen A and B and Wilkins ice shelves around the Antarctic Peninsula rapidly disintegrated [IPCC AR6 WGI 9.4.2.1]. These events have been attributed to the ponding of meltwater on their surfaces causing hydrofracturing, the loss of their sea ice buffers which exposed the ice shelves to storm-generated ocean swells, and increased regional sea surface temperatures (SSTs) enhancing sub-surface melt [IPCC AR6 WGI 9.4.2.1].

The thinning, retreat and disintegration of Antarctica's ice shelves has increased AIS mass loss (*very high confidence*) (see Section 4.4 Ice Sheets) [IPCC AR6 WGI 9.4.2.1].

4.3.2 Projected changes and risks

Projections for future changes to Antarctic ice shelves are characterised by *low confidence* and *deep uncertainty*. There is *low confidence* in sub-ice shelf melt rate predictions for the 21st century due to limitations in modelling ice shelf cavity melt rates and variation among observations of basal melt sensitivities in the Weddell and Amundsen Seas [IPCC AR6 WGI 9.4.2.3]. Likewise, there is *low confidence* in projections for ice shelf disintegration around Antarctica due to modelling uncertainties around meltwater feedbacks on ice shelves, which may both increase sub-shelf melting and decrease ice shelf surface melt [IPCC AR6 WGI 9.4.2.3].

Rapid and potentially irreversible ice shelf loss may occur via two processes, sub-ice shelf ocean-driven melting and surface melting and hydrofracturing, the latter caused by high meltwater production on the surface of the ice shelf. Without their stabilising ice shelves, glaciers may lose mass rapidly due to non-linear processes of Marine Ice Sheet Instability (MISI) and Marine Ice Cliff Instability (MICI) which could lead to the collapse of an ice sheet sector, or even the entire WAIS [IPCC SROCC Cross Chapter Box 8; IPCC AR6 WGI 9.4.2.4; Box 9.4]. The potential for these poorly understood instabilities to cause rapid future ice mass loss, and therefore sea level rise, above the projected *likely* ranges for emissions scenarios IPCC AR6 WGI SPM] are outlined below in Box 4.1.

Box 4.1 Antarctic Ice Sheet instabilities and high-end sea level rise

Instabilities

A major uncertainty in future Antarctic ice mass loss is the possibility of rapid and/or irreversible ice loss through instability of marine parts of the ice sheet, proposed via the mechanisms of Marine Ice Sheet Instability (MISI) and Marine Ice Cliff Instability (MICI), and whether these processes will lead to a collapse of the WAIS [summarised in Pattyn & Morlighem 2020; IPCC AR6 WGI 9.4.2.2; 9.4.2.3] (**Figure 4.2**).

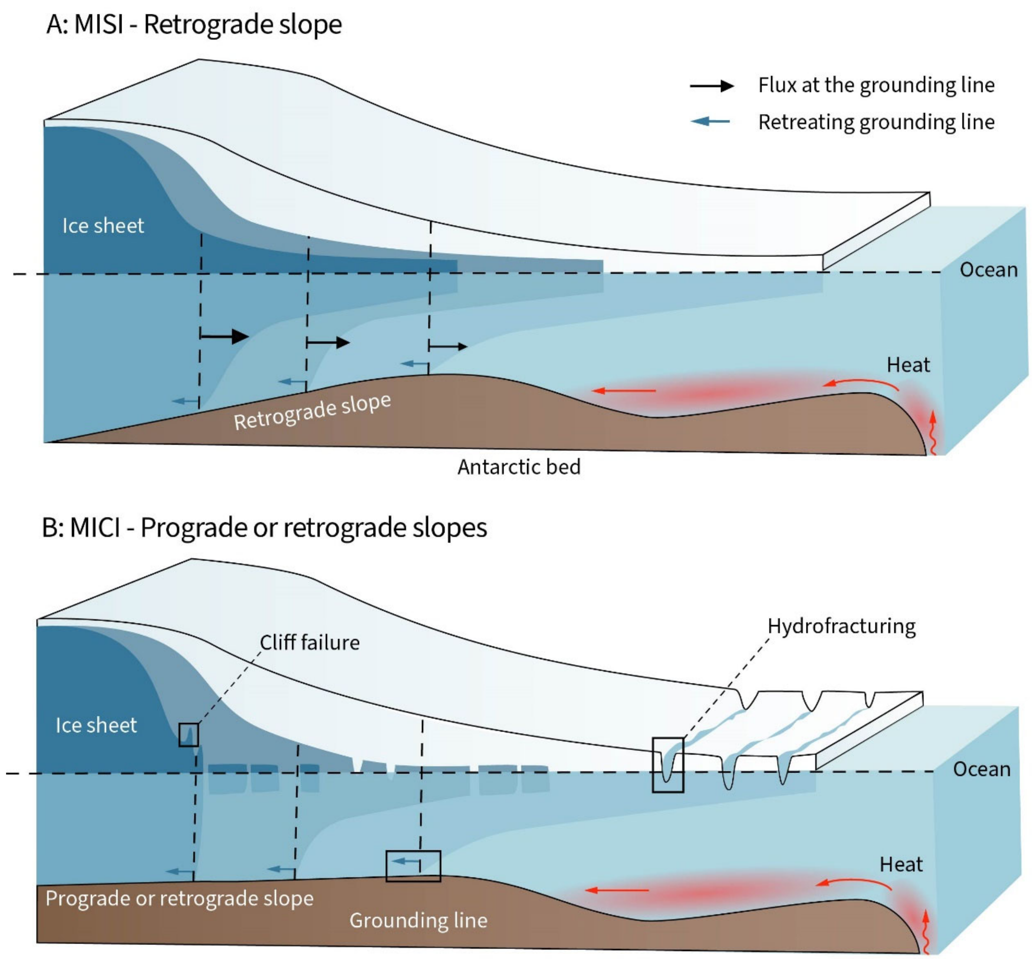


Figure. 4.2. Schematics of the marine ice sheet instability and marine ice cliff instability. (A) Marine Ice Sheet Instability (MISI), invoking unstable grounding line retreat on retrograde bed slopes due to reduced ice shelf buttressing. (B) Marine Ice Cliff Instability (MICI), where grounded ice cliffs may rapidly collapse after ice shelf breakup (redrawn with permission from Pattyn & Morlighem 2020).

MISI is a proposed self-reinforcing mechanism within marine ice sheets that lie on a bed that slopes down towards the interior of the ice sheet, whereby, in the absence of ice shelf buttressing, the position of the grounding line is inherently unstable until reaching an upward sloping bed (**Figure 4.2A**). As the ice sheet retreats down a reverse slope, the height of the ice sheet above the grounding line increases leading to an exponential increase in the flux of ice across the grounding line, that is potentially unstoppable.

The sea level rise contribution of the AIS therefore crucially depends on the behaviour of individual ice shelves and the timing of their demise, and outlet glacier systems and whether they enter MISI for a given level of warming. For Antarctic simulations generally [IPCC AR6 WGI 9.4.2.2; 9.4.2.3], there is *medium confidence* in simulating MISI, but *low confidence* in projecting the sub-ice shelf melting and ice shelf disintegration that drive it.

The MICI hypothesis describes rapid, unmitigated ice cliff calving (**Figure 4.2B**) triggered by, but also occurring after, ice shelf collapse [Pollard *et al*. 2015]. New simulations show later 21st and 22nd century ice shelf disintegration, in agreement with other models [DeConto *et al*. 2021; IPCC AR6 WGI 9.4.2.3], and therefore higher Antarctic ice mass loss projections at 2100 [IPCC AR1 WGI 9.4.2.5; DeConto & Pollard 2016]. New theoretical evidence suggests that ice cliff collapse may only occur after very rapid ice shelf disintegration caused by unusually high meltwater production [Clerc *et al*. 2019; Robel & Banwell 2019], and that the subsequent rate of retreat depends on the terminus geometry [Bassis & Ultee 2019]. Only Crane Glacier on the Peninsula has shown retreat consistent with MICI, after the Larsen B ice shelf collapsed. MICI-style behaviour at Jakobshavn and Helheim glaciers in Greenland might not be representative of wider Antarctic glaciers. Observations from Greenland show that steep cliffs commonly evolve into short floating extensions, rather than collapsing catastrophically [Joughin *et al*. 2020]. There is therefore *low confidence* in simulating mechanisms that have the potential to cause widespread, sustained and very rapid ice loss from Antarctica this century through MICI, and *low confidence* in projecting the drivers of ice shelf disintegration [IPCC AR6 WGI 9.4.2.2; 9.4.2.3].

In summary, poorly understood processes of instabilities, characterised by *deep uncertainty*, have the potential to strongly increase Antarctic mass loss under high greenhouse gas emissions on century to multi-century timescales [IPCC AR6 WGI 9.4.2.2, 9.4.2.3; Box 9.4]. These instabilities were therefore considered separately in assessments of the future contribution to GMSL rise in the IPCC AR6 WGI Report.

A high-end sea level projection (low confidence-high impact)

Stakeholders with a low risk tolerance (e.g., those planning for coastal safety in cities and long-term investment in critical infrastructure) may wish to consider GMSL above the assessed *likely* range by the year 2100 (0.33—1.02 m) [IPCC AR6 WGI 9.6.3.3], because "*likely*" implies an assessed likelihood of up to 16 % that sea level rise by 2100 will be higher. Therefore, in light of this deep uncertainty, IPCC AR6 WGI [Box 9.4] presents a storyline for high-end sea level projections that considers rate-determining processes known with *low-confidence* that drive faster-than-projected disintegration of marine ice shelves leading to the abrupt, widespread onset of MICI and MISI in Antarctica. The main uncertainty related to high-end sea level rise is considered to be "when" rather than "if" the processes will occur. This uncertainty is strongly linked to the time of emergence of an amplified global warming signal over Antarctica with associated positive feedbacks. Hence, GMSL might rise well above the *likely* range of SSP5-8.5 (1.02 m) before 2100, which is reflected by assessments of ice sheet contributions based on structured expert judgment [Bamber *et al*. 2019].

In Antarctica, high warming might lead to widespread hydrofracturing and ocean thermal melting of ice shelves [IPCC AR6 WGI, Box 9.4]. In particular, the Thwaites and Pine Island Glacier ice shelves could potentially disintegrate this century, which might trigger MICI before 2100. MISI could potentially develop earlier and faster than simulated by the majority of models if fast flowing ice streams follow plastic, instead of currently assumed more viscous, sliding. Oceanic forcing could drive high-end sea level rise by meltwater-driven feed backs. The strength of all these processes depends strongly on global mean temperature and polar amplification, with additional solid earth linkages through feedbacks from global mean sea level [Gomez *et al*. 2020]. Global mean sea level rise by 2100 is substantially higher in projections including *low confidence* processes reaching in 2100 as high as 1.6 m at the 83rd percentile and 2.3 m at the 95th percentile. Global mean sea level rise above the likely range – approaching 2 m by 2100 and 5 m by 2150 under a very high GHG emissions scenario (SSP5-8.5) (low confidence) – cannot be ruled out due to deep uncertainty in ice sheet processes [IPCC AR6 WGI SPM B.5.3].

The urgency to improve knowledge of non-linear processes that drive MICI, MISI and ice shelf disintegration and their relative importance in model projections of future Antarctica ice mass loss is a high priority research area currently being addressed by SCAR's new strategic research programmes ANTClimNow and INSTANT [Colleoni *et al*. 2021; SCAR 2022] and the World Climate Research Programme's Climate and Cryosphere Core Project [WCRP 2022].

4.4 Ice sheets

4.4.1 Observed changes and impacts

The Greenland and Antarctic Ice Sheets lost a combined 7 560 Gt of ice between 1992 and 2020, with greater mass losses observed in Greenland (4 890 Gt (4 140—5 640)) than in Antarctica (2 670 Gt (1 800—3 540)) [IPCC AR6 WGI 2.3.2.4].

The rate of AIS mass loss has accelerated since 2006 (*very high confidence*) due to major losses from the WAIS and the Antarctic Peninsula [IPCC SROCC 3.3.1.1; IPCC AR6 WGI 9.4.2.1].

Mass loss from the AIS is dominated by the rapid acceleration, retreat, and dynamic thinning of the outlet glaciers of the WAIS (*very high confidence*) [IPCC AR6 WGI 9.4.2.1].

In East Antarctica, no significant ice sheet mass loss has been observed, except in Wilkes Land [IPCC AR6 WGI 2.3.2.4.2]. In Wilkes Land, there is *high confidence* that the Totten Glacier has lost mass since 2000 [IPCC AR6 WGI 9.4.2.1].

Many Antarctic glaciers have recently experienced grounding-line retreat associated with dynamic thinning, including glaciers on the WAIS (e.g., Pine Island, Smith, and Thwaites glaciers), Antarctic Peninsula, and the Totten and Denman Glaciers in East Antarctica (*high confidence*) [IPCC AR6 WGI 9.4.2.1].

In the Amundsen Sea Embayment of the WAIS, the grounding-line retreat of several glaciers may indicate the onset of high-impact, low-probability MISI (*medium confidence*) [IPCC AR6 WGI 9.4.2.1], although other climate drivers may also be responsible.

While it is *very likely* that anthropogenic forcing contributed to recent Greenland Ice Sheet melt, there is *medium agreement* but *limited evidence* that human influence caused the observed reduction in AIS mass since 1950 [IPCC AR6 WGI 3.4.3.2]. Ice loss from the WAIS is predominately driven by basal melt of ice shelves by warm ocean waters, however, there is a *lack of consensus* among experts as to whether this basal melt is driven by anthropogenic forcing and its effect on wind-driven ocean currents, or natural variability [IPCC AR6 WGI 3.4.3.2].

4.4.2 Projected changes and risks

Under all Socio-Economic Pathways, it is *likely* that the AIS is committed to lose mass throughout the 21st century due to ocean warming and ice shelf disintegration (*medium confidence*) [IPCC AR6 WGI 9.4.2.5]. At 2ºC of warming, basal melt of the WAIS and/or MICI may cause a large or total loss of the WAIS over multi-century timescales (*low confidence*) [IPCC AR6 WGI 9.4.2.6].

The SROCC assessed that ice sheet interactions with the solid Earth are not expected to substantially slow sea level rise from marine-based ice in Antarctica over the 21st century (*medium confidence*), but that these processes could become important on multi-century and longer time scales. More recent modelling of deglaciation of the Ross Embayment is consistent with this assessment [Lowry *et al*. 2020]. However, new projections for Pine Island Glacier [Kachuck *et al*. 2020] support previous work [Barletta *et al*. 2018] suggesting lower mantle viscosity in this region leads to a negative feedback on decadal time scales. Grounding-line stabilisation by the solid Earth response may therefore occur over the 21st century in the Amundsen Sea Embayment, where most mass loss is occurring [IPCC AR6 WGI 9.4.2.1], but more generally occurs over multi-centennial to millennial timescales (*medium confidence*).

Even if warming is limited to less than 2ºC above pre-industrial temperatures (i.e., the goal of the Paris Climate Agreement), the loss of the WAIS may still occur over millennia and returning atmospheric temperatures to pre-industrial conditions may not be enough to prevent or reverse this loss (*limited agreement, medium confidence*) [IPCC AR6 WGI 9.4.2.6].

Ice sheets require tens of thousands of years to re-grow after they are lost, creating long-term consequences for global sea level. Antarctic Ice Sheet loss may, therefore, be irreversible over decades to millennia (*low confidence*) [IPCC SROCC 3]. Many challenges remain in assessing the complex and partially non-linear causes of accelerated ice sheet loss, thus process studies and simulations constrained by robust observations are key to better projections.

4.5 Frozen ground

4.5.1 Observed changes and impacts

The establishment of permafrost monitoring sites in Antarctica is much more recent than for the Northern Hemisphere and a limited number of sites exists. Some indication exists of temperature increases at shallow depths since 2010, but at greater depths longer-term trends are less evident [Biskaborn *et al*. 2019; Smith *et al*. 2022]. Continuous-zone permafrost temperatures increased by 0.37 ± 0.10°C over the 2007 to 2016 period [IPCC SROCC 3.3; 3.4.1.2.1].

In the ice-free regions of Antarctica, Active Layer Thickness has been monitored at 16 ice-free area sites across Antarctica since 2006. No evidence of longer-term increasing trends has been found and inter-annual variability is high [Smith *et al*. 2022].

4.5.2 Projected changes and risks

Permafrost is projected to thaw in all regions where it is present (*high confidence*) [IPCC AR6 WGI TS 4.3.1]. Simulations predict ongoing warming and permafrost degradation, but considerable uncertainty exists about the magnitude and timing of expected changes [Smith *et al*. 2022].

The total area of ice-free ground in Antarctica is expected to expand under future climate scenarios by as much as 25% by 2098 [Lee *et al*. 2017]. Changes to ice-coverage are expected to be most pronounced along the northern Antarctic Peninsula and on the maritime Antarctic islands.

4.6 Policy recommendations

The Antarctic Ice Sheet (AIS) is changing rapidly, with the anthropogenic signal starting to become apparent. The AIS is projected to contribute substantially to global mean sea level rise, but the risks of significantly larger rates and magnitudes of sea level rise from rapid ice sheet mass loss in the coming decades to centuries are not well known, particularly from vulnerable marine basins in West Antarctica and parts of East Antarctica. Reducing this uncertainty is a globally urgent research priority that will require further support from National Antarctic Programs (NAPs). Novel observations along sensitive marine-based sectors, and from paleoclimate archives, are urgently needed over the time scale of a decade to improve understanding of the physical processes driving the retreat, document the current evolution in detail, and comprehensively, and critically improve the skills of numerical projections.

The loss of sea ice, fast ice and ice shelves together with the expansion of ice-free areas on the Antarctic continent and changes to temperatures and precipitation, including extreme weather events, will present new challenges for the management of areas of high human activity in the Antarctic (including where infrastructure and other NAP assets are deployed). Biodiversity will change and conditions will become more suitable for the establishment of non-native species, especially along the Antarctic Peninsula. These challenges should be urgently addressed by the Antarctic Treaty Parties and by members of the Committee for Environmental Protection.

4.7 Research recommendations

RR 4.1 Reconstruct how Antarctic sea ice extent and volume varied over multi-decadal to millennial timescales and monitor ongoing changes.

RR 4.2 Determine Antarctic mass balance accurately and analyse its driving mechanisms in different regions in Antarctica over decadal to millennial timescales.

RR 4.3 Reveal how oceanic processes beneath ice shelves vary in space and time, how they are modified by sea ice, and how they affect ice shelf stability or potential ice shelf loss.

RR 4.4 Determine how small-scale morphology in subglacial and continental shelf bathymetry affects Antarctic Ice Sheet response to changing environmental conditions. Major gaps in the bathymetry chart of the Southern Ocean should be filled by providing additional coverage from multibeam echosounders, especially in East Antarctica.

RR 4.5 Further reveal how large-scale processes in the Southern Ocean and atmosphere will affect the Antarctic Ice Sheet, particularly the rapid disintegration of ice shelves and ice sheet margins, including an exploration of ice shelf cavities.

RR 4.6 Further understand what the processes and properties are that control the form and flow of the Antarctic Ice Sheet.

RR 4.7 Better understand how subglacial hydrology affects ice sheet dynamics, and how important the process is for ice sheet fate.

RR 4.8 Determine how the characteristics of the ice sheet bed, such as geothermal heat flux and sediment distribution, affect ice flow and ice sheet stability.

RR 4.9 Determine which are the key rate-determining processes affecting the mass loss of marine-based sectors of the Antarctic Ice Sheet, and incorporate these into the next generation of process-based ice sheet models.

RR 4.10 Reveal how fast the Antarctic Ice Sheet has changed in the past and what information that provides about the future.

RR 4.11 Use the sedimentary record beneath the ice sheet and the ocean floor around the periphery of Antarctica to inform knowledge of the historical presence or absence of continental ice and discern the causes.

RR 4.12 Assess how changes in ocean surface waves influence Antarctic sea ice, land-fast ice and ice shelves.

RR 4.13 Define how changes in sea ice extent, seasonality and other properties affect Antarctic atmospheric and oceanic circulation.

RR 4.14 Continue to determine how changes in surface melt in the coastal regions will evolve, and what the impact of these changes will be in the context of ice mass loss and ocean circulation.

RR 4.15 Understand the pattern of freshwater release from iceberg calving, their numbers and size distribution, and how this affects Antarctica and the Southern Ocean.

RR 4.16 Determine whether increased crustal deformation, seismicity, and volcanism will characterise Antarctica if its ice sheet mass is greatly reduced in the future, and if so, how glacial systems and ecosystems will be affected.

RR 4.17 Determine how permafrost, the active layer and water availability in Antarctic soils and marine sediments will change in a warming climate and reveal what the effects are and will be on ecosystems and biogeochemical cycles.

5. Sea Level

5.1 Background

The Antarctic Ice Sheet (AIS) contains enough water to contribute, if totally melted, approximately 58 m of global mean sea level (GMSL) rise. Such extensive mass loss is not expected even in models extending out to 2300 [DeConto *et al*. 2021]. Nonetheless, land ice (Antarctic, Arctic and mountain glaciers) is losing mass at an accelerating rate [Hugonnet *et al*. 2021], placing approximately 800 million people at risk from sea level rise [IPCC AR6 WGII].

Antarctic contributions to GMSL over coming centuries will be net positive, and will largely depend on how marine-based sectors of both the West and East Antarctic ice sheets evolve in response to global warming, although the rate and magnitude of that contribution remains uncertain [Bamber *et al*. 2019; Golledge *et al*. 2019; Edwards *et al*. 2021]. It is clear that if the targets of the Paris Climate Agreement are not met, contributions to sea level rise will increase [Frederikse *et al*. 2020; Garbe *et al*. 2020; DeConto *et al*. 2021], with significant implications for society and for natural systems, including through impacts associated with multiple and compounding sea level driven hazards; increased frequency of storm surge, coastal erosion, landslides, groundwater inundation and salinisation [Chown & Duffy 2017; Le Cozannet *et al*. 2017; Brown *et al*. 2018; IPCC AR6 WGII Figure SPM.2; SPM B.2.5; SPM B.3.1].

The uncertainty in estimates of future contributions of the AIS to sea level rise stems from a lack of comprehensive understanding of the key rate-determining processes (see Section 4.1, including Marine Ice Sheet Instability (MISI) and Marine Ice Cliff Instability (MICI) [DeConto *et al*. 2021; Edwards *et al*. 2021]). This has resulted in the release of a low-probability, high-impact future sea level rise scenario in IPCC AR6, based on a numerical ice sheet model that included MICI, in which global mean sea level (GMSL) rise of up to 2 meters by 2100 could not be ruled out.

Antarctic Ice Sheet contribution remains the biggest uncertainty in predicting global sea level rise [van de Wal *et al*. 2019; Colleoni *et al*. 2022]. Reducing the process uncertainty in ice sheet models remains a key priority for the effective anticipation and appropriate management of climate and sea level rise impacts and risks for coastal zone stakeholders and users [Haasnoot *et al*. 2020; McMichael *et al*. 2020; IPCC AR6 WGII SPM B.4.5] (**Figure 5.1**). Furthermore, equitable decision-making and solutions within the context of changing economic and social conditions, such as both domestic and international migration [Hauer *et al*. 2020], require a means to incorporate uncertainty [Hinkel *et al*. 2019] into such planning, as many users have a wide range of values and tolerance to risk and action. Planning of this nature is being incorporated by many regional, state, and city agencies [e.g., Haasnoot *et al*. 2020] and is also now becoming available for assessing the exposure and vulnerability of research stations, and natural and built assets on the coast of the Antarctic continent [Levy *et al*. 2020].

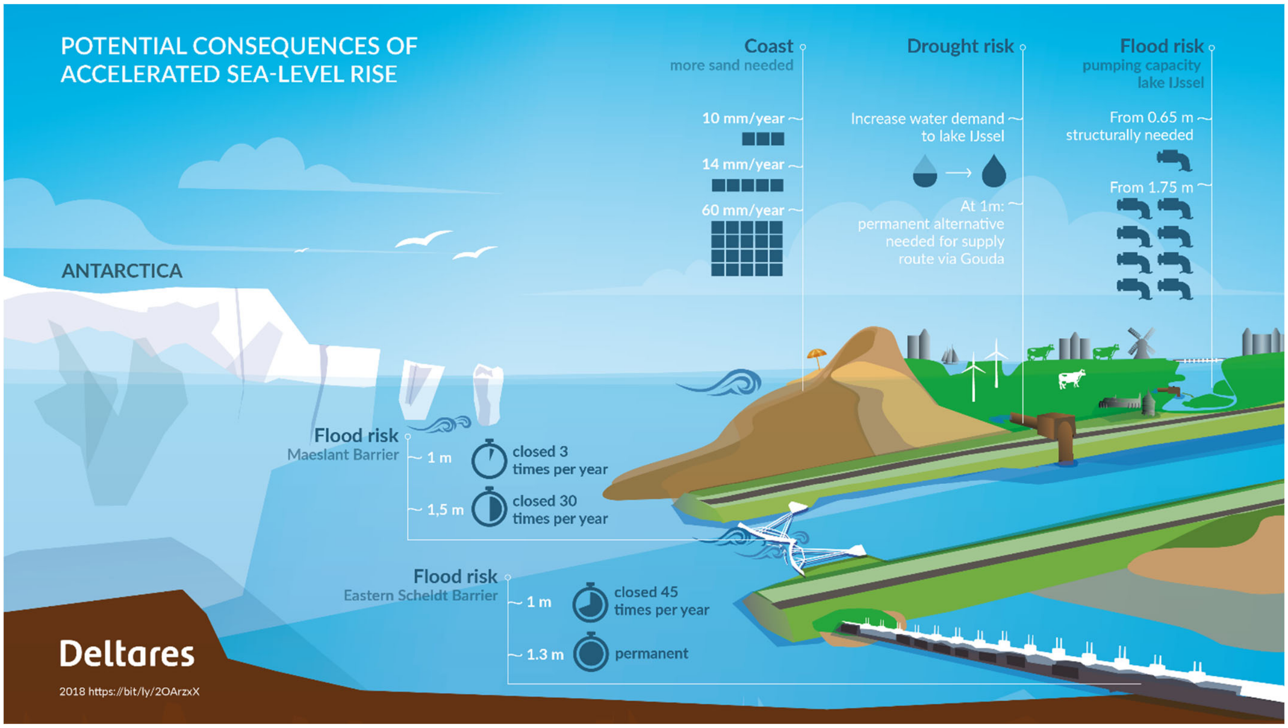


Figure 5.1 An example of local planning for the impacts of Antarctic Ice Sheet change. Planners from the Netherlands have incorporated uncertainty in the timing and extent of Antarctic Ice Sheet mass loss into assessments for adaptation requirements (provided courtesy of M. Haasnoot and Deltares, see Haasnoot *et al*. 2020). Note the increase in adaptation requirements under different scenarios for change, notably the frequency of closure of flood barriers expected under different sea level rise scenarios.

5.2 Observed changes and impacts

Since 1901, GMSL has risen by 0.20 m (0.15—0.25), at a faster rate than in any other century during the last three millennia (*high confidence*) [IPCC AR6 WGI 2.3.3.3; 9.6.1.1]. Since at least 1971, GMSL rise has been attributed to human activities (*very likely*) [IPCC AR6 WGI 3.5.3.2].

GMSL change over the 20th century has been dominated by thermal expansion of the ocean (thermosteric sea level rise) and mass loss from glaciers and the Greenland Ice Sheet [IPCC AR6 WGI 9.6.1.1]. Antarctica's contribution to GMSL rise has so far been quite limited, but has recently increased. In total, mass loss from the AIS between 1992 and 2020 has contributed 7.4 mm (5.0—9.8) to GMSL rise [IPCC AR6 WGI 9.4.2.1].

5.3 Projected changes and risks

Global mean sea level will continue to rise throughout the 21st century (*virtually certain*) [IPCC AR6 WGI B.5.3].

Projections are that GMSL will rise by 0.44 m (0.33—0.61) by 2100 under a low emissions scenario (SSP1-2.6) and 0.77 m (0.63—1.02) under a high emissions scenario (SSP5-8.5), relative to 1995—2014 levels (*medium confidence*) [IPCC AR6 WGI B.5.3; Table 9.8].

With 40 cm of GMSL rise, the present 1% annual exceedance probability (i.e., a 100-year coastal flood event), will become an annual event for most of the world's coastline [IPCC SROCC 4.2.3.4].

Antarctica is expected to contribute 0.11 m (*likely* range: 0.03—0.27) under the low emissions scenario and 0.12 m (*likely* range: 0.03—0.34) under the high emissions scenario (*medium confidence*) [IPCC AR6 WGI Table 9.8]. Large contributions to future sea level rise are expected from the thermal expansion of the ocean, and, in the high emissions scenario, Greenland Ice Sheet and glacier mass loss [IPCC AR6 WGI Table 9.8].

Antarctic contributions are expected to be rather small because of increased snowfall associated with warming air temperatures offsetting mass loss from increased ice drainage to the ocean and surface meltwater runoff under all SSP scenarios for the 21st century. Antarctica may even contribute negatively to GMSL rise until 2100 (*medium confidence*) [IPCC AR6 WGI 9.4.2.3].

Deep uncertainty around low likelihood, high impact ice sheet processes, including MISI and MICI, means that Antarctica may contribute more significantly more to 21st century sea level rise than expected [IPCC AR6 WGI 9.6.3; Box 9.4].

This uncertainty increases for long-term sea level projections beyond 2100. Under high emissions scenarios considering these abrupt ice sheet processes (SSP5-8.5), GMSL could rise by as much as 1.61 m (*likely* range: 0.63—1.61 m) by 2100, and 4.83 m (*likely* range: 1.02—4.83 m) by 2150 (*low confidence*) [IPCC AR6 WGI Table 9.9]. By 2300, high emissions climate models that consider MICI predict up to a 16 m GMSL rise (*low confidence*) [IPCC AR6 WGI 9.6.3.5]. Monitoring areas that may be especially vulnerable to MISI and MICI, such as the Thwaites Glacier, is critical to the early detection of these high-impact ice sheet processes [IPCC AR6 WGI Box 9.4].

A recent assessment has suggested that if the Paris Climate Agreement targets are exceeded, rapid and unstoppable sea level rise as a consequence of a changing AIS can be expected [DeConto *et al.* 2021]. This projection incorporates MICI which is assigned a low-likelihood, high-impact scenario by IPCC AR6 WGI.

Regional sea level change is expected to be relatively minor south of 60ºS compared to the global average under low (SSP1-2.6) and high (SSP 5-8.5) emissions scenarios for 2100 (*high model agreement*) [IPCC AR6 WGI Figure 9.12].

By comparison, northern areas of the Southern Ocean between 45ºS and 60ºS are expected to experience higher than average sea level anomalies driven by ocean dynamics and the thermal expansion of ocean waters (*high model agreement*) [IPCC AR6 WGI Figure 9.12; Figure 2.26].

Because regional trends in sea level have been highly variable across the Southern Ocean to date, and the projected changes are relatively small compared to other ocean areas, the impact of anthropogenic forcing on Southern Ocean sea level may not emerge by 2080—2100 [IPCC AR6 WGI 9.6.1.4].

5.4 Policy recommendation

The consequences of sea level rise and melting ice (sea, land and shelves) around Antarctica's coastline will present significant risks to society. The need for, and outcomes from, research on sea level in the Antarctic should be communicated by the Antarctic Treaty Parties and observers: to international agreements, governments at all levels, the economic sector, and to civil society, as these entities will largely have to plan for, manage, and endure the impacts of sea level rise and its associated costs.

5.5 Research recommendations

RR 5.1 Reduce uncertainties in the Antarctic Ice Sheet contribution to future sea level rise and refine estimates of the rate and magnitude of that contribution.

RR 5.2 Adopt a research-based approach to help ensure the impacts and risks of Antarctic-driven sea level rise to humans and nature are well-communicated and understood by stakeholders and decision makers, leading to effective and appropriate coastal zone management and adaptation.

RR 5.3 Work with the user community to ensure that regulatory frameworks and decisions on coastal zone management and adaptation are based on peer-reviewed scientific research.

6. Marine Life

6.1 Background

The Southern Ocean biota is unique. Extreme conditions, a long history of low, but changing temperatures and variable habitat availability, and the extensive nature of a region characterised by seasonal ice, low temperatures, light limitation by sea ice, and seasonal dark, have resulted in a distinctive blend of biodiversity [Peck 2018]. Some groups that are common elsewhere, such as sharks, rays and some crustaceans, are poorly represented or absent. Others, such as bryozoans and sea spiders, reach the highest numbers of species for almost any global region [Chown *et al*. 2015; Peck 2018; Convey & Peck 2019].

Even in groups with relatively low numbers of species, the Southern Ocean seems to have acted as a biodiversity pump, with high speciation rates and much diversification as the region cooled from the Miocene onwards [Crame 2018; Rabosky *et al*. 2018; O'Hara *et al*. 2019]. Deep sea life is immensely diverse and hosts a large proportion of unknown species [Brandt *et al*. 2007].

Many of the species present in the region belong to groups that have undergone significant radiations and which have a unique suite of adaptations that enable them to thrive in the low temperature conditions of the region [Pörtner 2006; Chown *et al*. 2015; Peck 2018]. Among these, the antifreezes of Antarctic fish are perhaps best known [Peck 2018; Kim *et al*. 2019]. Other physiological challenges of low Antarctic water temperatures include the difficulty of synthesizing and retaining proteins [Fraser *et al*. 2002; Fraser *et al*. 2022].

Pelagic seabirds and seals, which either come ashore on the continent, the sub-Antarctic islands, or on sea ice, to breed, are, along with cetaceans, among the most iconic species of the region. Their movements and foraging areas can be used to define areas of ecological significance in the Southern Ocean [Hindell *et al*. 2020]. Their colonies, which change in extent and position through time [e.g., Emslie *et al*. 1998; Chen *et al*. 2021], are important nutrient sources for terrestrial ecosystems [Bokhorst *et al*. 2019]. Inter-annual and seasonal variation in sea ice extent has a significant influence on the population dynamics of seabirds and seals [Fretwell & Trathan 2019; Redfern & Bevan 2020; Watanabe *et al*. 2020; Oosthuizen *et al*. 2021; Wing *et al*. 2021].

For pelagic systems, 20 ecoregions have been identified based on physical characteristics, while for benthic systems, 23 ecoregions have been identified, founded on a wide variety of characteristics, including both physical environmental and biological variables [Chown & Brooks 2019] (**Figure 6.1**). A further 15 candidate important marine mammal areas [di Sciara & Hoyt 2020] and 63 important bird areas [Handley *et al*. 2021] have also been proposed for the region.

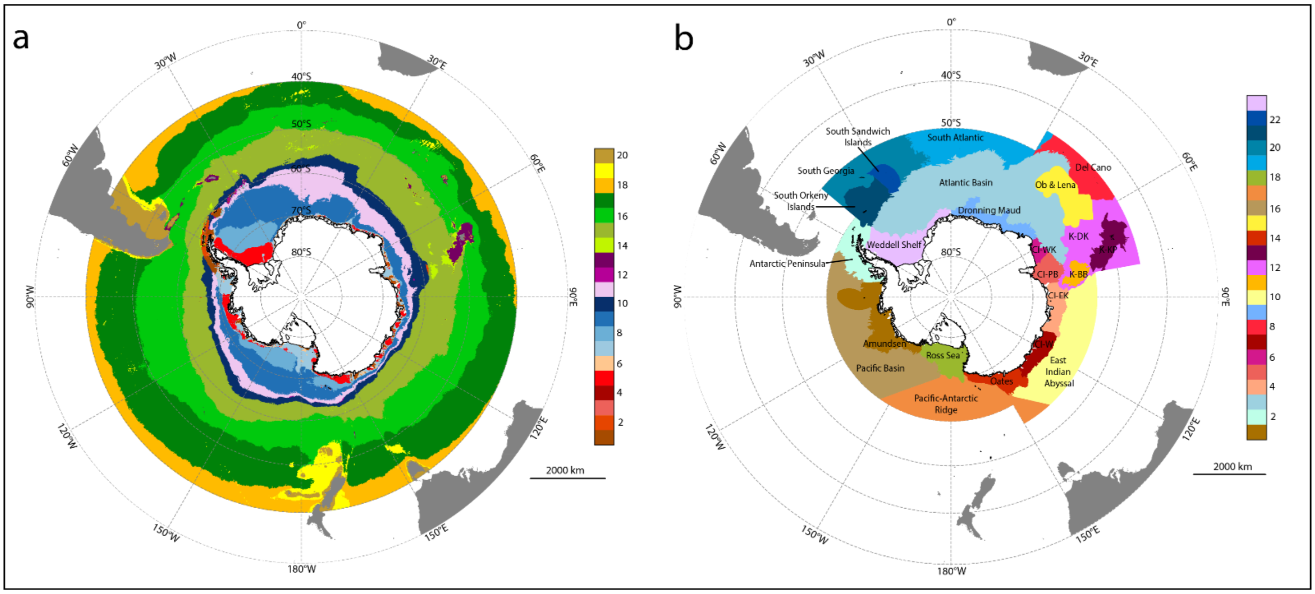


Figure 6.1 Biogeographic classifications of the Southern Ocean. (a) The pelagic ecoregions of the Southern Ocean: **1** Moderately shallow areas (to ~1 000 m) with moderate ice cover and low sea surface temperature (SST) <2°C; **2** Areas with low ice cover and low sea surface temperatures (<2°C); **3** Shallow shelf areas with moderate ice cover; **4** Shallow areas with high ice cover; **5** Shelf areas with almost perennial ice cover; **6-7** Moderate depths (~200—1 000 m) and ice cover (~50—75%); **8-11** Sea ice zone; **12** Moderate depth (~1 000—2 500 m) and sea ice cover (~40%); **13-14** Shallow island plateaus; **15-16** Deep oceanic waters; **17-18** Temperate waters; **19-20** Continental and island shelf areas with temperate to warm temperatures. **(b) The benthic ecoregions of the Southern Ocean**: **1** Pacific Basin; **2** Antarctic Peninsula; **3** Atlantic Basin; **4** Central Indian-East Kerguelen Subregion (CI-EK); **5** Central Indian-Prydz Bay Subregion (CI-PB); **6** Central Indian-West Kerguelen Subregion (CI-WK); **7** Central Indian-Wilkes Subregion (CI-W); **8** Del Cano; **9** Dronning Maud Land; **10** East Indian Abyssal Plain; **11** Kerguelen-Banzare Bank Subregion (K-BB); **12** Kerguelen-Deep Kerguelen Subregion (K-DK); **13** Kerguelen-Kerguelen Plateau Subregion (K-KP); **14** Oates; **15** Ob & Lena; **16** Pacific Basin; **17** Pacific-Antarctic Ridge; **18** Ross Sea; **19** South Atlantic; **20** South Georgia; **21** South Orkney Island; **22** South Sandwich Islands; **23** Weddell Shelf (redrawn from Chown & Brooks 2019).

Vulnerable marine ecosystems (VMEs) are those vulnerable to the impacts of fishing activities. They include seamount communities, deep-sea hydrothermal vents, cold water corals, and sponge fields. Vulnerable marine ecosystems are found throughout the Antarctic [De Broyer *et al*. 2014]. Deep-ocean climate change impacts on habitats, fish and fisheries, including VMEs and species targeted by fisheries (krill, toothfish) in the Southern Ocean have been summarised by the United Nations Food and Agriculture Organisation (FAO) [Levin *et al*. 2019].

Ocean warming is a significant climate change stressor. In Antarctic species, individuals generally require 2—15 times as long as temperate species to acclimate to warming [Peck 2018]. Long-term thermal tolerance limits are generally 2—3°C above ambient temperature, similar to species of the thermally stable tropics, compared to 6—9°C for temperate species [Gutt *et al*. 2021]. Southward range shifts of many species are expected as ocean warming progresses [IPCC AR6 WGII CCP 6.2.1]. Animal distributions and breeding locality preferences can be tightly connected to specific, localised conditions of temperature and primary productivity, illustrated by the vast breeding colony of *Neopagetopsis ionah* ice fish in the southern Weddell Sea [Purser *et al*. 2022].

Ocean acidification is a concern for Antarctic marine biodiversity, but much variation in response exists among different groups, life stages and studies. Some studies reveal large acidification impacts, while others show that Antarctic species cope well in low pH.

Salinity, oxygen, and sedimentation are all changing and are expected to continue to change in the region too, with effects on marine populations, species and communities. An increase in ice loss, and hence freshwater and sediment release, is expected to have large impacts on marine biodiversity [Convey & Peck 2019]. For example, high freshwater and sediment inputs have been associated with mass mortality events in krill [Fuentes *et al*. 2016].

Governance for managing climate impacts in marine ecosystems of the Southern Ocean is considered poorly developed [Cavanagh *et al*. 2021b], despite its importance for decision-making. Identifying sustainable practices in a changing environment has been identified as a major challenge [IPCC AR6 WGII CCP 6.4.1].

6.2 Pelagic systems

6.2.1 Background

The research focus on Southern Ocean pelagic systems has primarily been concerned with the food webs that support the iconic vertebrate species of the region (whales, seals, seabirds), populations of commercially important species such as krill and toothfish, and the information required for the management of these systems [Constable *et al*. 2014; Gutt *et al*. 2015; Chown & Brooks 2019; Rogers *et al*. 2020; Gutt *et al*. 2021]. A variety of factors has contributed to changes in Antarctic food webs, including historical exploitation of marine mammals and fish, and changes driven both by climate factors and by the ozone hole [IPCC AR6 WGII CCP 6.2.1.4].

Despite extensive knowledge of pelagic systems, information from different regions (or CAMLR Convention Areas) is variably developed. Some regions, such as the western Antarctic Peninsula and Scotia Arc (CAMLR Convention Subareas 48.1-48.4), are better understood than others. In part this owes also to the availability of long-term monitoring information that can be used to assesses changes in the populations of marine pelagic species and in the ecosystems they constitute. Most documented changes, because of sea ice losses and warming, relate to shifts in dynamics and ranges of species, with most known impacts in the Antarctic Peninsula area [IPCC AR6 WGII CCP 6.2.1.4].

6.2.2 Observed changes and impacts

Changes in phytoplankton biomass for the Southern Ocean are associated with changes in the spatial extent of ice-free waters. Little overall change in biomass per area at the Southern Ocean scale is thus suggested [IPCC SROCC 3.2.3.2.1].

Local-scale forcings (such as sea ice duration, topographically-steered circulation, retreating glaciers) and associated changes in stratification are important drivers of phytoplankton bloom dynamics at coastal stations on the western Antarctic Peninsula (*medium confidence*). Changes in mixed layer depth in the southern part of the Peninsula (as opposed to no trend in the north) associated with changes in sea ice duration over a 24-year period (1993—2017) have been linked to enhanced phytoplankton productivity. Southern Ocean phytoplankton blooms in this region may be shifting to earlier in the growth season [IPCC SROCC 3.2.3.2.1].

The effect of climate change on Southern Ocean pelagic primary production is difficult to determine given regional and interannual dynamics and the fact that the length of time series data is frequently insufficient to enable the climate change signature to be detected and attributed. At the circumpolar scale, no consistent changes in primary productivity have been found: sectors and regions also show differences in trends (*medium confidence*). Primary productivity has declined in the Atlantic sector and the Ross Sea, but increased in the Pacific sector (*low confidence*) [IPCC AR6 WGII CCP 6.2.1.2]. In regions where rapid change has occurred, such as in areas with declining sea ice cover and in the immediate neighbourhood of retreating ice sheets on the Antarctic Peninsula, higher productivity has been observed (*medium confidence*) [IPCC AR6 WGII CCP 6.2.1.2].

Current understanding of climate change effects on Southern Ocean zooplankton is based largely on information from the South Atlantic and the western Antarctic Peninsula. Comparison of the meso-zooplankton community in the southwestern Atlantic sector between 1926—1938 and 1996—2013 has revealed no evidence of change despite surface ocean warming. Sub-decadal cycles of macro-zooplankton community composition adjacent to the western Antarctic Peninsula are strongly linked to climate indices, with evidence of increasing abundance for some species over the 1993—2013 period [IPCC SROCC 3.2.3.2.1].

The spatial distribution and size composition of Antarctic krill has changed in the South Atlantic sector, including a poleward contraction of the highest densities of krill, in association with changes in the sea ice environment (*medium confidence*) [IPCC SROCC 3.2.3.2.1; IPCC AR6 WGII CCP 6.2.1.1]. This may have resulted in different regional trends in numerical krill abundance (*medium confidence*). Thus, there has been a southward shift in the distribution of Antarctic krill in the South Atlantic, the main area for the krill fishery (*medium confidence*) [IPCC SROCC 3.3, 3.2.3.2.1; IPCC ARG WGII]. Little information exists for other regions of the Southern Ocean.

Recent studies on the ecological effects of acidification in coastal waters near the continent indicate a negative effect of acidification on primary production and changes to the structure and function of microbial communities (*medium confidence*). Laboratory manipulations and *in situ* experiments show that sea ice algae are tolerant to acidification (*medium confidence*) [IPCC SROCC 3.2.3.2.1]. However, species-specific responses in growth and primary production exist, strongly modulated by iron and light availability (*high confidence*) [IPCC AR6 WGII CCP 6.2.1.3].

The responses to acidification are generally variable, between species and between life stages, and with respect to CO_2 thresholds for responses. Calcifying species using aragonite or high-magnesium calcite are more vulnerable to the effects of acidification than species using low-magnesium calcite or with mechanisms to protect their skeletons (*high confidence*) [IPCC AR6 WGII CCP 6.2.1.3].

Pteropods are vulnerable to the effects of acidification, and new evidence indicates that eggs released at high CO_2 concentrations lack resilience to ocean acidification in the Scotia Sea region (*medium confidence*) [IPCC SROCC 3.2.3.2.1].

There is limited understanding of the consequences of climate change for Southern Ocean finfish fisheries. No effects of climate change on Patagonian and Antarctic toothfishes have yet been observed [IPCC SROCC 3.2.3.2.3].

Life history, morphological, physiological and behavioural characteristics of birds and marine mammals in the Southern Ocean, as well as their patterns of activity, are changing as a result of climate change (*high confidence*) [IPCC SROCC 3.2.3.2.4].

Climate-induced changes in populations and ranges of some Antarctic predators such as seabirds and marine mammals vary between different regions of the Southern Ocean, reflecting differences in important drivers, notably food availability and sea ice extent across regions (*high confidence*) [IPCC SROCC 3.2.3.2.1; IPCC AR6 WGII CCP 6.2.1.1].

Population trends of Antarctic penguins affected by climate change include decreasing Adélie and chinstrap penguin populations and increasing gentoo penguin populations on the western Antarctic Peninsula and associated islands (*high confidence*) [IPCC SROCC 3.2.3.2.4]. In other areas of Antarctica, Adélie penguin populations are generally increasing, but highly regionally variable in space and time [Iles *et al*. 2020]. Emperor penguins are particularly difficult to monitor due to their remoteness and the complexity of their breeding cycle, but global populations have declined over the last ten years (*high confidence*) [IPCC SROCC 3.2.3.2.4]. Satellite and other remote sensing techniques are providing further information on which to evaluate trends [Borowicz *et al*. 2018; Herman *et al*. 2020; Strycker *et al.* 2020].

Southward population shifts with increased intensity and frequency of westerly winds affect demographic rates, foraging range, rates of travel and other characteristics of flying birds. These shifts also increase overlap with fisheries activities, thus increasing the risk of bycatch and the need for mitigation measures (*medium confidence*) [IPCC SROCC 3.2.3.2.4].

No unified global, let alone synchronous, estimate of the abundance of Antarctic pack ice seal species (Ross, crabeater, leopard, Weddell seals) is available as a baseline for understanding climate change impacts on these species. Remote sensing approaches are only now starting to provide the potential to alter this situation [Gonçalves *et al*. 2020; LaRue *et al*. 2020]. These approaches, combined with other technologies such as acoustic observatories, can also help to improve knowledge of the distribution and abundance of whales in the Southern Ocean, and their connectivity with the global ocean, and are key for protection and management [El Gabbas *et al*. 2021; Marcondes *et al*. 2021].

Given the contribution of the Southern Ocean to global ocean productivity and export flux, assessing the dynamics of carbon fluxes and the role of climate, ocean and food web change for these fluxes is important [Hauck *et al*. 2015; MacGilchrist *et al*. 2019]. Recent assessments of food web interactions and species roles – especially of whales – suggest a fundamental relevance for remineralisation and export of carbon and nutrients that deserves further study [Savoca *et al*. 2021].

6.2.3 Projected changes and risks

Considerable change is projected for Southern Ocean species and ecosystems (**Figure 6.2**). Stronger upwelling in the Southern Ocean, because of strengthening westerly winds, is projected to increase primary productivity at the circumpolar scale in the vicinity of the continent (Antarctic zone) and to the north of the sub-Antarctic Front, but not in the sub-Antarctic (*low to medium confidence*) [IPCC AR6 WGII CCP 6.2.1.2]. Ocean acidification may, however, have a detrimental effect on coastal phytoplankton communities (*medium confidence*) [IPCC SROCC 3.2.3.2.1; 3.2.3.2.5].

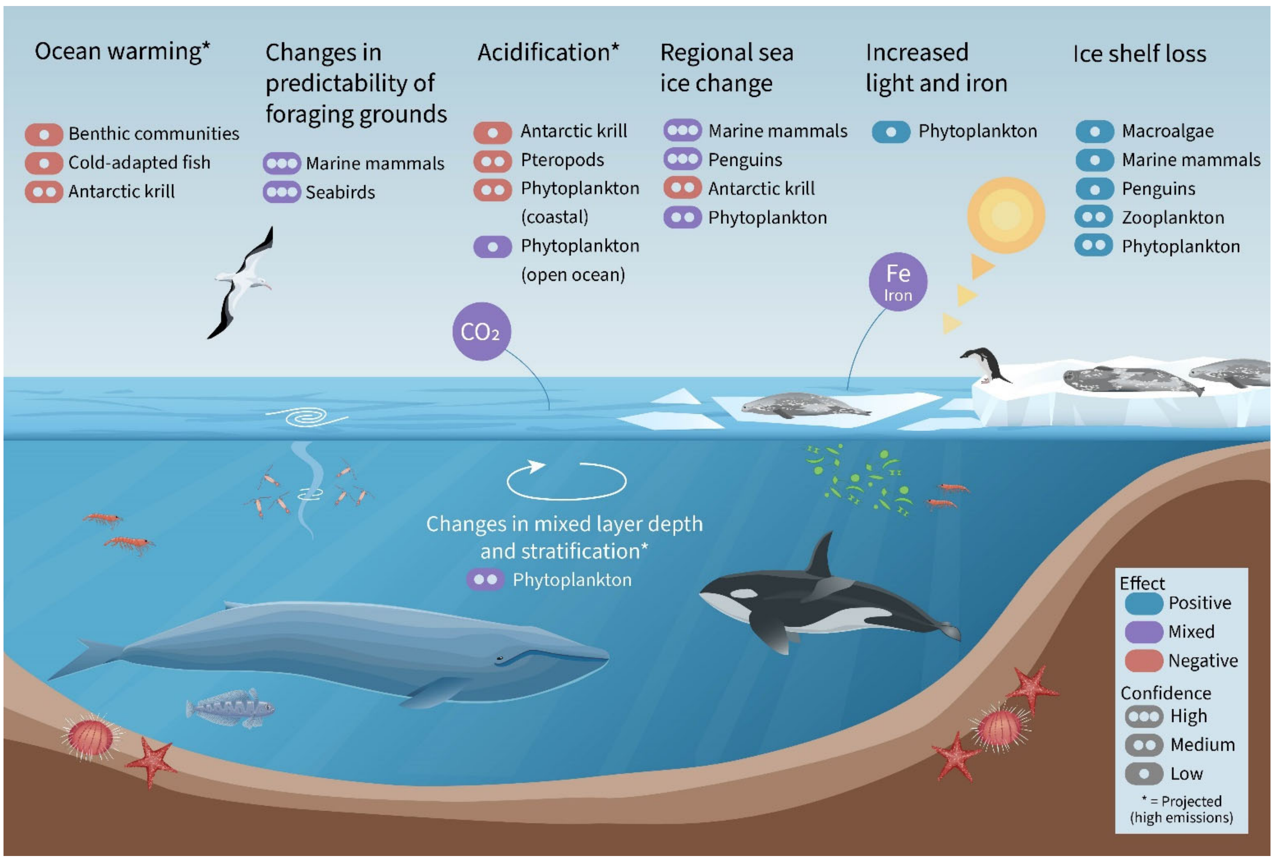


Figure 6.2 Key drivers of change, both current and projected, in the Southern Ocean (redrawn from IPCC SROCC Figure 3.6).

Large changes are projected to occur after 2100 with >4°C of ocean surface warming [IPCC AR6 WGI Figure 9.3], including an expected decline in global ocean productivity because of nutrient trapping in the Southern Ocean and related mechanisms (*medium confidence*) [IPCC AR6 WGII CCP 6.2.1.2]. This may negatively impact ecosystems elsewhere, and in consequence fisheries [Moore *et al*. 2018]. Recent work proposes that this nutrient trapping effect may be realised sooner, i.e., within the 21st century [Bronselaer *et al*. 2020].

Negative effects of ongoing ocean acidification have been projected for several marine groups, including Antarctic krill (early life stages), diatoms, pteropods, and coastal phytoplankton [IPCC SROCC 3.2.3]. Long-term studies have indicated, however, that some groups and life stages (including adult krill) can cope well with pH declines. This is especially the case when long experimental exposure periods allow animals to adjust their physiology [Convey & Peck 2019; Gutt *et al*. 2021].

Ocean deoxygenation may impact the respiratory function of marine species, and shift the marine nitrogen cycle from nitrate-dominated conditions to an ammonium-dominated cycle [Naafs *et al*. 2019].

The distribution of Antarctic krill is projected to change under future climate change owing to changes in the location of the optimum conditions for recruitment and growth, which are predicted to move southwards. Decreases will be most apparent in the areas with the most rapid warming (*medium confidence*). The greatest projected reductions in krill due to the effects of warming and ocean acidification are for the southwest Atlantic/Weddell Sea region (*low confidence*). This is the area of highest current krill concentrations, contains important foraging grounds for krill predators, and is also the main area of operation of the krill fishery [IPCC SROCC 3.2.3.2.1]. The projected effects of climate-induced stressors on polar marine ecosystems present risks for commercial fisheries (*high confidence*) that have to be taken into consideration in management [IPCC SROCC 3.5.2.1].

Many Antarctic fish have a narrow thermal tolerance, which makes them vulnerable to the effects of rising temperatures. Some species may move southward, but those unable to do so (e.g., those which occupy waters over shelf areas) will be especially pressured by ocean warming [Caccavo *et al*. 2021; IPCC AR6 WGII CCP 6.2.1.1]. Increasing water temperatures may displace icefish from marginal habitats (*low confidence*). Future warming may also reduce the planktonic duration and increase egg and larval mortality for fish species. This is predicted to affect population connectivity and the ability of fish species to adapt to change [IPCC SROCC 3.2.3.2.3]. Small mesopelagic fish may play an important ecological role in changing circumstances given their growing recognition as important mid-trophic level species [IPCC AR6 WGII CCP 6.2.1.4].

Given differences in temperature tolerances for Patagonian toothfish (wide temperature tolerance) and Antarctic toothfish (low tolerance for water temperatures above 2°C), Antarctic toothfish may be faced with potential competition with southward-moving Patagonian toothfish and with habitat loss as climate change progresses (*very low confidence*) [IPCC SROCC 3.2.3.2.3]. The FAO assessment of deep-ocean climate change impacts on habitats, fish and fisheries considers both species to be at risk from future change [Levin *et al*. 2018].

The location of environmental features that facilitate the aggregation of prey and the suitability of breeding habitats are influenced by climate change, thus influencing the distribution of marine mammals and birds (*medium confidence*). Projected changes in prey distribution and sea ice decline are expected to shift the distributions of sub-Antarctic predators (seabirds and seals) southwards with elevated foraging costs [IPCC AR6 WGII CCP 6.2.1.1]. These influences are projected to continue with climate change, altering areas of ecological significance and influencing the efficacy of Marine Protected Areas [Hindell *et al*. 2020].

Emperor penguins are expected to be impacted substantially, with the population projected to decline close to extinction with business-as-usual climate scenarios, but with much better population prognoses with reductions of anthropogenic greenhouse gas emissions [IPCC AR6 WGII CCP 6.2.1.1].

6.3 Benthic systems

6.3.1 Background

Southern Ocean benthic biodiversity is ecologically diverse and biogeographically structured [De Broyer *et al*. 2014, Chown *et al*. 2015]. The large and deep continental shelves around Antarctica are home to an estimated 17 000 species [Peck 2018]. They are characterised by a high degree of patchiness in diversity and abundance: in places biomass can be high [Pineda-Metz *et al*. 2020]. The world's largest fish breeding colony, with over 60 million nests of the Antarctic icefish *Neopagetopsis ionah*, has only recently been discovered over a 240 km^2 area in the southern Weddell Sea, where warm deep water wells up onto the shelf [Purser *et al*. 2022].

Surprisingly little is known, however, about changes to Southern Ocean benthic systems in response to currently changing conditions. Short-term responses, such as to disturbance by sea ice or by ice scour, or to ice shelf collapse, are being increasingly documented for both species and the communities they form [Gutt *et al*. 2021; Ingels *et al*. 2021].

The importance of the availability nutrients and of light, which is affected by sea ice (and naturally, by seasonality) is well appreciated [Clark *et al*. 2013; Peck 2018; Pineda-Metz *et al*. 2020]. The development of polynyas and other changes to sea ice cover have either been demonstrated to affect benthic assemblages, or are thought to be likely to do so [Grebmeier & Barry 2007; Clark *et al*. 2013].

The slow growth and significant sensitivity of benthic species to changing temperature compared with temperate species are appreciated too [Constable *et al*. 2014; Peck 2018]. Some invertebrate species may have the poorest ability to survive experimentally elevated temperatures of any marine species so far reported [Peck 2018].

6.3.2 Observed changes and impacts

Little information on the direct effects of changing Southern Ocean conditions exists for the benthos. The IPCC SROCC provides little information on current change compared with projected effects. Some experimental work is proceeding, however, indicating the kinds of changes that may be expected, including massive increases in growth rates, notably of pioneer species, and changes to community structure as a consequence [Ashton *et al*. 2017].

Some information is known about changes to sub-ice shelf systems following ice shelf collapse, but remains very poorly developed. Sub-ice shelf ecosystems prior to collapse are poorly known because of the difficulty of access through the ice [Griffiths *et al*. 2021; Ingels *et al*. 2021]. Nonetheless, benthic faunas below ice shelves may be diverse and have existed for thousands of years [Barnes *et al*. 2021].

Benthic community changes following ice shelf collapse and changing food conditions have been described in a range of works [summarised in Ingels *et al*. 2021]. Faunal assemblages accustomed to the food-poor, sub-ice shelf environment are altered by the new primary production and export regimes associated with collapse. The exposure of extensive seafloor areas to phytodetrital input after ice shelf collapse leads to a shift from an oligotrophic to a more eutrophic benthic system. This initiates colonisation processes and a change to communities (**Figure 6.3**), which also leads to strengthened pelagic-benthic coupling (*high confidence*) [IPCC AR6 WGII CCP 6.2.1.1]. Such changes may also increase carbon uptake and long-term sequestration (blue carbon), though much remains to be understood about this process [Bax *et al*. 2021].

What knowledge is available of sub-ice shelf biodiversity and its responses to collapse suggests that variation in the physical, chemical, and biological settings will result in variation in responses among benthic sub-ice shelf communities [Griffiths *et al*. 2021; Ingels *et al*. 2021]. Thus, there is *high agreement* based on *medium evidence* that ice shelf collapse or retreat has led to biological colonisation and new marine habitats [IPCC SROCC 3.3.3.4].

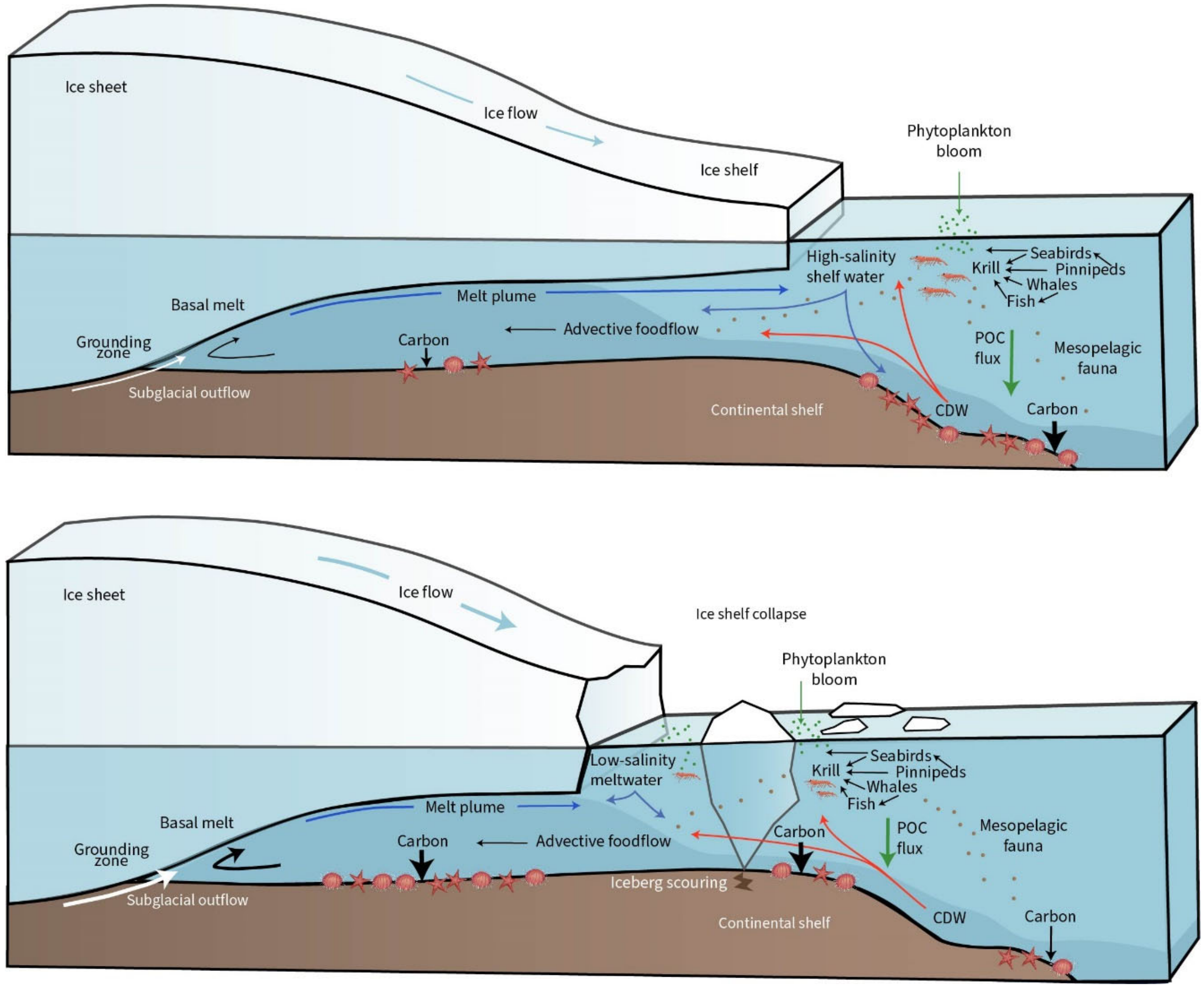


Figure 6.3 The impacts of ice shelf collapse. Changes in the spatial and temporal ranges of pelagic and benthic biodiversity after ice shelf collapse (lower figure) leads to changes in system structure and functioning (redrawn with permission from Ingels *et al*. 2021). CDW = Circumpolar Deep Water; POC = Particulate Organic Carbon.

6.3.3 Projected changes and risks

Carbon uptake and storage by Antarctic benthic communities is projected to increase with sea ice losses, because growth gains from longer algal blooms across the full shelf outweigh ice scour mortality in the shallows [IPCC SROCC 3.2.3.2.2].

Increases in the amount of light reaching the shallow seabed under climate change may result in ecological regime shifts, in which invertebrate-dominated communities are replaced by macroalgal beds (*low confidence*) [IPCC SROCC 3.2.3.2.2].

Changes to ice shelves are expected to expose new pelagic and benthic habitats and to change the structure and functioning of benthic communities [IPCC AR6 WGII CCP 6.2.1.4]. These changes are expected to reduce the extent of previously unique and unusual sub-ice shelf communities [Griffiths *et al*. 2021; Ingels *et al*. 2021].

Modelled distribution changes for benthic invertebrate species in the Southern Ocean under RCP8.5 for 2099 suggest that 79% of endemic species will face a decline in suitable habitat over the current century. Predicted reductions in the number of species are most pronounced for the western Antarctic Peninsula and the Scotia Sea region [IPCC SROCC 3.2.3.2.2].

Several studies have suggested that range changes up the shelf slope by crabs in the Antarctic region could readily take place with warming, indicating that species which crush shells for feeding could have a large impact on benthic communities [Aronson *et al*. 2015a,b; Smith *et al*. 2017]. This idea remains at least partially contested [Griffiths *et al*. 2013].

6.4 Non-native species

6.4.1 Background

The likelihood of incursion of non-native marine species to the Southern Ocean south of 60°S has been appreciated for some time. Among the first detailed studies were those from investigations of hull fouling and ballast water of research and supply vessels departing from Hobart, Australia [Lewis *et al*. 2003]. The work included assessments of the potential for changing management interventions – in this case the use of antifouling agents – to affect the likelihood of transfer of non-native species [Lewis *et al*. 2004].

A range of subsequent studies has considered the suite of organisms likely to be transported to the region by ship from different departure ports, their probability of surviving Antarctic conditions, and probabilities of establishment based largely on modelling work [Lee & Chown 2007, 2009a; Byrne *et al*. 2016; Hughes & Ashton 2017; McCarthy *et al*. 2019; Hughes *et al*. 2020; McCarthy *et al*. 2022]. Transport pathways have also been shown to include macro-plastic pollution [Barnes 2002; Barnes & Fraser 2003]. In all cases, substantial biotas have been found associated with shipping and plastic, and the likelihood of establishment in Antarctic waters adjudicated as greater than zero.

Transport of species from outside the region is also a natural process, however, and may take place more regularly than previously thought [Barnes *et al*. 2006; Fraser *et al*. 2018; Avila *et al*. 2020]. This raises the question of distinguishing anthropogenic introductions from natural colonisations and from range expansions of indigenous species. Answering this question is critical in a management context where a species previously unrecorded from a well-surveyed area is detected. In the case of poorly surveyed areas, the challenge is far greater because the 'new record' may stem from lack of previous detection of a given species indigenous to the area.

6.4.2 Observed changes and impacts

The current status of marine invasions in the region has recently been assessed, with limited evidence for species living freely in the region [McCarthy *et al*. 2019]. Five of these have been documented, with just two in any abundance: the grass kelp *Ulva intestinalis* throughout the South Shetland Islands, and the pinkmouth hydroid *Ectopleura crococea* off Dronning Maud Land and Queen Mary Land. Thus, invasive macroalgae and benthic invertebrates have been detected (*medium confidence*) [IPCC AR6 WGII CCP 6.2.1.1].

By contrast, a wide range of species has been detected being transported to the region [McCarthy *et al*. 2019] from an exceptionally wide variety of shipping routes, exceeding the number and diversity of pathways typically expected from the departure ports of research and tourist vessels visiting the region [McCarthy *et al*. 2022]. The most likely areas of establishment for non-native species, based on shipping frequency and duration of visits by vessels, have been identified for the continent [McCarthy *et al*. 2022]. These areas are typically those also experiencing the greatest changes in temperature, such as the Antarctic Peninsula [Etourneau *et al*. 2019; Morley *et al*. 2020].

No impacts of non-native marine plant or animal species on the Antarctic marine biota have been detected thus far.

The introduction of diseases (of plants and animals) by humans into the Antarctic and Southern Ocean regions has been a long-standing concern [Kerry & Riddle 2009]. Records of such arrivals and their establishment within populations have been made, especially for pelagic vertebrates, with local impacts, though assignment to given disease-causing agents has not always been made [Smeele *et al*. 2018].

Surveillance has continued to highlight the risks of disease introductions [Smeele *et al*. 2018; Cerdà-Cuéllar *et al*. 2019]. Recent studies have provided risk assessments, notably for the current COVID-19 pandemic [Barbosa *et al*. 2021]. However, the likely influences of climate change on disease risk remain poorly investigated.

6.4.3 Projected changes and risks

Projected changes will favour the establishment and spread of invasive species [IPCC AR6 WGII CCP 6.2.1.1]. Several studies have proposed that with warming and other changes to the Antarctic marine environment, the probability of establishment of marine non-native species will increase [Aronson *et al*. 2007; McCarthy *et al*. 2019], aided by increasing ship traffic, the main vector for such species, notably via hull fouling [Lewis *et al*. 2003; Lee & Chown 2009a; Hughes & Ashton 2017; McCarthy *et al*. 2022]. Ballast water exchange policies and limited exchange in the region make this pathway less likely.

An explicit, expert elicitation study for the Antarctic Peninsula identified thirteen non-native species with high risks for the region. These include animals that are known to have substantial effects on the ecosystems to which they have been introduced elsewhere on the planet [Hughes *et al*. 2020]. Examples are the Mediterranean mussel, the sea vase, and the green shore crab.

Range expansions by crabs indigenous to the region are also expected to pose a threat, though these are range shifts of indigenous species, rather than introductions of non-native species. Nonetheless, the risks of invasion by shell-crushing crustaceans from outside the region are of special concern because of the ability of these species to alter a benthos poorly adapted to this form of predation [Aronson *et al*. 2015a,b; Smith *et al*. 2017].

Other groups absent from south of the Antarctic Circumpolar Current, including shipworms (their absence accounts for the good condition of the wreck of *The Endurance*), may find the region more accessible owing to anthropogenic warming and increases in resource availability [Glover *et al*. 2013].

What the timeframe is for significant establishment of non-native species is not clear, but most studies consider the risk imminent given rapid changes to some parts of the Antarctic, especially the Peninsula, and the growth in ship traffic to this region.

Prognoses for changes to risks of disease introductions are less clear, though several works have suggested that with rising temperatures and growing visitor numbers to the region, these risks will increase too [Woehler *et al*. 2014; Cerdà-Cuéllar *et al*. 2019].

6.5 Research recommendations

RR 6.1 Further determine how ecosystems in the Southern Ocean have responded to warmer climate conditions in the past and how this informs and refines projections for change.

RR 6.2 Establish which species, ecosystems and food webs are most vulnerable in the Southern Ocean, how they are likely to change, and which organisms are most likely to go extinct and over what period, as a consequence of climate change and local interactions such as with non-native species.

RR 6.3 Assess the distributions, life cycles and interactions of Antarctic marine mammals and birds in the context of environmental dynamics, including their food web and soundscape signatures, and their role as sentinels of change

RR 6.4 Determine how increases in marine living resource harvesting in the context of climate change impacts will affect harvested, associated and dependent species and Southern Ocean biogeochemical cycles, in contrast with other groups.

RR 6.5 Investigate the synergistic effects of multiple stressors in the context of environmental change drivers on Southern Ocean biota.

RR 6.6 Further explore, in a spatio-temporally explicit manner, the extent to which climate change will affect existing and future Southern Ocean fisheries, especially toothfish and krill populations.

RR 6.7 Determine how successful Southern Ocean Marine Protected Areas will continue to be in meeting their protection objectives, and how they will affect ecosystem processes and resource utilisation.

RR 6.8 Investigate the response of deep-sea ecosystems to modifications of deep-water formation.

RR 6.9 Document and project how deep-sea species interact and will continue to interact with shallow water ecosystems as the environment changes.

RR 6.10 Observe and determine the impacts caused by climate change induced reduction of sea ice and intrusion of warmer water masses on marine species and ecosystems, including VMEs, found on the continental shelves around Antarctica.

RR 6.11 Determine how increases in the ice-free Antarctic intertidal zone impact biodiversity and the likelihood of biological invasions.

RR 6.12 Establish how linkages between marine and terrestrial systems will change in the future.

RR 6.13 Further understand the impacts of changing seasonality and transitional events on Southern Ocean marine ecology, biogeochemistry, and energy flow by establishing a circumpolar observation network.

RR 6.14 Comprehensively establish the efficacy of Southern Ocean conservation measures for preserving evolutionary potential and those properties that best anticipate change.

RR 6.15 Establish how the sources and mechanisms of dispersal of propagules into and around the Southern Ocean will change over the coming decades.

RR 6.16 Determine how invasive species and the ranges of indigenous species will change in the Southern Ocean and in so doing alter ecosystems.

RR 6.17 Establish how climate change will affect the risk of spreading emerging infectious diseases in Antarctica.

RR 6.18 Develop mechanisms to distinguish human-induced environmental changes from natural ones.

7. Terrestrial Life

7.1 Background

Terrestrial life, including in extensive lake and less extensive stream environments, is depauperate on the Antarctic continent relative to other continental settings [Chown *et al.* 2015; Convey & Peck 2019]. No truly terrestrial vertebrate species are present except for the Snowy Sheathbill (a land bird) on the Antarctic Peninsula. Flowering plants and insects are each restricted to two species in the Antarctic Peninsula region. By contrast, invertebrates, mosses, lichens and other groups are common [Phillips *et al.* 2022] (**Figure 7.1**), with microbial diversity predominating in most areas [Cary *et al.* 2010; Cavicchioli 2015; Ortiz *et al.* 2022].

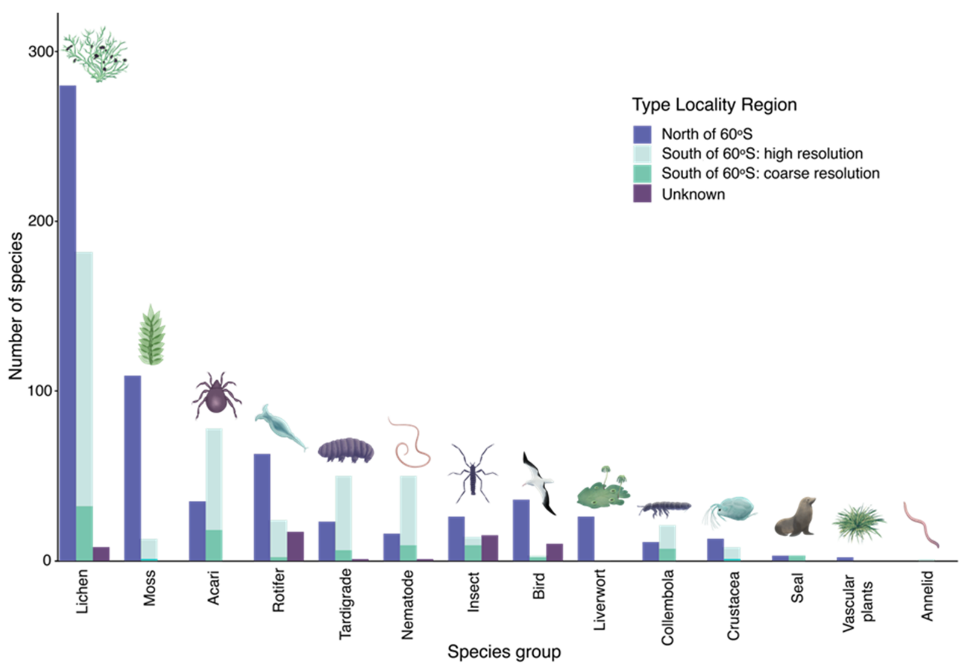


Figure 7.1 Terrestrial and freshwater species present in Antarctica. The information is for 14 taxonomic groups with type localities outside Antarctica (north of 60°S), within Antarctica (south of 60°S), and unknown type localities. Antarctic type localities are categorised as high resolution (≤25 km^2 area) and coarse resolution localities (>25 km^2 area). Note that for the insects, ectoparasitic species of birds and mammals are included (reproduced from Phillips *et al*. 2022).

Much of this life is restricted to the small ice-free areas of the continent (<0.5% by total area), although microbial systems can be found almost wherever they are sought, except possibly under the most extreme conditions [Pearce *et al.* 2009; Christner *et al.* 2014; Cavicchioli 2015; Goordial *et al*. 2017; Davey *et al.* 2019; Dragone *et al.* 2021; Gray *et al*. 2021]. Even the permafrost is not free from biological activity, but includes a wide range of viable microbiota, such as bacteria and fungi [Gilinchinsky *et al*. 2007; Efimenko *et al*. 2018; da Silva *et al*. 2020].

At the continental scale, isolation of ice-free areas and constraints on the dispersal of organisms have structured both soil-based and lake-based systems such that they can be divided into a series of ecoregions, known as the Antarctic Conservation Biogeographic Regions (ACBRs) [Terauds *et al.* 2012; Terauds & Lee 2016; Verleyen *et al.* 2021]. The extent to which the microbiota (e.g., bacteria, fungi) is dispersal limited is, however, not yet settled [e.g., Herbold *et al*. 2014; Archer *et al*. 2019].

The predominant factors influencing the abundance and distribution of Antarctic terrestrial biodiversity are temperature, liquid water availability, salinity, nutrient availability and exposure [Convey *et al.* 2014]. Historical features, such as geothermal refugia [Fraser *et al.* 2014], also play a role, as do interactions between species, though this is more limited than on other continents [Caruso *et al.* 2013; Caruso *et al.* 2019; Lee *et al.* 2019].

Because temperature and liquid water availability (and obviously the influence of the former on the latter) play such key roles in determining the abundance, composition and distribution of Antarctic terrestrial biodiversity, expectations are that where climates are changing, changes in the distribution, composition and abundance of life will result. In part these changes will also be mediated by microclimates, by changing interactions with newly arrived species, and potentially by nutrient alteration [Yergeau *et al*. 2012; Nielsen & Wall 2013; Colesie *et al*. 2014; Lee *et al.* 2017; Convey & Peck 2019; Bokhorst *et al*. 2022].

7.2 Observed changes and impacts

Temperatures and other climate conditions are changing in different ways across different major parts of Antarctica [Jones *et al.* 2016; Vignon *et al.* 2021]. Therefore, the biological changes that have been recorded are proceeding in ways dependent on that regional change. Largely as a consequence of limited long-term research, evidence demonstrating such change is, however, limited [Convey 2006; Convey & Peck 2019].

Warming and increases in precipitation along the Antarctic Peninsula and parts of West Antarctica are expected to have led to increases in the abundance and distribution of a variety of species [Nielsen & Wall 2013; Convey & Peck 2019]. The strongest evidence for such change is for the indigenous grass *Deschampsia antarctica* and the indigenous forb *Colobanthus quitensis*. The former increased in the number of sites occupied on Signy Island by 104% and in abundance by 191% between the 1960s and 2009. For the latter, these numbers are a 208% increase in cover and a 35% increase in the number of sites present [Cannone *et al.* 2016]. Between 2009 and 2018, the increase in the number of sites occupied and the area covered by these species continued on Signy Island [Cannone *et al*. 2022]. The rate of decadal increase showed a marked acceleration, from +20.8% to +28.2% per decade (1960—2009 versus 2009—2018) for *D. antarctica*, and from +6.9% to +154.3% per decade over the same periods for *C. quitensis* (**Figure 7.2**).

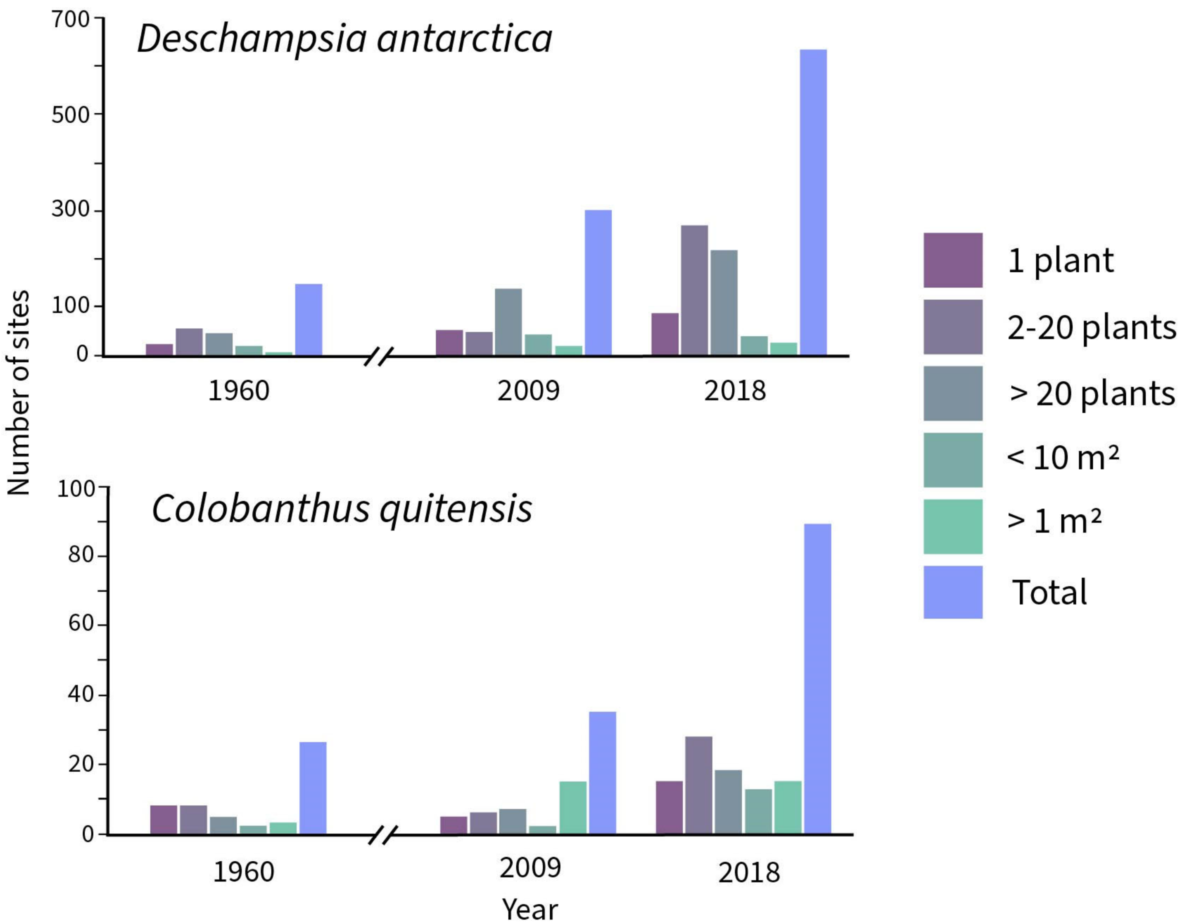


Figure 7.2 Increase in the sites occupied by Antarctica's flowering plants. Increases in the number of sites occupied on Signy Island by the two indigenous Antarctic flowering plant species, *Deschampisa antarctica* and *Colobanthus quitensis*, as a consequence of warming (redrawn with permission from Cannone *et al*. 2022).

Increases in biological activity associated with changing, and notably warming, climates have also been recorded for moss banks in the Antarctic Peninsula. Along a 600 km transect from Elephant Island (61°S) to Green Island (65°S), cores from moss banks have demonstrated sharp increases in growth rates, dry matter accumulation rate, and microbial productivity of moss turves, with a major state change in the

1950s [Amesbury *et al.* 2017] (**Figure 7.3**). Growth rate changes associated with changing temperatures have also been recorded for lichens, but with a shorter time-series [Sancho *et al.* 2019].

Overall, West Antarctica is showing evidence of greening in the dominant cryptogam vegetation (*high confidence*) [IPCC AR6 WGII CCP 6.2.2].

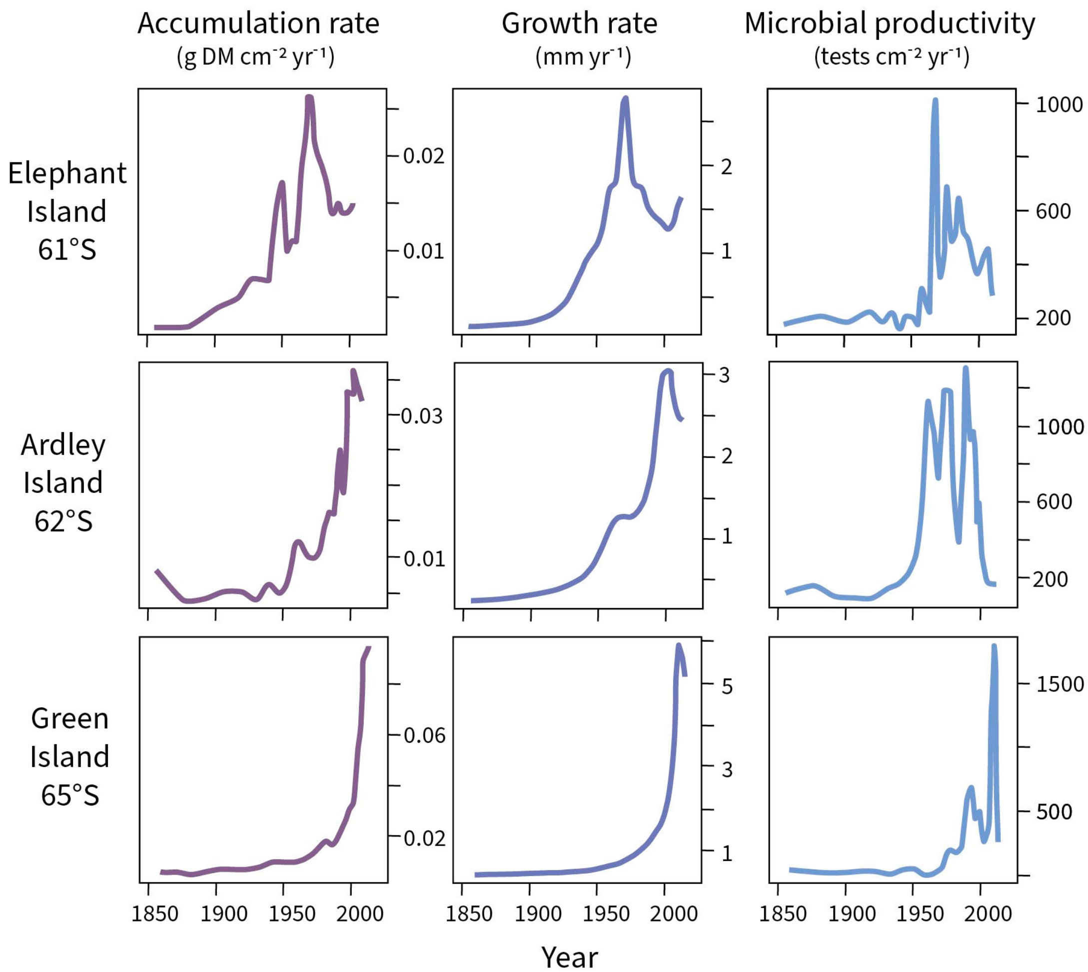


Figure 7.3 Changes in biological rates over 150 years. Changes in rates in moss banks and their microbial systems at three sites along the Antarctic Peninsula. Note the sharp acceleration in rates (redrawn with permission from Amesbury *et al.* 2017).

In East Antarctica, a single long-term study in the Windmill Islands area has found that drying conditions, associated with increasing windspeeds and changes to the Southern Annular Mode (SAM), have resulted in replacement of localised moisture-loving moss species with more widespread, drought tolerant counterparts [Robinson *et al.* 2018] (**Figure 7.4**). Declines in the health of moss communities, with more moribund plants in more recent times, along with results from isotope analyses, further demonstrate a drying trend affecting moss communities. Additional information on lakes (both salinity and extent) in the region suggests that the trends are more widespread in this region of East Antarctica. *High confidence* in these trends exists [IPCC AR6 WGII CCP 6.2.2]. Whether these trends will continue is dependent on the long-term behaviour of the ozone hole and the subsequent changes to the SAM and wind regimes in the region along with teleconnections between Antarctic and low latitude large-scale climate features.

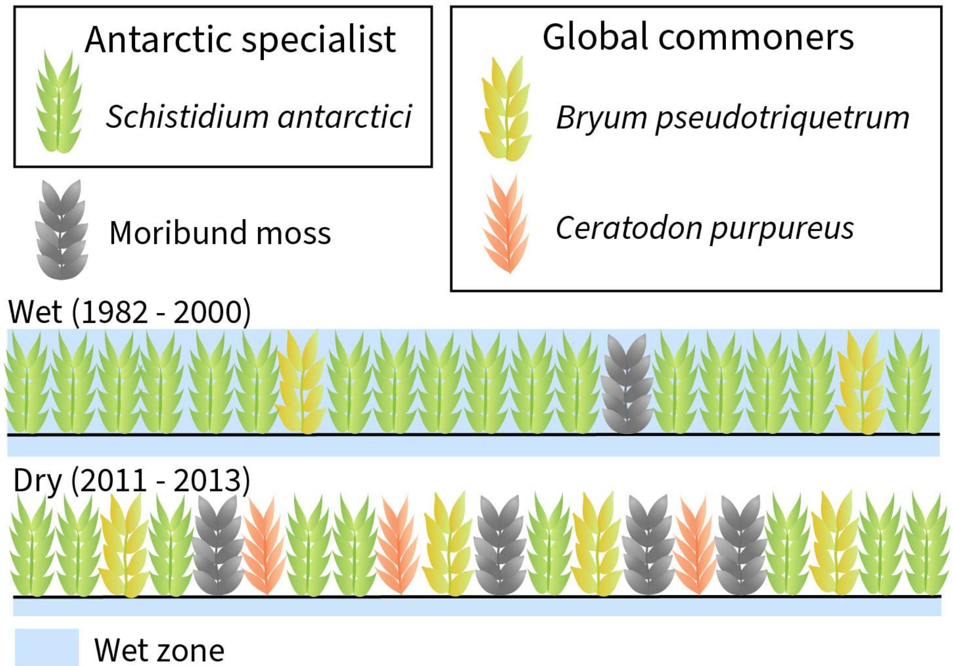


Figure 7.4 Moss community change in East Antarctica. Change in moss beds at the Windmill Islands in East Antarctica, with replacement of specialist species preferring wet conditions to more widespread, generalist species preferring dry conditions, and an increase in dying individuals, due to drying (reproduced with change courtesy of Sharon Robinson, see also Robinson *et al*. 2018).

In the McMurdo Dry Valleys, long-term research has shown that extreme events can cause significant changes to soil and lake systems [Gooseff *et al.* 2017]. Despite a cooling trend from the early 1990s until the summer of 2001, followed by a current trend of warming summers and more frequent warming events, the signals of climate change impacts on biodiversity are becoming clear [Andriuzzi *et al.* 2018]. Projections of declines in dominant invertebrate species and increases in previously less dominant ones have been borne out by changes in the abundances of the nematode *Scottnema lindsayae* relative to the less common nematodes and other soil fauna, earlier than expected, with declines in soil moisture playing an important role. Transient, but extreme weather events may be especially significant in altering the biodiversity of the region [Andriuzzi *et al.* 2018]. Turnover in other systems, such as in aquatic microbial mats on Livingston Island (Antarctic Peninsula) blighted by fungi [Velázquez *et al*. 2016], is also thought to be associated with warming.

By contrast with these limited demonstrations of climate change impacts, the biodiversity impacts of human activity have been more widely shown, either as a consequence of infrastructure development or other activities such as trampling or pollution [Convey 2011; Chown *et al.* 2017; Brooks *et al.* 2019; Chown & Brooks 2019; Convey & Peck 2019]. Human activity is growing in Antarctica's ice-free areas. Those areas considered most valuable for conservation or representing Antarctica's biodiversity values are inadequately protected [Shaw *et al.* 2014; Wauchope *et al.* 2019; Leihy *et al.* 2020; Phillips *et al.* 2022].

In consequence, *high agreement* now exists that rates of colonisation and use of coastal environments by terrestrial species and by land-based colonies of seabirds and seals are increasing [IPCC AR6 WGII CCP 6.2.2].

7.3 Projected changes and risks

General projections for terrestrial biodiversity change on the continent have typically either been inferred from the strong relationships between diversity and both temperature and liquid water availability, from relatively short-term field manipulative studies, or from a limited range of physiological studies of species [Convey *et al.* 2014; Convey & Peck 2019]. Many works have provided such projections [Walther *et al.* 2002; Convey 2006; Lyons *et al.* 2006; Convey 2011; Bokhorst *et al*. 2012; Nielsen & Wall 2013].

Although a growing number of experimental studies has been undertaken, many of the conclusions from the older works are limited by early design difficulties that are now being overcome [Convey & Peck 2019]. Expectations are generally for increased biomass, population density and/or cover, though the outcomes depend on particular species sensitivities and interactions among environmental variables and taxa. These findings accord in part with changes already documented for the continent (see previous section). In concert with a projected increase in ice-free areas [Lee *et al.* 2017], they suggest widespread biodiversity change where conditions are changing, though microclimate alterations and nutrient availability will also play a significant role.

Importantly, the role of microclimate for the distribution, abundance and functioning of Antarctic life, while widely appreciated [Green *et al*. 2011; Colesie *et al*. 2014; Convey *et al*. 2018; Perera-Castro *et al*. 2020], is yet to be fully considered from the perspective of mediation of climate change impacts. Limited microclimate data for the continent are partly an explanation [Convey *et al*. 2018], though new modelling approaches [e.g., Kearney *et al*. 2020] may prove useful for alleviating this bottleneck.

Despite their widespread application elsewhere on the globe [Elith & Leathwick 2009; Latombe *et al.* 2017; Araújo *et al.* 2019], regional-scale or continental-scale species distribution models to aid understanding and projection of expected biodiversity change are rare for Antarctica [for local scale studies see Lee *et al.* 2013; Bartlett *et al.* 2019]. Indeed, their application has been primarily to understand and project invasive species impacts [Duffy *et al.* 2017; Pertierra *et al.* 2017, 2020]. A recent illustrative exception is a study of Collembola species restricted to the Antarctic Peninsula, demonstrating the utility of the approach [Vega *et al.* 2020]. In particular the outcomes highlight the role that human activity might play in dispersing indigenous species as well as introduced ones.

Overall, based on changes in the climate and availability of ice-free area [Lee *et al.* 2017; Convey & Peck 2019], the expectation is for increases in the abundance and diversity of many continental taxa, but also for complex changes in species turnover associated with some species being winners and others losers when exposed to change [Yergeau *et al*. 2012; Nielsen & Wall 2013; Andriuzzi *et al.* 2018; Robinson *et al.* 2018; Misiak *et al.* 2021; Kohler *et al.* 2021]. Non-native species (or invasive alien species) are expected to establish more readily and to grow in both abundance and diversity with climate change. These species are dealt with below.

The details for changes in individual species and for spatial structure in biodiversity, such as to the ACBRs, are not available, however. Work on these topics is too limited for such conclusions, in part reflecting the low priority given to terrestrial biodiversity research by many Antarctic nations. Thus, projections for the efficacy of Antarctic Specially Protected Areas set aside for particular biodiversity values [Wauchope *et al.* 2019] cannot be made. Nor is it currently possible to provide evidence-informed projections of where to establish additional such areas to conserve terrestrial biodiversity in the face of change.

These major impediments to the conservation of Antarctic terrestrial biodiversity, that are largely policy-founded, have been raised repeatedly, but infrequently taken up explicitly in policy discussions [Convey 2006; Chown 2009; Turner *et al.* 2009; Convey 2011; Chown *et al.* 2017; Convey & Peck 2019; Hughes *et al.* 2021].

7.4 Non-native species

The synopsis provided here is drawn largely from the pending IPBES Thematic Assessment of Invasive Alien Species and Their Control [IPBES 2021], for which the Antarctic Terrestrial sections were drafted by two authors of this report (SLC, RIL).

7.4.1 Observed changes and impacts

Propagules of both plants and invertebrates routinely reach the Antarctic continent and its surrounding islands (*high confidence*) [Hughes *et al.* 2005; Chwedorzewska *et al.* 2013; Houghton *et al.* 2016; Newman *et al.* 2018]. Routes of transport into the terrestrial Antarctic are through human activity (and travel via ships and aircraft) comprising human individuals that carry propagules (seeds or individual animals) on clothing and in bags, and in material used for scientific research, infrastructure building and maintenance (*high confidence*) [Lee & Chown 2009b,c; Hughes *et al.* 2010; Huiskes *et al.* 2014; Bergstrom 2022] (**Figure 7.5**).

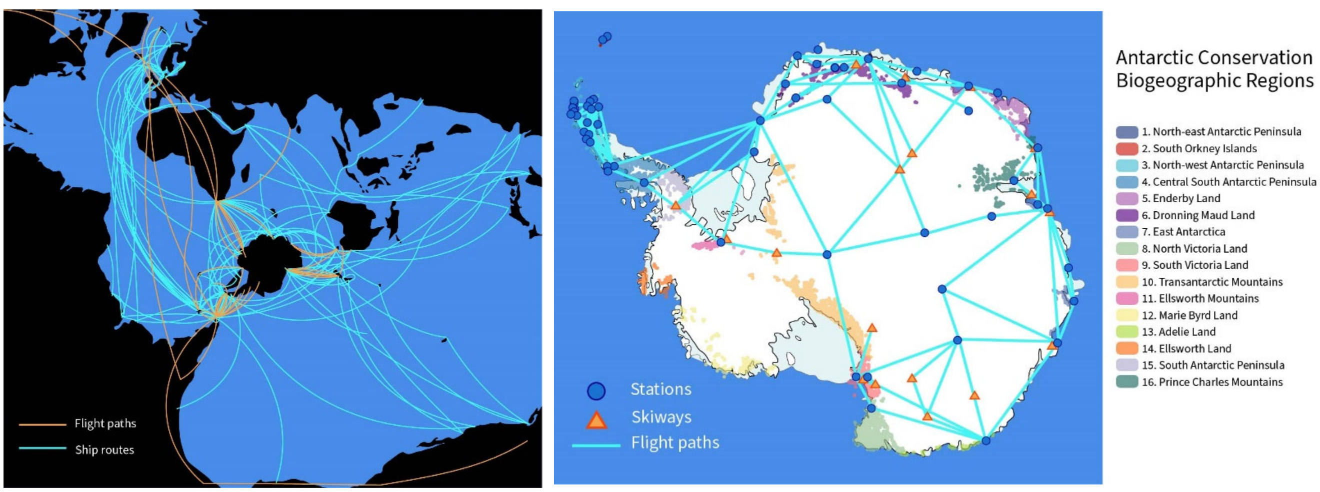


Figure 7.5 Pathways for the transport of species into and around Antarctica. Ship and flight pathways to Antarctica (left) and flight paths within Antarctica (right) illustrating potential vector pathways between other continents and Antarctica and between the Antarctic Conservation Biogeographic Regions (redrawn with permission from Bergstrom 2022).

Little is known about microbial incursions now and measures to reduce them are not well developed [Pearce *et al.* 2009; Cowan *et al.* 2011; Hughes *et al.* 2018]. Although microbial pathogens represent a minority of the microbiota, introduced pathogens can affect species in the region as found or suspected for sub-Antarctic islands plants [Kloppers & Smith 1998; Lebouvier *et al.* 2011; Bergstrom *et al.* 2015].

The relative contributions of scientific and tourism activities to introduction likelihood are less important than the range of activities undertaken and the risks associated with each. Scientists tend to carry more seeds than tourists, but the difference in visitor numbers of each renders their risks equivalent (*medium confidence*) [Chown *et al.* 2012; Huiskes *et al.* 2014]. Over time, however, attributions of recorded introductions to the broader region have been dominated by those due to science activities.

Non-native species have established and spread widely in the broader Antarctic region, including the sub-Antarctic (*high confidence*) [Frenot *et al.* 2005; McGeoch *et al.* 2015]. Several plant and invertebrate species are now known to have established in the Antarctic Peninsula region (*high confidence*) [Volonterio *et al.* 2013; Chwedorzewska *et al.* 2014; Hughes *et al.* 2015; Enríquez *et al.* 2019], in those areas predicted by models to be most suitable for establishment both now and into the future [Chown *et al.* 2012; Duffy *et al.* 2017]. Soil temperatures along the Antarctic Peninsula are sufficient for germination of a variety of non-native plants, with limitation of establishment potentially switching to nutrients and away from temperature and liquid water availability [Bokhorst *et al*. 2021, 2022; IPCC AR6 WGII CCP 6.2.2].

Impacts of non-native species on species and communities on the Antarctic Peninsula or continent have not been investigated in the field, though laboratory studies suggest negative impacts of the established non-native grass species *Poa annua* on the only two indigenous vascular plants found on the Peninsula might occur [Molina-Montenegro *et al*. 2012]. In the sub-Antarctic, non-native species have significant impacts on ecosystems generally and on indigenous species, such as invertebrates, petrels and albatrosses, being a major cause of decline in IUCN red list status (*high confidence*) [Frenot *et al.* 2005; Jones & Ryan 2010; McGeoch *et al.* 2015; Dilley *et al.* 2017; McClelland *et al.* 2018; Chown *et al.* 2022].

7.4.2 Projected changes and risks

Current climatic barriers to alien species establishment are projected to weaken as warming continues across the region, especially on the Antarctic Peninsula (*medium confidence*) [Chown *et al.* 2012; Duffy *et al.* 2017; Hughes *et al.* 2020]. An increase in the ice-free area linked to glacier retreat in Antarctica is furthermore expected to increase the available opportunities for non-native species establishment [Lee *et al.* 2017; Duffy & Lee 2019]. Along with growing numbers of visitors, this is expected to increase the numbers of non-native terrestrial species that will become established on the Peninsula particularly (*medium confidence*) [Chown *et al.* 2012; Hughes *et al.* 2015; Hughes *et al.* 2020]. Thus, invasions by non-native species are expected to increase with rising temperatures (*medium confidence*) [IPCC AR6 WGII CCP 6.2.2]. In the case of fungal disease, increasing precipitation in the form of rain may play a role too, given the importance of high humidities for this group in wooden infrastructure settings [Farrell *et al*. 2011; Held & Blanchette 2017].

In turn, established species are expected to have negative impacts on local systems based on limited experimental work undertaken to date demonstrating that the introduced grass *Poa annua* can outcompete the indigenous flowering plants *Deschampsia antarctica* and *Colobanthus quitensis* under projected conditions [Molina-Montenegro *et al.* 2019].

Little is known about the likelihood of microbial incursions and their impacts into the future, though expectations are for greater likelihood of establishment and impact [Held & Blanchette 2017].

With increasing connectivity between and within the ACBRs owing to human activities [Hughes & Convey 2010; Bergstrom 2022], expectations are that species currently restricted to one or a small number of these regions will spread to others (*low confidence*) [Lee & Chown 2011; Hughes *et al.* 2019].

Surveillance and removal of established individuals is effective for plants, though with some complexity arising from persistent seedbanks and management of eradication effort (*low confidence*) [Hughes & Convey 2012; Galera *et al.* 2016; Malfasi *et al*. 2020; Galera *et al*. 2021]. No information exists, however, for other species. Pesticide-based interventions are precluded from use south of 60°S by the Protocol on Environmental Protection to the Antarctic Treaty.

Biosecurity to reduce the number of propagules entering the region, or being moved between ACBRs, remains the most effective adaptation response because detections are high and removal is effective (*high confidence*) [Lee & Chown 2009b, 2011; Hughes & Convey 2010]. Advice to national operators already exists for extra-regional introductions through the checklists for supply chain managers produced by the Council of Managers of National Antarctic Programs and SCAR [COMNAP/SCAR 2020]. The efficacy of biosecurity protocols [Lee & Chown 2009b; Bartlett *et al.* 2020] remains under-investigated.

7.5 Policy recommendations

The Antarctic Treaty Parties and the members of the Committee for Environmental Protection are encouraged to increase the priority given to documenting terrestrial and marine biodiversity (including in lakes and streams) at the population, species, and community levels. In some cases, to enable observation of these systems before they disappear. Such an enhanced focus, further informed by long-term monitoring of change, is essential to ensure the efficacy of environmental protection and to document the benefits of environmental management.

National Antarctic Programs and International Association of Antarctica Tour Operators members are encouraged to strengthen biosecurity protocols for all pathways (ships, aircraft, and people), especially to the Antarctic Peninsula. Procedures to remove weeds and to trap other pests in ports of departure to the Antarctic need to be strengthened in anticipation of growing ease of establishment of non-native species owing to climate change. Surveillance and decision-making processes for determining actions for newly arrived species, especially in the vicinity of stations and sites with high visitor numbers, should be adopted. Collaborations with SCAR and other researchers are needed to establish an image- and DNA-based diagnostic service for newly detected species, building on the Barcode of Life Data System approach.

7.6 Research recommendations

RR 7.1 Determine how terrestrial ecosystems have responded to warmer climate conditions in the past and how this informs projections.

RR 7.2 Establish which terrestrial ecosystems and food webs are most vulnerable, how they are likely to change, and which organisms are most likely to decline and/or to go extinct and over what time period, as a consequence of climate change and local interactions such as with non-native species.

RR 7.3 Investigate the synergistic effects of multiple stressors and environmental change drivers on terrestrial biota.

RR 7.4 Determine how effective Antarctic Specially Protected Areas designation and monitoring is in meeting protection and conservation objectives under changing climate regimes.

RR 7.5 Understand the efficacy of *in situ* and *ex situ* terrestrial conservation measures for preserving evolutionary potential.

RR 7.6 Establish how natural and human-induced environmental changes can be distinguished in terrestrial ecosystems.

RR 7.7 Establish a circumpolar terrestrial life observatory network to provide terrestrial/coastal biological time series to detect and monitor species colonisation, local extinctions, and invasions.

RR 7.8 Deliver continent-wide species distribution modelling approaches that include community-level assessments, founded on comprehensive and integrated biodiversity data, facilitated through the SCAR Antarctic Biodiversity Portal.

RR 7.9 Continue to improve understanding of the factors that lead to loss of biodiversity, how ecosystems respond to changing environments, and the efficacy of protection and conservation practices.

RR 7.10 Further consider the full range of species likely to establish, especially those from Antarctic gateway ports via mechanistic and species distribution modelling approaches.

RR 7.11 Further assess the efficacy of current biosecurity protocols, such as boot washing.

RR 7.12 Establish how the sources and mechanisms of dispersal of propagules into and around the Antarctic will change in the future.

RR 7.13 Determine how invasive species and range shifts of indigenous species will change Antarctic ecosystems.

8. Concluding Remarks

Global climate change is gaining momentum due to the unbated, increasing emissions of greenhouse gases due to human activities. The IPCC AR6 WGIII Report Mitigation of Climate Change (IPCC AR6 WGIII) [IPCC 2022b] makes clear that net anthropogenic GHG emissions have increased since 2010 across all major sectors globally [IPCC AR6 WGIII SPM B.2].

This momentum increases the likelihood of crossing irreversible thresholds in physical and living systems, both known and unknown.

The IPCC AR6 WGII Report [SPM D.5.3] unambiguously emphasises the need for action: *The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all.*

The urgency is clear from the IPCC AR6 WGIII Report [SPM C.1]: *Global GHG emissions are projected to peak between 2020 and at the latest before 2025 in global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%) and assume immediate action. In both types of modelled pathways, rapid and deep GHG emissions reductions follow throughout 2030, 2040 and 2050 (high confidence). Without a strengthening of policies beyond those that are implemented by the end of 2020, GHG emissions are projected to rise beyond 2025, leading to a median global warming of 3.2 [2.2 to 3.5] °C by 2100 (medium confidence).*

In other words, to limit global warming to 1.5°C, and to limit change to Antarctica and the Southern Ocean, immediate and deep emissions reductions are required across all sectors.

Already, observations, modelling and global assessments describe significant changes in Antarctic marine and terrestrial, physical and living systems.

The most significant potential influence of Antarctica's changes will be on global mean sea level change and its influence on society and nature in all coastal regions of the globe.

Further global impacts influenced by Antarctic change include extreme climate and weather events, droughts, wildfires and floods, and ocean acidification. These impacts cause ecosystem disruption and loss of biodiversity beyond the Antarctic region.

Under current projections, and without nations at the very least meeting the Nationally Determined Contributions of the Paris Climate Agreement, the rate of global change will outpace societal, political, and economic responses that will facilitate adaptation and strengthen resilience to the impacts of climate change.

The agreements of the Antarctic Treaty System will not escape these influences. Rapidly changing Antarctic and Southern Ocean environments require similarly rapid environmental governance responses, including potential changes to agreements that have previously taken many years to reach. Impacts of climate change are also likely to challenge geopolitical relations in regions outside the Antarctic, in turn influencing relations within the Antarctic Treaty System.

Past global arrangements and isolated responses have been ineffective in addressing cross-boundary challenges that require an Earth System approach. Research conducted in the Antarctic and Southern Ocean regions, and strong policies developed from its results, are critical for the development of an integrated Earth System approach and the discernment of a path to a sustainable future for the planet.

Cooperative and coordinated international responses are required to address critical research needs in Antarctica and the Southern Ocean. In turn, receptive Antarctic governance is needed to use the knowledge generated by the research to create effective policy and decisions. Enhanced investment in science will provide policymakers and planners with more comprehensive and coherent sets of information over time to help put in place timely, scalable adaptation and mitigation strategies. Investment in new science and technology that provides updated information on the likelihood of major drivers of climate risk will more than repay itself.

Science communication and education in partnership with other cultural and societal actors is essential to enable further appreciation of the value of Antarctica and the Southern Ocean for current and future human well-being, for biodiversity, and for the interdependence of humans and nature.

Effective action is now more urgent than it has ever been.

8.1 Policy recommendation

The Antarctic Treaty Parties (ATPs) have declared an obligation to implement the mitigation and adaptation actions that will reduce climate change-related and other human impacts on Antarctic marine and terrestrial environments, their ecosystems and biodiversity, and the ecosystem services they deliver.

Continued support for the research required to deliver evidence-informed options for action, including through coordinated, international and transdisciplinary research efforts across Antarctica and the Southern Ocean by all ATPs; the development of an appropriately-resourced scientific workforce for the future; and well-supported long-term monitoring programs of the physical and living environment, are essential to meet this obligation. Our human future depends on the success of these actions.

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