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CONCLUSIONS

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Antarctica and the Earth System

The chapters of this book have emphasised the centrality of Antarctica and the Southern Ocean in multiple aspects of the Earth System. The importance of these connections can be partially envisaged by considering the financial value of ecosystem services provided by Antarctica to the rest of the world (conservatively estimated at US$180 billion), or by the financial cost of sea level rise in 2100 caused by Antarctic Ice Sheet melt (estimated at >US$60 billion per year even with low greenhouse gas emissions and optimal adaptation – rising to around US$1 trillion per year with no adaptation). Of course, such financial estimates, whilst vast, only represent part of the true scientific, societal and cultural value of Antarctica to humanity, even aside from the intrinsic value of the region.

Numerous key messages have emerged from this book, many of which point to priorities for future actions, scientific research and policymaking (Figure 12.1). Underpinning several of these is a critical need to better understand the drivers of observed and ongoing changes in Antarctic climate. Many of these changes have been attributed to global atmospheric forcing, including human-driven perturbations such as greenhouse gas-driven warming and ozone depletion. Superposed on these are natural phenomena such as coupled modes of climate variability, some of which can transmit tropical and equatorial signals to high latitudes, though it should be noted that the strength and frequency of such events are themselves susceptible to global climatic forcing. Resolving this scientific complexity demands comprehensive networks of sustained *in situ* observations, linked to satellite observations and coupled models for their current and future trajectories to be adequately addressed. However, there are persistent gaps across this capability due to the remote and harsh nature of the Antarctic environment.

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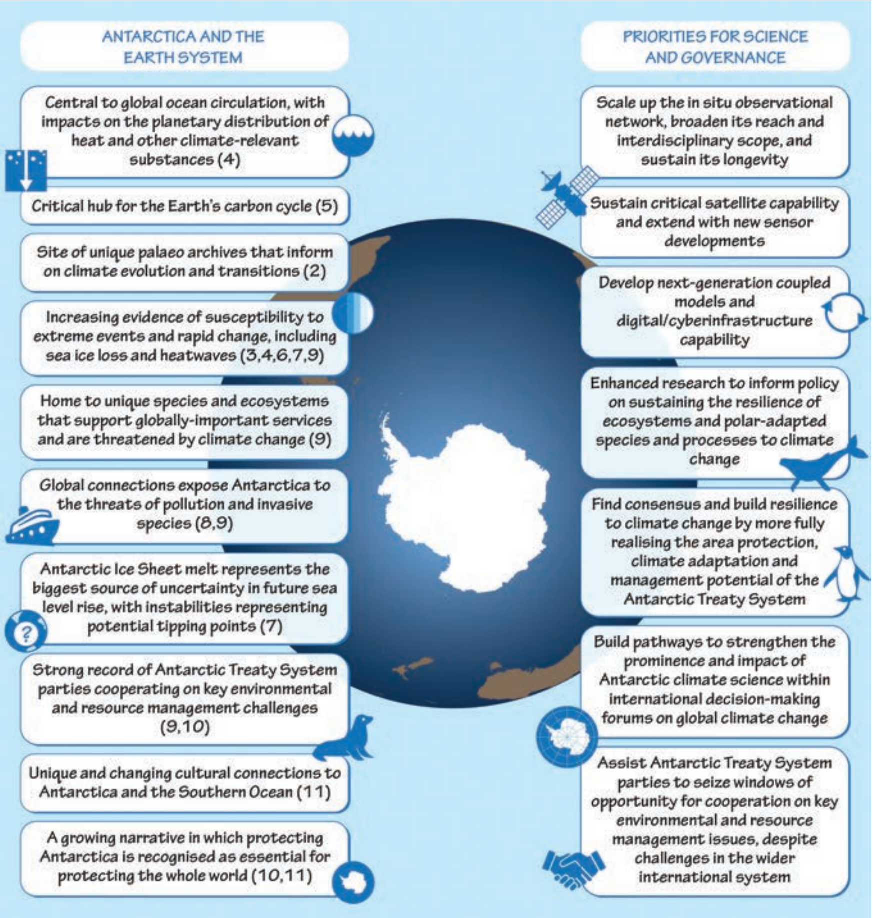

FIGURE 12.1 Key connections between Antarctica and the rest of the Earth System, and priorities for science and governance Relevant chapters are cited in brackets.

Sea ice serves as a clear exemplar of the potential for rapid change around Antarctica. This sea ice cover has long been known as dynamic and variable on timescales from days to decades, incorporating one of the largest annual cycles on Earth. However, satellite monitoring has revealed a very rapid dwindling of Antarctic sea ice cover since 2016, following a gradual expansion in the preceding decades. The full causes of this are, at the time of writing, the subject of active research, but include both atmospheric and oceanic drivers and complex feedbacks. There is increasing thought that this change may represent the transition to a new state, with global climatic implications via albedo changes and dense water production, and ecosystem consequences through the loss of a key habitat for ice-dependent species.

There is mounting evidence that the changing atmospheric and cryospheric forcings of the Southern Ocean (including a contracting polar vortex, retreating sea ice and accelerating ice sheet melt) may be driving a major reorganisation of the Southern Ocean overturning circulation. Given the circulation's importance to planetary climate on timescales of decades and longer, via its moving of vast quantities of heat and other climatically-important tracers around the world, this has profound implications for the rest of the planet, its ecosystems and inhabitants. However, accurately assessing the structure, rate and global consequences of this reorganisation poses formidable observational and methodological challenges, due to the circulation's spatially-distributed nature, its vast scales, and the inaccessibility of many focal sites of overturning such as areas of dense water production at the Antarctic margins.

Alongside the Southern Ocean's important role in global ocean circulation, it is also a critical hub of Earth's carbon cycle, whose variability readily and profoundly impacts global atmospheric carbon dioxide and climate. The amplitude – and even the sign – of these impacts can however be extremely challenging to predict, due to the Southern Ocean's central involvement in a suite of physical and biogeochemical climate-system feedbacks. Achieving a step advance in predictive capability will require substantial leaps in process understanding in a range of science areas – from the turbulent dynamics controlling ocean ventilation and physical carbon uptake and storage to the micronutrient-physiology dynamics shaping biological uptake by phytoplankton or the biogeochemical regulation of clouds over the Southern Ocean.

One way to gain more insight into the operation of the Antarctic and Southern Ocean system is via the unique perspectives on climate variability and ecosystem changes that are available from palaeo-environmental archives, including ice cores, ocean sediment cores, lake sediments, and so on. Each of these contributes vital information on conditions that prevailed on Earth in the past, how they evolved into the conditions we are living in today, and, by extension, which future trajectories are possible under different scenarios. Critically, they provide insight into transitions between environmental states, including knowledge on the potential for rapid climate shifts and the passing of tipping points, and the timescales upon which such changes are irreversible. Extending current knowledge and using new techniques to better integrate this understanding into enhanced predictive capability is a high priority.

Perhaps the most tangible impact that Antarctica can have across the planet is via sea level rise. The ice sheet is presently undergoing a dramatic shift, with some major sectors shrinking at accelerating rates. It is widely agreed that Antarctic Ice Sheet mass loss will continue for centuries to come and that this loss will result in substantial global sea level rise. However, the rate and ultimate extent of ice sheet waning and associated rising seas are the subject of deep uncertainty, leaving humanity significantly unprepared for what lies ahead. To address the ice sheet and climate model shortcomings underpinning such deep uncertainty, it will be necessary to radically advance our understanding of a range of key atmosphere–ocean–ice interaction and ice sheet dynamical processes, such as marine ice sheet and ice cliff instabilities. The complexity of the scientific problem and the scale of what is at stake for global society makes the prediction of the Antarctic Ice Sheet's future one of the most critical and pressing challenges facing us today.

Concerning biodiversity, it is known that sealing, whaling, fishing and human presence have been the major historical threats in the Antarctic. However, the most significant drivers of future ecosystem change are likely to be climate change and ocean acidification, which are mostly caused by human activity outside the region. There is a pressing need for enhanced research to be coupled with a management focus on what is needed to sustain the resilience of Antarctic and Southern Ocean ecosystems in the face of global threats from future change to many polar-adapted species and processes. At present, our scientific knowledge of these ecosystems as a whole is insufficient to closely manage increased human presence and allow any significant expansion of fisheries. Current fisheries levels may in fact threaten the long-term resilience of marine ecosystems, particularly for high-latitude fisheries. Across both marine and terrestrial ecosystems, there is a need for evidence-informed projections of where to establish protected areas to enable resilience and to conserve biodiversity in the face of global threats from climate change and ocean acidification.

Antarctica and the Southern Ocean are vulnerable to both local and globally-dispersed pollutant threats. Of these, the local pollutant threat is established, regulated, and relatively well understood, but the impacts of pollutants that are dispersed via atmospheric and oceanic pathways (particularly nanoplastics) are currently poorly understood. Human activities have led to substantial increases in the long-range deposition of pollution into Antarctic and sub-Antarctic regions; future climatic changes (including strengthened ice melt and increased precipitation as rainfall) will lead to enhanced (re)deposition, and possibly increased concentrations of globally-derived pollutants across Antarctic terrestrial and marine environments. Accordingly, understanding how pollutants might decrease the resilience of biological organisms and ecosystems to other stressors is an important research priority.

Whilst Antarctica and the Southern Ocean are geographically remote from major centres of population and much of the economic activity on our planet, human interaction there is still influenced by both regional and global geopolitics. The Antarctic Treaty System (ATS) has been remarkably successful in setting aside arguments over sovereignty and allowing the region to be used by all states involved for peaceful activities such as science, tourism and controlled fishing. However, the success of the ATS has also perhaps set unrealistic expectations about its ability to manage all political and other challenges that impact the region. Just as during the 1950s, when the ATS was formed, tensions and changes in the wider international political system are affecting relations between states in Antarctic governance forums, including current armed conflicts between some member states.

Such tensions create obvious problems for decision-making in forums, which rely on the consensus of all states present. Without downplaying the difficulties of such violent conflicts, we have seen the strong track record of the ATS parties in seizing windows of opportunity for cooperation on the key environmental and resource management challenges for the region. The ATS parties must be ready to act quickly when such windows for cooperation are opening again.

The chapters in this book have demonstrated the climatic and ecological importance of Antarctica for the whole planet. Whilst the ATS has an important role in generating scientific knowledge and political momentum that might be brought into key global forums to manage climate change by reducing emissions, such as the meetings of the United Nations Framework Convention on Climate Change, the Treaty System itself is not set up to reduce global emissions of greenhouse gases. To suggest otherwise would be to burden it with a task that it is unable to fulfil. However, the ATS needs to continue to play a strong role in generating robust and compelling climate-relevant science, clearly expressing the risks of climate change impacts on the region and how regional climate impacts will influence the global climate system. The ATS can also do more in building the resilience of Antarctic ecosystems to climate change impacts by realising more fully the area protection and management mandate of the Madrid Protocol, but this has proven challenging. Finding consensus and realising more fully the area protection and management potential of the ATS, in the face of increasing climate change impacts, is a key challenge.

Antarctica and the Southern Ocean have meant different things to people at different points in time. In this book, Nielsen et al. suggest that it is useful "to think not of one Antarctica, but of many – the region is deeply storied, and these stories accumulate and shift year upon year, much like the ice of the Antarctic continent itself." There is a growing narrative of Antarctica as embodying an existential threat to communities around the globe – not only impacted by us but also impacting upon us. In this context, melting polar ice is more than a symbol for a planet facing a climate crisis but also increasingly narrated as a central factor in that crisis: a source of catastrophic impacts projected especially for low-lying communities. This narrative highlights global entanglements – as protecting Antarctica becomes about protecting the rest of the world – and is gaining increasing traction in media and in multilateral political discourse. Examples include the Helsinki Declaration at the 2023 Antarctic Treaty Consultative Meeting as well as several intergovernmental cryosphere coalitions, such as the "Ambition on Melting Ice" high-level group led by Chile and Iceland, the "One Planet Polar Summit" high-level effort led by France, and the "Polar Initiative" led by Monaco.

Closing Messages

A recurring theme across many of the aspects discussed here is that, despite their critical importance to the rest of the planet and their marked susceptibility to global change, Antarctica and the Southern Ocean remain significantly undersampled.

This has been the case since Antarctic science began, and it remains a key constraint on better scientific understanding and predicting the future of our planet as a whole. Autonomous and robotic systems, and increasingly capable Earth Observation satellites, will go some way to alleviating this issue, but key domains, such as the ocean interior and abyss, and the vast areas beneath the sea ice and ice sheets, remain data deserts and will do for some time. Priorities for future action include scaling up the *in situ* observing networks, securing their longevity, and broadening their interdisciplinary scope to include a greater breadth of key measurements. In parallel, ensuring the continuity of satellite missions is essential, as is developing new satellite sensor capabilities to generate unique new information on key ongoing and future changes. Collectively, this will require strengthened international cooperation and enhanced coordination of interdisciplinary observing system components, in addition to sustained funding commitments. Nonetheless, increasingly robust, long-duration robotic and remotely-piloted platforms offer great scope for this to be feasible, by driving capability for data generation to transcend what is currently possible, and by allowing human-based sampling and measurement to be targeted where it can have the most impact.

In synergy with these developments, next-generation coupled models of Antarctica and the Southern Ocean, and their global connections, are required. These will span a range of capabilities but will include data-assimilative ice–ocean–atmosphere models that can capitalise on advances in the observing system and process understanding with greater agility than current models. Such models will increasingly need to represent complex elements of the ecosystem, so that biogeochemical and biological carbon cycles can be adequately represented, and climate change impacts on biodiversity be projected and assessed as part of management frameworks. The traditional separation of observations and models will dwindle over time, such that both operate more seamlessly as parts of a cyberinfrastructure environment, thus maximising the usefulness of both and providing optimal outputs and scientific evidence upon which to base policy and management decisions. This will create more opportunities for innovative digital techniques, such as artificial intelligence and machine learning, which are now beginning to revolutionise some aspects of polar science.

Such developments are critical, and there is an urgent need to progress them. Antarctica and the Southern Ocean are increasingly recognised as susceptible to extreme events and the potential passing of tipping points, including major loss of ice sheets with impacts on global sea levels, rapid loss of sea ice, marine and atmospheric heatwaves, and impacts on ecosystems and biodiversity. Such occurrences reinforce the requirement to urgently enhance our understanding of Antarctica and its global connections, and emphasise the need for the science we do (and the way that we do it) to be increasingly capable and agile, creating the information essential to inform policy and governance in both regional and global contexts. By so doing, we can contribute to securing Antarctica and the Southern Ocean, and their critical climatic, biological, societal and cultural benefits, for future generations.