

The State and Future of Antarctic Environments in a Global Context

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Abstract

Antarctica and the Southern Ocean comprise a critical part of the Earth System. Their environments are better understood than ever before, yet the region remains poorly considered among international agreements to improve the state of the global environment. In part the situation owes to isolated regional regulation within the Antarctic Treaty System, and in part to the dated notion that Antarctica and the Southern Ocean are well conserved and relatively free from human impact. Here we review growth in knowledge of Antarctic environments and anthropogenic pressures on them. We show that the region's unusual diversity is facing substantial local and globally mediated anthropogenic pressure, on a par with environments globally. Antarctic environmental management and regulation is being challenged to keep pace with the change. Much benefit can be derived from consideration of Antarctic environmental and resource management in the context of global agreements.

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1. INTRODUCTION

Antarctica, its surrounding islands, and the Southern Ocean together constitute a critical part of the Earth System. Any assessment of the state of the global environment and plans to improve it more generally therefore require explicit inclusion of the region. Despite well-developed regulatory regimes for the conservation of Antarctica, its surrounding islands, and the Southern Ocean (hereafter the Antarctic) (1), consideration of the broader region within global assessment frameworks is uncommon. For example, the Fourth Global Biodiversity Outlook (2) paid scant attention to the Antarctic. Similarly, the special governance arrangements for the region have not been recognized by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, suggesting that it will not be closely considered.

The neglect of Antarctic environments in global assessments may in part stem from their being considered well governed, effectively conserved, and—excluding historic fishing, whaling, and sealing activities in the Southern Ocean—free from excessive human impact compared with regions elsewhere (3). A suite of agreements, collectively known as the Antarctic Treaty System (ATS), govern Antarctica and the Southern Ocean, largely south of 60°S but extending northward beyond this latitude in the case of the Convention on the Conservation of Antarctic Marine Living Resources (CAMLRL Convention) (1). At its heart lies the Antarctic Treaty, Parties to which meet annually to develop and implement governance of the region. The sub-Antarctic islands, which surround the continent, are under national jurisdiction, but generally they are also accorded substantial protection (4). Reluctance of the Antarctic Treaty Consultative Parties to engage with international agreements of the United Nations, despite explicit mechanisms to do so (e.g., Antarctic Treaty Article III.2) (5), or to appreciate the advantages of such engagement (6), may also account for the region's absence in global environmental assessments. In effect, the

Southern Ocean:

the ocean area approximately south of 40°S, including the sub-Antarctic islands, sub-Antarctic New Zealand, the Scotia Sea, and the high Antarctic

Antarctic Treaty

System (ATS): the suite of international agreements applying to the Antarctic region

assumption of environmental conservation and decision-making effectiveness as well as self-imposed isolation from other international regimes have led to a situation where the extraordinary diversity of Antarctic environments and life (7, 8), and their importance in delivering global ecosystem services (9, 10), have in part been marginalized from international environmental developments. Such marginalization means lack of appreciation for the region's global significance, along with inadequate anticipation of its management needs.

The current situation is problematic for several reasons, of which three stand out. First, any claim by global assessments to such a title will necessarily be inaccurate when excluding an important part of the Earth System. Arguments that Antarctic environments are depauperate in diversity, and therefore might be relatively unimportant, and are also not subject to growing human use, are clearly misplaced (7, 8, 11, 12). Second, opportunities for improving governance and environmental conservation globally derived from learning among regulatory regimes (13, 14) are largely lost. Third, lack of appreciation of the significance of change in the Antarctic for environments elsewhere hinders development of the global understanding required to secure a sustainable future. For example, the Southern Ocean dominates the global ocean uptake of anthropogenic carbon (10). Change that alters the ecosystems delivering this role will have profound planetary-wide consequences. Likewise, the behavior of Antarctic ice sheets has extraordinary global implications (15). From a physical perspective, the Intergovernmental Panel on Climate Change's (IPCC's) (16) *Special Report on the Ocean and Cryosphere in a Changing Climate* represents an example of efforts to improve inclusion of the Antarctic in global assessments.

Deepening appreciation for the role of teleconnections between the Antarctic and the rest of the globe, documentation of rapid change in the Antarctic, and forecasts for accelerating impacts of global environmental change on the region (reviewed in 10, 17) have been instrumental in prompting recent scientific investigations of the state and future of Antarctic environments. So too has emerging evidence globally for the importance of regulatory actions, coupled with the realization that their deployment in the Antarctic is inadequate (reviewed in 18). The designation of protected areas for the conservation of marine and terrestrial diversity, given their demonstrable efficacy, provides one example (9). Another is offered by rapid development of agreements on access and benefit sharing for biological resources elsewhere, but comparative stagnation of discussions about how to regulate bioprospecting in the Antarctic (19). A third comes from minimal deployment of sophisticated conservation planning tools, which enable stakeholder engagement in conservation planning elsewhere (20), to help develop widely agreed measures of ensuring sustainability of Antarctic tourism. Consequently, although political engagement in broad-based assessments of the state and future of Antarctic environments is lagging, the evidence-base for doing so is developing rapidly.

Here we synthesize developments in this area. First, we review growth in the knowledge of the diversity of Antarctic environments over the past decade. Next, we consider the state of Antarctic environments, the main pressures on them, and some of the drivers of those pressures. Climate change is considered a key pressure on environments in the region. No doubt exists that parts of the region have been changing rapidly. For example, the Southern Ocean has warmed and freshened over the past several decades (21). Sea ice extent has shown a more complex trend, with slow increases between 1979 and 1999 ($0.12 \pm 0.11 \times 10^6 \text{ km}^2 \text{ decade}^{-1}$), a fivefold more rapid rate of increase from 2000 to 2014 ($0.57 \pm 0.33 \times 10^6 \text{ km}^2 \text{ decade}^{-1}$), and a sudden decline in 2016, with relatively low extent since then (22, 23) (**Figure 1a**). Surface air temperature changes have also been regionally variable over the 1979–2014 period, with positive trends over the Antarctic Peninsula and East Antarctic Plateau, but negative trends elsewhere (24) (**Figure 1b**), and with a hiatus in the warming trend on the Peninsula (25). By contrast, the Antarctic ice sheet has shown an increasing decline in mass (26) (**Figure 1c**). Nonetheless,

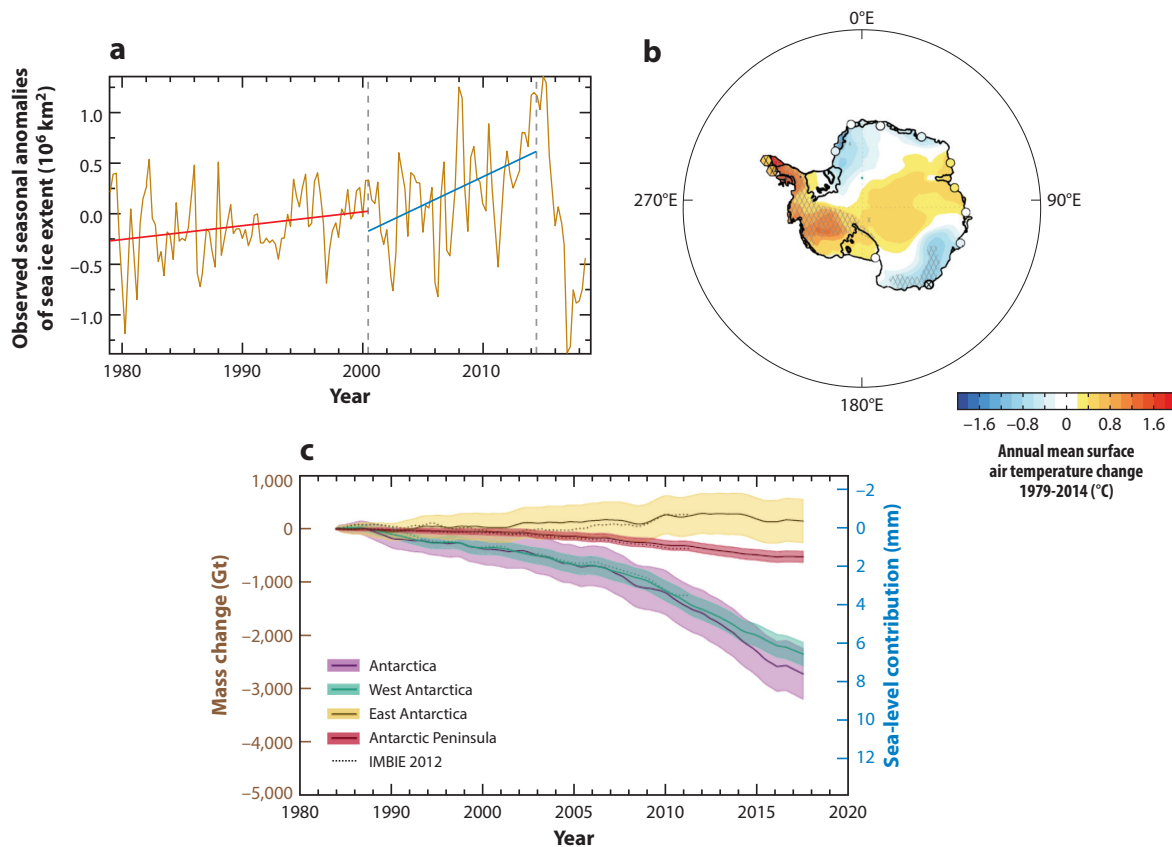


Figure 1

Change in the physical environment of Antarctica and the Southern Ocean. (a) Increases in sea ice extent between 1979 and 2014, with a rapid decline in 2016 (22). Trend lines are indicated and vertical lines indicate changes in the interdecadal Pacific oscillation. (b) Regionally variable trends in Antarctica's surface air temperature over the 1979–2014 satellite observing period, with cross-hatching indicating significant trends (24). Reprinted with permission from Springer Nature. (c) Changes in Antarctica's ice sheet mass since 1990, with estimated 1σ uncertainty shaded (26). Modified, with permission from Springer Nature (24).

the evidence for attribution to anthropogenic causes of physical changes to parts of the Antarctic is complex (10, 21, 24, 25). In consequence, we touch briefly on what the current physical evidence suggests, noting the fast pace of developments in the field. By contrast with change to date, models clearly forecast profound physical change to the region over the coming decades (17, 27). Thus, we review briefly what models indicate might take place across the region, recognizing the variation among current models for the Antarctic. We then consider explicitly the prognoses for marine and terrestrial environments. Because of the significance of Antarctic ice sheets for global sea-level rise (15, 27), we touch briefly on how understanding their behavior is of global environmental and societal significance. Finally, we comment on current Antarctic regulatory regimes and their adequacy to deal with the environmental change facing the region. In particular, we contend that collaboration and colearning among Antarctic and global regulatory and policy processes have mutual benefits and will strengthen rather than incapacitate existing legal arrangements.

2. CURRENT ENVIRONMENTAL CLASSIFICATIONS

Mention of Antarctic environments usually conjures images either of a vast ice field or a tempestuous ocean (**Figure 2**). Both are accurate, but only in part. Recent estimates place the proportion of ice-free area on the continent at only 0.18% (21,475 km²), or less than the area of New Jersey in a continent much larger than the size of the continuous United States (9). Yet these exposed areas vary from being covered in grasses and mosses, to having little sign of life at all (**Figure 2**), though home to unusual biodiversity (7). Seascapes are more difficult to characterize. While the stormy epithet is accurate given the unimpeded scope of the Southern Ocean, both pelagic and benthic systems are diverse. They include unusual ecosystems such as those disturbed by ice scour and deep-sea hydrothermal vents (7, 8). Knowledge and classification of the biodiversity of Antarctic species, systems, and environments has developed rapidly over the past decade.

2.1. The Southern Ocean

In the Southern Ocean pelagic systems, 20 bioregions have been identified based on an integrated clustering procedure using depth, summer climatological sea surface temperature, and proportion of time covered by sea ice (28) (**Figure 3**). These bioregions are based on the physical environment only, with biogeographic patterns of pelagic taxa reflecting them partially, but driven by other factors too (28). Fifteen candidate important marine mammal areas have also been proposed for the Southern Ocean and sub-Antarctic. These are based on species or population vulnerability; distribution and abundance; key areas for species' lifecycles such as migration routes and reproduction and feeding areas; and areas that either support a diversity of species or are distinctive for genetic, ecological, or behavioral reasons (29). For benthic systems, 23 ecoregions (**Figure 3**), further classified into 562 environmental types, have been identified. These ecoregions are founded on a wide variety of characteristics, including both physical environmental variables and biological variables (30). They include depth, geomorphology, seabed temperature, species endemism and distribution, productivity, currents, distance, barriers, and ecoclines. Vulnerable marine ecosystems (VMEs), those vulnerable to the impacts of fishing activities and including seamount communities, deep-sea hydrothermal vents, cold water corals, and sponge fields, exist throughout the Antarctic (28, 30). However, the locations, distribution, abundance, and community structure of VMEs remain poorly known because of sampling and data deficiency. Overall, complex Southern Ocean biogeographic patterns reflect the region's rich biodiversity, which may reach levels similar to that of some tropical locations (8).

2.2. The Antarctic Continent

Despite their small surface area, the ice-free environments of the continent are diverse. They have been classified into 16 ecoregions [called Antarctic Conservation Biogeographic Regions (ACBRs)] based on a suite of abiotic environmental variables, including aspects of climate, geology, and ice cover as originally provided in a comprehensive environmental domains analysis for the continent, biodiversity information sourced from point data records of a variety of taxa, and expert opinion on biogeographic variation across the region (31) (**Figure 3**). The ACBRs vary widely in their environments and diversity, from relatively warm coastal environments with grasses and moss turves, to depauperate, cold inland nunataks, representing the peaks of mountains buried beneath the Antarctic ice sheet. Environmental classifications using smaller suites of species have also been undertaken. Most notable of these is the Important Bird Areas (IBAs) classification of typically pelagic, but land-breeding, Antarctic birds, based on population estimates, species present, and

Pelagic: the water column of the open ocean, usually further characterized and classified by depth, temperature, available light, and salinity

Antarctic Conservation Biogeographic Regions (ACBRs): Antarctica's 16 ecoregions, defined on the basis of climate and biodiversity



Figure 2

Antarctic and Southern Ocean environments illustrating the region's diversity (7, 8, 28). (a) Wandering Albatrosses (*Diomedea exulans*) in the Southern Ocean. (b) Killer Whales (*Orcinus orca*), sea ice, and icebergs. (c) Mummified seal in the McMurdo Dry Valleys. (d) Benthic diversity represented by sea stars in anchor ice. (e) Sub-Antarctic South Georgia with a rapid gradient from coastal tussock to mountain glaciers, with King Penguins (*Aptenodytes patagonicus*) in the foreground. (f) Marion Island's Tafelberg area illustrating the tundra-like vegetation of the lower elevations on more northerly sub-Antarctic islands. Panels b, d, and e reproduced with permission of John B. Weller. Panels a, c, and f reproduced with permission of Steven L. Chown.

a suite of globally agreed criteria for identifying such areas (32). Across the Antarctic and sub-Antarctic, 220 IBAs have been identified (**Figure 3**).

Antarctica is also characterized by an exceptionally diverse suite of water bodies. These range from hypersaline lakes to freshwater bodies to flows with unusual chemistry, such as the sulfate-rich Blood Falls in the McMurdo Dry Valley system (33). The physicochemical characteristics and biology of Antarctic and sub-Antarctic lakes have been extensively explored (34), although recognizing that knowledge is variable given the size of the region and the variety of water bodies and biologies present. For example, lakes in the vicinity of Syowa station (East Antarctica) are characterized by unusual pillar-like colonies of aquatic mosses (35). Antarctic aquatic systems include the chemically and microbially unique subglacial lakes and waterways that are extensive but poorly explored (33). The significance of viruses in Antarctic environments is only now starting to be appreciated, although they may be critical to system function in these extreme environments (36).

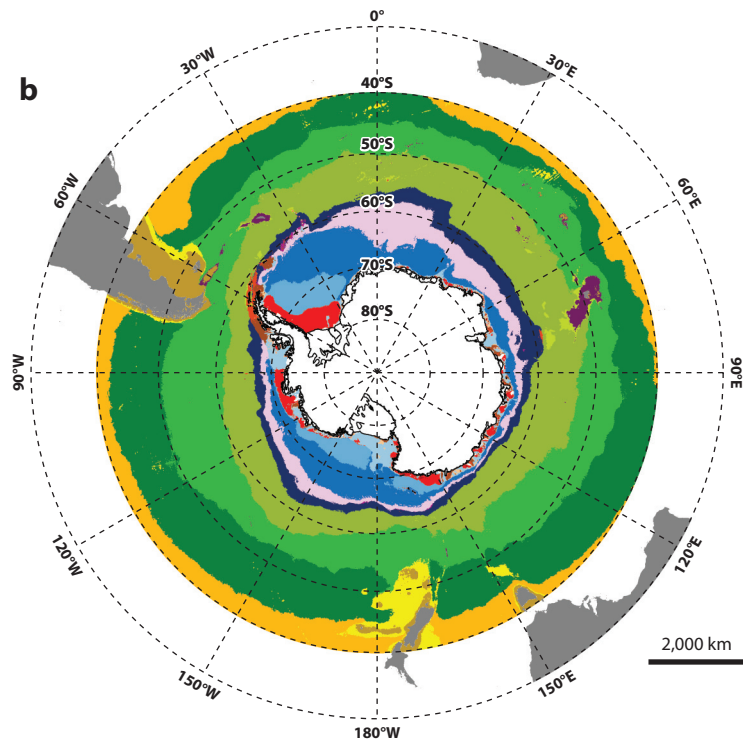
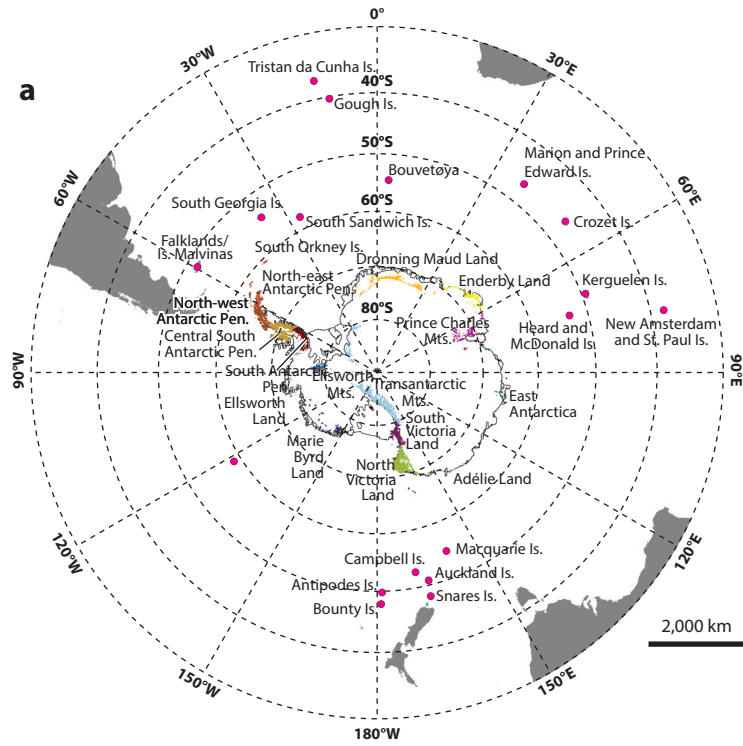
2.3. The Sub-Antarctic Islands

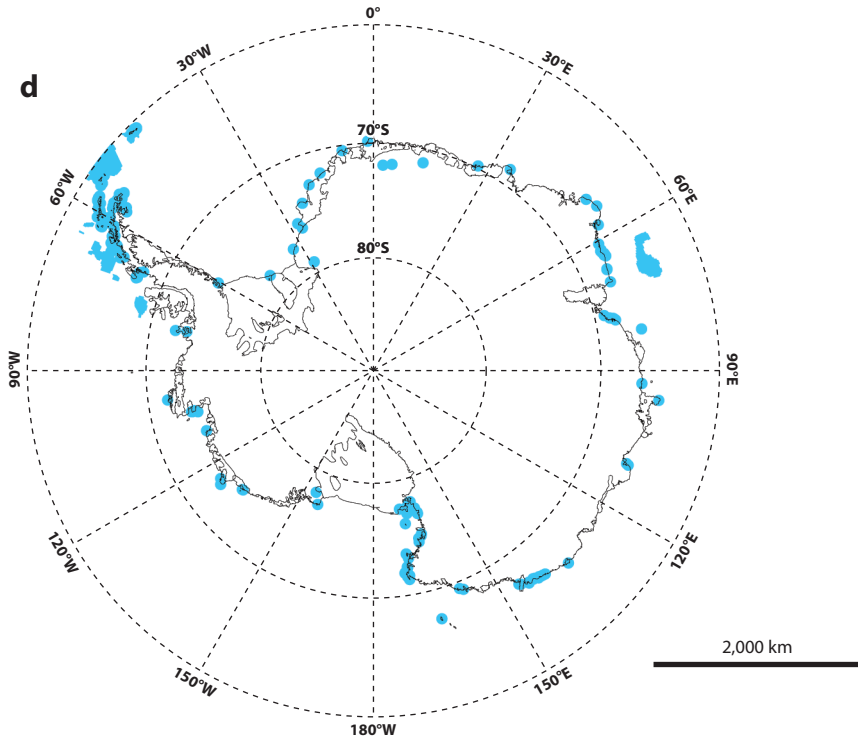
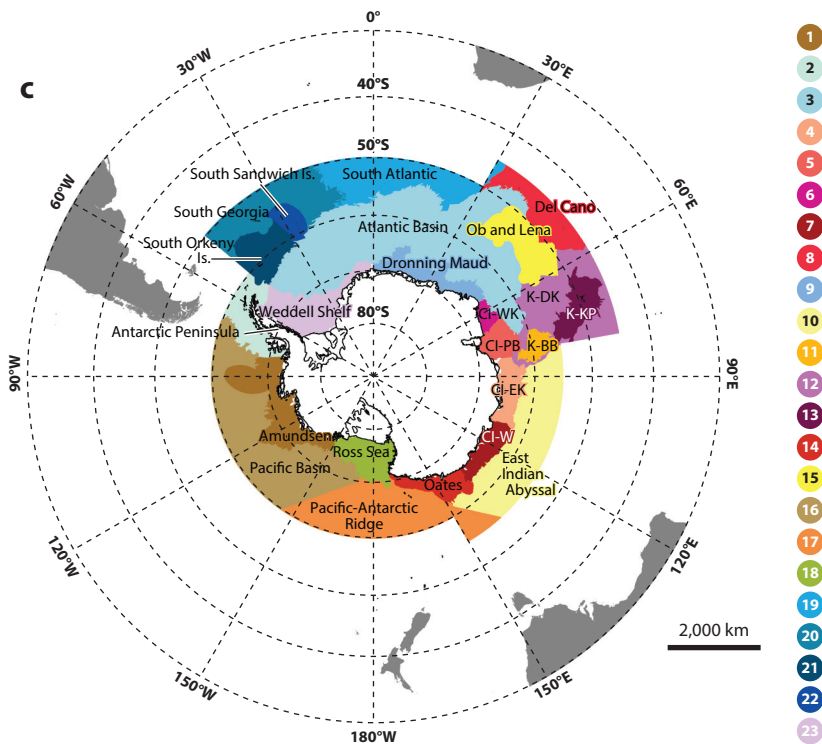
Further north, the sub-Antarctic islands, which stretch from South Georgia in the Atlantic to the Pacific sub-Antarctic islands such as Macquarie Island and Campbell Island and include archipelagos such as the Îles Crozet and Îles Kerguelen in the Indian Ocean, are diverse. The islands vary substantially in their geological origins and in the extent to which they were glaciated during the Last Glacial Maximum and previously (37). They also differ significantly in current climate, with warmer, lower islands having no presence of glaciers (e.g., Macquarie Island) and others retaining extensive, although rapidly melting, glaciers (e.g., South Georgia, Heard Island).

The sub-Antarctic islands house rich terrestrial biotas. These include endemic megaherbs, insects, and land birds (such as parrots) (38, 39). Their environments vary from lush tussock grasslands and mires on the coast, to spatially extensive fellfields dominated by cushion-forming plants, to harsh, high-altitude polar deserts (39, 40) (**Figure 2**). Early comparative classifications of sub-Antarctic environments exist (41), but modern approaches are lacking, with some notable exceptions (42). Such approaches could usefully be applied given rapid changes to systems in the region, which are resulting in the redistribution of species across elevational environmental gradients, rather than the wholesale movement of particular associations of species (43). Such changes are not unexpected given the strong relationships, across the islands of the sub-Antarctic, between species richness of indigenous insects and plants, and both mean annual temperature and island isolation (38). Nonetheless, and remarkably, the underlying spatial form of biodiversity variation and reasons for this variation on a given island or group of islands remains poorly appreciated for most of the sub-Antarctic, with only a handful of studies available (39, 44, 45).

2.4. Knowledge Shortfalls

Despite rapid growth in knowledge about Antarctic environments and their biodiversity, much remains unknown. Indeed, a first-order estimate of diversity for the continent's terrestrial and aquatic systems has never been made. New techniques, such as automated observing platforms (46), satellite remote sensing (47, 48), and citizen science (49), are rapidly helping to overcome survey barriers and have been especially effective for estimating the abundance and spatial location of birds and mammals. Nonetheless, some biodiversity knowledge shortfalls (50), such as in taxonomic expertise, are growing, rather than diminishing. In marine systems, knowledge progress is somewhat better (8), with new information emerging not only from local studies of the abundance and interactions of species, but also from the application of new techniques to extant biodiversity data. The former includes the considerable consumption of jellyfish by albatrosses (51); the latter





(Caption appears on following page)

Figure 3 (*Figure appears on preceding page*)

Biogeographic classifications of Antarctica and the Southern Ocean. (a) The general region illustrating the sub-Antarctic islands and the Antarctic Conservation Biogeographic Regions (31, 39). (b) The 20 pelagic bioregions of the Southern Ocean (28): ❶ moderately shallow areas (to ~1,000 m) with moderate ice cover and low sea surface temperature <2°C, ❷ areas with low ice cover and low sea surface temperatures (<2°C), ❸ shallow shelf areas with moderate ice cover, ❹ shallow areas with high ice cover, ❺ shelf areas with almost perennial ice cover, ❻–❼ moderate depths (~200–1,000 m) and ice cover (~50–75%), ❽–❶ sea ice zone, ❷ moderate depth (~1,000–2,500 m) and sea ice cover (~40%), ❸–❶ shallow island plateaus, ❸–❶ deep oceanic waters, ❸–❶ temperate waters, and ❸–❶ continental and island shelf areas with temperate to warm temperatures. (c) The 23 benthic ecoregions recognized for the Southern Ocean (30): ❶ Pacific Basin, ❷ Antarctic Peninsula, ❸ Atlantic Basin, ❹ Central Indian-East Kerguelen Subregion (CI-EK), ❺ Central Indian-Prydz Bay Subregion (CI-PB), ❻ Central Indian-West Kerguelen Subregion (CI-WK), ❼ Central Indian-Wilkes Subregion (CI-W), ❽ Del Cano, ❾ Dronning Maud Land, ❶ East Indian Abyssal Plain, ❶ Kerguelen-Banzare Bank Subregion (K-BB), ❶ Kerguelen-Deep Kerguelen Subregion (K-DK), ❶ Kerguelen-Kerguelen Plateau Subregion (K-KP), ❶ Oates, ❶ Ob and Lena, ❶ Pacific Basin, ❶ Pacific-Antarctic Ridge, ❶ Ross Sea, ❶ South Atlantic, ❶ South Georgia, ❶ South Orkney Island, ❶ South Sandwich Islands, ❶ Weddell Shelf; (d) The Important Bird Areas of Antarctica (32). All images produced from spatial data made available by the publications cited and redrawn by Rachel I. Leihy.

includes a recent global phylogenetic analysis of fish diversity demonstrating that, although richness is low in the Southern Ocean, the region has among the highest speciation rates globally and may be an important source for global fish diversity (52). As is the case elsewhere in the world, the rate of knowledge accumulation appears to be slower than the growth rate of pressures on the Antarctic system.

3. THE STATE OF ANTARCTIC ENVIRONMENTS

Antarctic environments are often considered relatively free from human disturbance given their isolation and the technical challenges of operating there. Although this may once have been the case, it is no longer. Several recent assessments of the state of Antarctic environments and their biodiversity have been undertaken. The most recent, for example, demonstrates that Antarctic stations and associated infrastructure impact half of the large coastal ice-free areas of the continent (53). Indeed, most of the recent assessments highlight changing environmental states, identify growing and diversifying local human impacts, and document increasing pressures from the outcomes of human activity outside the region (11, 21, 54, 55).

3.1. Recent Comprehensive Assessment

The most comprehensive recent assessment has focused on the state of Antarctic biodiversity and its conservation from the perspective of the Convention on Biological Diversity's (CBD) Strategic Plan for Biodiversity 2011–2020 and its 20 Aichi Targets intended to improve the state of global biodiversity (9). Some of these Aichi Targets, such as Target 7 pertaining to agriculture, aquaculture, and forestry, are clearly not relevant to the Antarctic. Most others are applicable, however, and modifications thereof to suit the specific circumstances of the Antarctic are in keeping with the approach recommended by the CBD. Perhaps surprisingly for some, who view Antarctic conservation and the state of its environments as a global gold standard, the assessment indicates that the biodiversity prospects for Antarctica and the Southern Ocean are similar to those of the rest of the planet—that is, relatively poor without concerted additional action.

With respect to some of the Aichi Targets, such as Target 12 aiming to reduce extinction and improve the status of species in decline, the Antarctic region is doing especially well. No anthropogenic extinction has been recorded from the Southern Ocean and Antarctica, a situation very different from that elsewhere. Moreover, on some sub-Antarctic islands, multimillion-dollar

programs to remove threats to seabirds and ecosystems have been undertaken or are planned (56). These programs typically involve the removal of invasive alien species (i.e., nonindigenous species introduced from elsewhere by humans, such as rats, mice, rabbits, and cats). Indeed, in the case of Aichi Target 9, concerning the identification and control of priority invasive alien species and the pathways through which they are introduced, the Antarctic region is also in a much better position than the rest of the globe. Although concerns remain about transfer of species among the ACBRs (55), overall, few species have been introduced and pathways of introduction are well understood (57). The substantial impacts that can be caused by invasive species—as demonstrated repeatedly elsewhere on the planet, including on the sub-Antarctic islands, such as predation of indigenous species and changes to nutrient cycles—have prompted much action. Considerable attention is being given to the prevention of biological invasions through the regulation and management of introduction pathways, by both national science operators who run the stations in and shipping to Antarctica, and the International Association of Antarctica Tour Operators, the industry organization to which the large majority of tour operators belongs (9).

Invasive alien species: species in a given area that have arrived due to intentional or unintentional human involvement, established and spread

Given the Antarctic's remote location, the region has been largely isolated from pollution. Thus, overall, pollution remains much less a threat to the region than elsewhere, with the situation largely improving for the Antarctic but declining globally (9). Local pollution, such as that from persistent organic pollutants, continues to be documented, along with plastic pollution from stations. Much is being done by the Council of Managers of National Antarctic Programs, responsible for operations in the region, to reduce local impacts. Nonetheless, global influences on the Antarctic continue, including from microplastics (58). Perhaps of most concern, the boundary of the Southern Ocean has been identified as the major risk area to seabirds from plastic pollution (59). Here, the numbers of seabird species likely to be impacted is highest, despite lower debris intensity. The impacts are also likely to increase markedly into the future.

For other targets, Antarctica and the Southern Ocean are trailing global developments. Terrestrial protected areas, the subject of Aichi Target 11, do not adequately cover the ice-free, biodiversity-rich ACBRs, which are threatened by pressures from rapidly rising human activity and from changing climates. Although declaration of the Ross Sea region Marine Protected Area (MPA) in 2016 is a major step toward a network of MPAs in the Southern Ocean, in other respects the state of the Southern Ocean system and efforts to conserve it are problematic. For example, although the CAMLR Commission (CCAMLR) has closed depleted fisheries, and has arguably been successful in many aspects of ensuring sustainable, legal, and ecosystem-based commercial fishing, no recovery plans are in place for depleted populations in any of the CCAMLR's management areas (9).

3.2. Status of Key Southern Ocean Species

What the state is of key, commercially targeted resources, such as Antarctic krill (*Euphausia superba*), is difficult to determine, with considerable variation in the outcomes of studies, but nonetheless with concerning signs. Although an early study suggested that Antarctic krill density was declining in the Southwest sector of the Atlantic Ocean (60), a later investigation found much interannual variability, but no signs of decline (61). A recent, comprehensive analysis has, however, brought further clarity. The distribution of Antarctic krill in this sector has contracted southward, with a strongly negative temporal trend north of 60°S, but a weaker one further south (62). Changes in krill length, reflecting changes in demography, further support evidence of changes to dynamics, which appear to be linked to changes in regional climate, although other factors likely also play a role. Given the significance of krill in the Southern Ocean trophic network, these indications of range shift and demographic change are worrying.

Substantial uncertainty appears to apply to the status of populations of Patagonian and Antarctic toothfish (*Dissostichus eleginoides* and *D. mawsoni*; sold as Chilean sea bass), the region's top fish predators. For example, the number, size, connectivity, and ecosystem dynamics of toothfish populations throughout the Southern Ocean, particularly for the more southern Antarctic toothfish, remain poorly known (63, 64). The status of fish populations caught as bycatch are even less known, including a variety of species of macrourids, skates, and sharks all incidentally caught in toothfish longline fisheries (65). While much progress has been made in the Southern Ocean to reduce seabird bycatch of threatened procellariiform seabirds (mostly albatrosses), several species have continued to decline (66). Many have very wide foraging ranges with distributions that extend outside the Southern Ocean, thus threats are also being posed by more northerly fisheries (67), though land-based predation by invasive alien species is also significant (56, 57).

Similar complexity is being encountered in determining the state of other predators, such as penguins. For example, in the case of the Adélie Penguin (*Pygoscelis adeliae*), population trends vary spatially and frequently reflect local dynamics, perhaps unsurprising in a species occupying >24,000 km of circum-Antarctic coastline (68). Chinstrap Penguin (*P. antarcticus*) populations appear to be declining throughout the Antarctic Peninsula (69–71). Gentoo (*P. papua*) and King (*Aptenodytes patagonicus*) Penguins are generally increasing across their range (69, 71), but declining at some specific colonies (e.g., 72). Changes in Emperor Penguin (*A. fosteri*) colonies are not well studied, with a few notable exceptions (73). Emperor Penguin colonies often show substantial interannual variability, although the world's second largest one at Halley Bay has shown almost total breeding failure for three consecutive years (74). Many colonies are predicted to decline substantially by 2100 (75). The drivers behind the dynamics of Southern Ocean penguin species are not well understood, but are likely a complex interaction of historical whaling (and the resulting prey release), environmental change (e.g., changes in sea ice), and current human impacts (e.g., fishing) (76, 77). Nonetheless, some relationships are well supported, such as that between Adélie Penguin abundance change and factors related to sea-ice extent.

The population status of marine mammals remains largely understudied and unknown, especially for the pack-ice seals [Ross (*Omatophoca rossii*), Crabeater (*Lobodon carcinophaga*), Weddell (*Leptonychotes weddellii*), and Leopard (*Hydrurga leptonyx*) (78, 79)]. Subantarctic and Antarctic fur seals (*Arctocephalus tropicalis* and *A. gazella*) and the Elephant Seal (*Mirounga lionina*) are overall generally abundant, having fully recovered from previous near extirpation on many sub-Antarctic islands in the nineteenth century. However, some specific populations of these sub-Antarctic seals are experiencing declines, although the causes are not clear (80, 81).

More than 2 million whales were removed from the Southern Hemisphere in twentieth-century commercial whaling operations (82). Some species, such as Humpback Whale (*Megaptera novaeangliae*) and Southern Right Whale (*Eubalaena australis*) are recovering in the Southern Ocean (83) with full recovery for Humpback Whale predicted by 2050 (84). Less clear is the status of populations of Fin Whale (*Balaenoptera physalus*) and Sei Whale (*B. borealis*) due to lack of data (83). Antarctic Minke Whale (*B. bonaerensis*), recognized as a separate species only in 2000, is listed as data deficient (83). Antarctic Blue Whale (*B. musculus intermedia*), with a population estimate at less than 1% of prewhaling abundance, is still listed as critically endangered (83). Yet these estimates are wrought with uncertainty and complexity.

Advances in remote sensing are providing more complete circumpolar estimates of Antarctic predators, including penguins (47), petrels (48), and seals (85). Similarly, acoustic approaches are offering new insights into presence, foraging behavior, and potential population monitoring of a variety of Antarctic whale species (86). New computational approaches, such as Bayesian methods, are also providing means to deal with demographic complexity to inform management decisions (68).

3.3. Recent Climate Change and the Antarctic Environment

The current impacts of global climate change (including change in temperature, precipitation, and ocean pH) on the environments and biodiversity of the Antarctic region, including the Southern Ocean, are only now becoming apparent. Such recorded impacts are to be distinguished from expected responses over the coming decades (as discussed in Section 4). Although signals of anthropogenic change are being detected in the region (10, 21, 24), understanding the underlying causes remains a rapidly developing area (22, 25, 87). For example, land surface temperature changes on the Antarctic Peninsula, although substantial, remain within natural late Holocene variability, although toward the upper end (88). The upward trend found since the 1950s ceased in the late 1990s, reflecting the very high natural variability of the region (25). Consideration of the rapidly developing area of current climate change, extent, and attribution in the Antarctic is certainly beyond the scope of this review, recognizing also the size of the continent and differences between East and West Antarctica.

Acknowledging these complexities, changing biological responses to the physical environment have certainly been detected. For example, on the ice-free land areas of the Antarctic Peninsula, the only two indigenous vascular plant species known from the continent [the grass *Deschampsia antarctica* and the forb *Colobanthus quitensis* (Caryophyllaceae)] have substantially expanded both their ranges and their cover at occupied sites in response to increases in temperature and to nutrient input from seals, which themselves are increasing (89). No changes in elevational position of these species has been found. In the sub-Antarctic, however, anthropogenic climate change-related warming has led to increases in the mean elevational position of vascular plant species of on average 3.4 ± 0.8 m year⁻¹ (43). The clubmoss *Lycopodium magellanicum* showed the greatest upslope range expansion of 388 m between 1966 and 2006, followed by the forb *Colobanthus kerguelensis* (275 m), the fern *Grammitis kerguelensis* (257 m), the brassicaceous megaherb *Pringlea antiscorbutica* (234 m), the dominant grass *Agrostis magellanica* (158 m), and the dominant fern *Blechnum penna-marina* (146 m). A few species also showed downslope range contractions, notably the ferns *Hymenophyllum peltatum* (-146 m) and *Elaphoglossum randii* (-110 m) and the clubmoss *L. saururus* (-126 m).

On the continent, changes in water availability are also playing a role in altering terrestrial environments and their communities. In the Windmill Islands of East Antarctica, temporal turnover of moss species (those with greater desiccation tolerance replacing species with less tolerance) has been linked to regional drying, associated with increases in greenhouse gases and reductions in stratospheric ozone, in turn resulting in a positive Southern Annular Mode (SAM) (90). The SAM describes the north-south position of the Southern Hemisphere's westerly wind belt. When the SAM is positive, westerly winds intensify and contract toward Antarctica, whereas a negative SAM reflects an equatorward expansion of the westerly wind belt.

In the McMurdo Dry Valleys, a period of cooling from 1987 to 2000 meant reduced melt and decreases in lake levels, lake primary productivity and soil nematode populations. A flood event during 2001–2002 changed the system dramatically in the years that followed, with asynchronous responses among different components of the living environment (91). The conclusion reached from this work is that climate change now and into the future will lead to significant effects on Antarctic systems, with abrupt short-term perturbations (or extreme events) playing an important role.

In the Peninsula region, substantial change in marine systems has also been documented (92, 93). Here, variation between the northern West Antarctic Peninsula (WAP) (e.g., in upper mixed layer depth—key for primary productivity—showing no trend) and southern WAP (upper mixed layer depth has declined by a factor of two since the 1990s) is important, along with interannual

variability in sea-ice extent and the timing of its melt. The changes in this well-studied region reveal complex spatially structured dynamics, which are only now starting to be fully comprehended (94, 95). What these studies have made clear is the importance of long-term data for understanding changes in dynamics and what their implications might be for other species in the Southern Ocean food web.

3.4. Ozone Depletion, Ozone Hole Recovery, and their Biological Implications

The discovery of the ozone hole (96), and swift realization of the implications for life on Earth, yielded an unprecedentedly rapid, globally endorsed response to phase out the anthropogenic chlorofluorocarbons (CFCs) responsible for ozone depletion. The discovery also resulted in much research to understand the direct and indirect effects of enhanced ultraviolet radiation on biological systems, especially in the Antarctic where the largest ozone depletion was initially recorded (97).

Over the past ~35 years since the discovery of the ozone hole, considerable understanding of the direct effects of enhanced ultraviolet radiation on marine and terrestrial systems has developed (98–101). For Antarctic marine systems, a variety of negative direct effects has been found, acknowledging considerable variation among species (100, 102). The ultimate effects on ecosystems, such as system modification through domination by microbial heterotrophs rather than larger phytoplankton (100), and implications for primary productivity and trophic networks, are not fully understood. They are thought to be of moderate importance compared with other change factors such as ocean warming and acidification (103).

In terrestrial plants, exposure to ecologically relevant levels of UV radiation is generally not damaging, and it is now also appreciated that UV-B radiation has regulatory roles in development and growth, which can be exploited to provide benefits under enhanced ultraviolet exposure (99, 101). By contrast, ultraviolet exposure can increase decomposition rates and significantly affect nutrient cycling. Enhanced direct exposure in Antarctic bryophytes does result in the synthesis of UV-B absorbing compounds, biomass reduction, and an increase in DNA damage (98), although for plants generally it has been shown that early laboratory studies often overestimated negative impacts owing to experimental design (101). Perhaps of far greater significance in the case of Antarctic bryophytes is demonstration of interactions between the effects of ozone depletion and the strength of the westerly winds (104, 105).

Owing to the stratospheric heating effects of ozone, and their decline since the development of the ozone hole, the Southern Hemisphere jet stream has shifted southward, especially during the Antarctic summer. This has been consistent with a more positive SAM, including an increase in the strength of the westerlies around the continent (105). Partly in consequence, East Antarctica has cooled and dried, whereas the Peninsula has warmed. That change is resulting in substantial effects on bryophyte communities (88, 90). These kinds of effects are being found not only in the Antarctic but also in other parts of the Southern Hemisphere (101, 105).

An increase in the strength of the westerly winds has also had effects on animals. Perhaps the most notable example is an increase in the body mass of adult Wandering Albatross by >1 kg (~9.5 to 10.5 kg in males and 7.5 to 8.5 kg in females) and an increase in breeding success (106). Adult birds now forage further south, travel faster, and spend less time foraging, given the higher wind speeds that relieve wind-associated foraging costs in this species. Similar effects are expected for related species given the strong influence of wind on the diversity of this taxonomic group (the Procellariiformes) (107).

What the future holds for the region in relation to the ozone hole and its recovery is not well understood, given complex interactions between climate change as a consequence of anthropogenic greenhouse gas forcing and the efforts to halt ozone depletion. The evidence for ozone

hole healing is starting to develop (108), with indications already that such change might have broad effects on Antarctic environments, such as changes to sea ice (109). Nonetheless, some complexity remains, with indications that for the nonpolar regions (between 60°S and 60°N) lower stratospheric ozone continues to decline, offsetting upper stratospheric ozone recovery (110). Moreover, despite the universal ratification of the Montreal Protocol and its instruments, recent increases in CFC-11 (trichlorofluoromethane) have also been detected (111).

3.5. Common Environmental Change Drivers and the Current State

Overexploitation, habitat alteration, biological invasions and disease, pollution, system modification, and climate change are the most significant global anthropogenic drivers of environmental change (112). In the broader Antarctic, those anthropogenic drivers with the predominant effects are, for the ocean, past, and current overexploitation (of whales, seals, fish, krill, and penguins), pollution, and climate change via responses to changing temperature, salinity, and the ice environment (8, 54, 103).

Currently, an industrial fishery for Antarctic krill operates throughout the Antarctic Peninsula region. The fishery has grown [to 300,000 tonnes (63)], and grown more concentrated in recent years, with increasing encroachment upon penguin and whale foraging grounds (113–116). Fisheries for Patagonian and Antarctic toothfish, the top fish predators in the Southern Ocean, are scattered throughout the CAMLR Convention area and are contentious. Some of these have historically resulted in overfishing, due in part to rampant illegal fishing with some populations still not recovered (e.g., BAZZARE Bank). Although illegal fishing appears to have decreased in recent years, national delegations to CCAMLR have been pushing for increased quotas, and for permitting fishing within currently closed management areas (117)—all despite large uncertainties about discreteness, distributions, sizes, and productivity of their populations and ecosystem impacts (64). These impacts of commercial fishing remain largely unquantified and fiercely debated (e.g., 118, 119), yet several recent studies have proposed that the toothfish fishery may be causing significant changes in the natural history patterns of related and dependent species, including Weddell Seal and Adélie Penguin (77, 120). However, it continues to prove difficult, if not impossible, to fully discern and understand cumulative impacts of fishing and environmental change. For example, after analyzing data collected over a span of 13 years, it remains uncertain whether recent declines in killer whales in the Ross Sea are the result of overfishing of toothfish or of changes in sea-ice cover (121). Furthermore, despite the designation of the Southern Ocean as a Whale Sanctuary (under the International Whaling Commission), Japan continues to kill whales throughout the Antarctic, including within the recently designated Ross Sea region MPA (122).

On land, for the Antarctic continent, habitat alteration in the broadest sense is of most significance, including alteration of the extent to which the continent's areas can be considered wilderness largely free from human impact (11, 53, 123). Biological invasions are a growing threat to the Antarctic Peninsula and its associated islands (55, 57), and some evidence is emerging of anthropogenic, climate change–related impacts. In the sub-Antarctic, the impacts of past and limited current exploitation of marine species and climate change in the Southern Ocean, and on land biological invasions, climate change, and their interactions, are by far the most significant drivers of system change (54, 57). For example, on sub-Antarctic Marion Island, global climate change–related local increase in the number of precipitation-free days has advanced the breeding season for invasive house mice (124). In turn, this had led to a 430% annual peak density increase of mice (between 1970–1980 and 2008–2011), decimating indigenous invertebrate populations, with substantial knock-on effects for the local ecosystem, such as changes in nutrient cycling and alterations in body size of particular species (124–126).

Cryosphere: the frozen component of the Earth system, including Antarctic sea ice, ice shelves, and ice sheets

Across the region, growing and diversifying local human activity and the impacts of human endeavors globally are the major drivers of current change (11, 53, 55). Although evidence for the broad patterns of biological responses to the main environmental change drivers is robust, the extent of that evidence for some drivers remains relatively limited compared with other systems (such as alpine areas globally). In the case of anthropogenic climate change effects in particular, the absence of support for long-term studies is a particular constraint. Notable exceptions are marine research at Palmer Station and terrestrial research in the McMurdo Dry Valleys as part of the US Long Term Ecological Research Program and seabird and terrestrial ecosystem studies in the French Polar Program. The detailed mechanistic assessments required to understand and thus respond to the environmental impacts of climate change (124, 127) are difficult to develop without such long-term research.

4. ANTICIPATED CHANGE AND ITS GLOBAL SIGNIFICANCE

Prognoses for change over the next several decades until 2100 and beyond are developing rapidly, although many uncertainties about interactions between the atmosphere, oceans, and cryosphere remain (27, 87, 109, 128, 129). Nonetheless, large physical changes to the Antarctic cryosphere, oceans, and terrestrial environment are to be expected, with local and global consequences (15, 27, 130) (**Figure 4**). What the extent of these changes will be depends on global decisions about anthropogenic greenhouse gas emissions reductions (17), which at best have a 13–32-year window remaining for implementation to avoid substantial climate change (131). Indeed, one recent estimate has suggested that by 2030, under the IPCC's Representative Concentration Pathway (RCP) 8.5 scenario, Earth's climate will already resemble that of the mid-Pliocene [i.e., 3 million years ago (Ma)] and stabilize under a scenario not seen since the Eocene (~40 Ma) (132). Under such conditions, by 2500 the West Antarctic Ice Sheet will disappear, as will parts of the East Antarctic Ice Sheet, with sea-level rise in excess of 1 m by 2100 and 13 m by 2500 (128; but see also 27), though some studies suggest that the timing may be earlier (87, 129). Such earlier timing implies faster rates of sea-level rise for the coming decades. Under RCP2.6 (aggressive emissions reductions) the prognosis is much better, although uncertainties remain considerable (15). Given that CO₂ emissions show signs of continued growth to 2040 (133), we assume that change in the Antarctic will follow RCP8.5, and draw the short synopsis of expectations largely from work outlining the effects of this scenario by 2070 (17).

4.1. The Southern Ocean

Warming, freshening, and acidification of the Southern Ocean (17, 21) are expected to continue. Sea-ice extent is also expected to decline, while ice shelf thinning and collapse will occur. Mass loss from the West and East Antarctic Ice Sheets will accelerate, contributing to rising sea levels (17).

A substantial and growing body of work indicates that most Southern Ocean benthic and pelagic ectotherm species, but especially those found south of the Polar Front, have little capacity to survive elevated temperatures (8). Fish have better capabilities than invertebrates, among which are species (e.g., the brachiopod *Liothyrella uva*) with the lowest known capabilities to survive experimental warming of any invertebrate ever investigated. Realistic (i.e., slow) rates of warming also suggest much greater sensitivity to warming than some of the faster rates used in laboratory studies (134). In situ experiments show similar sensitivities to warming of Antarctic species (135), supporting modeling assessments that forecast substantial rearrangement of communities in the Southern Ocean as warming progresses (136).

Prognoses for seabirds, seals, and whales suggest substantial impacts. In the case of seabirds, these involve rearrangement of ranges, often with contractions (137, 138), and extinctions

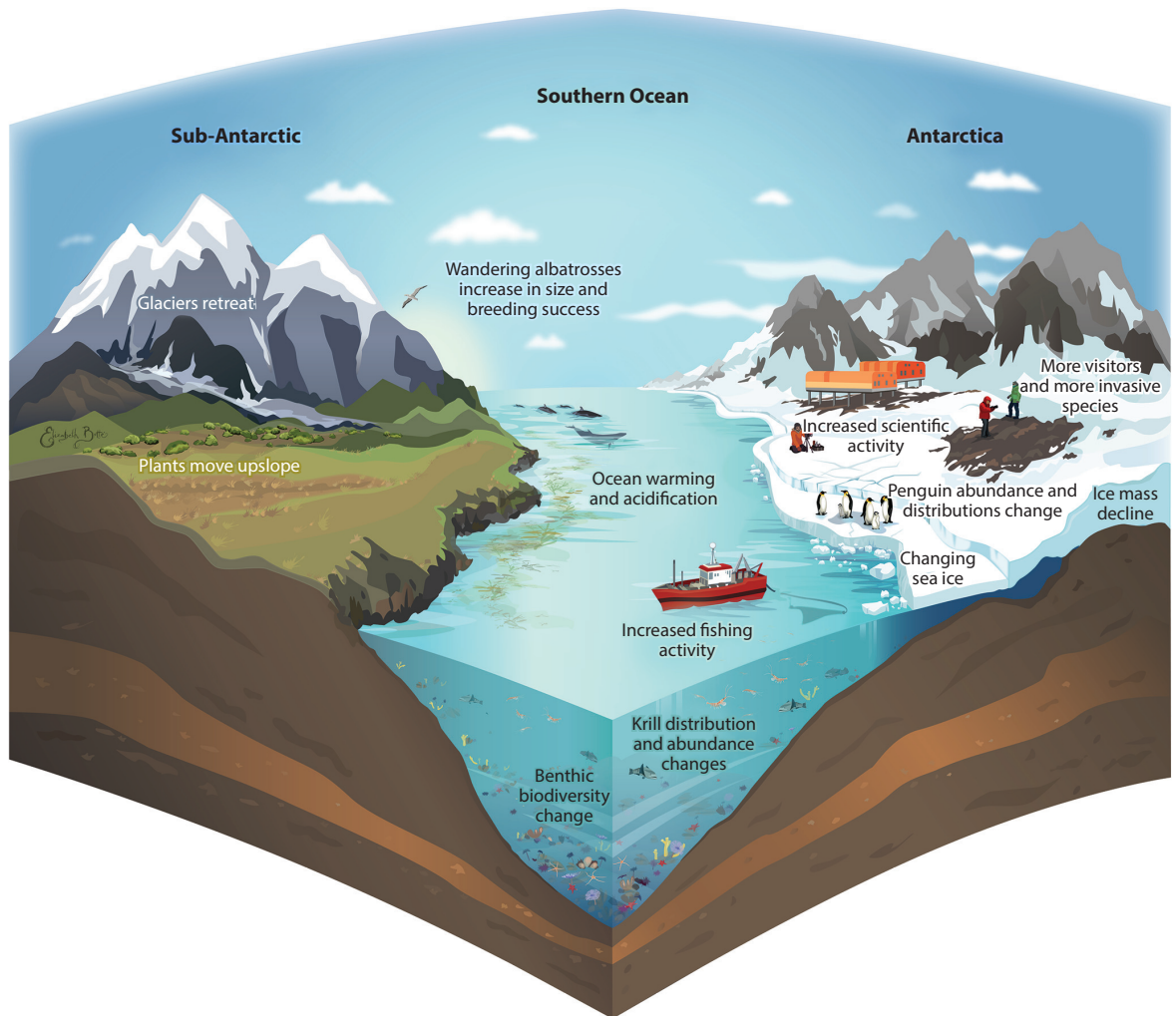


Figure 4

Schematic of the changes facing the sub-Antarctic (*left*), Southern Ocean (*center*) and Antarctic (*right*) environments. The changes indicated do not include broader regional-global interactions such as those to do with changing winds, temperatures and precipitation. They capture processes such as range shifts, increasing likelihood of biological invasions, further pressure from fishing, and expected alterations in the abundance of various species, such as expected declines in the numbers of Emperor Penguin. Image by Elizabeth Botte commissioned by the authors.

suggested for species such as the Emperor Penguin, depending on the outcomes of dispersal dynamics (75). Reductions in sea ice, and hence habitat that seals and whales depend on, are predicted to cause declines in multiple mammal species (e.g., 78). These impacts are expected also to have interactions with changes to and growth in the fishing industry (138, 139), especially since fishing in the Southern Ocean appears profitable even after subsidies are taken into account (140). Indeed, as global wild fisheries continue to decline, the Antarctic remains one of the few regions with relatively low fishing effort (141), and pressure on Antarctic fisheries is already increasing (12).

Ocean acidification has the potential to cause large changes to Southern Ocean ecosystems. Much of what is known about the effects of acidification comes from studies outside the region and a more limited number of Antarctic investigations. Although short-term investigations indicate effects on the benthos, longer-term studies all indicate either minimal effects or effects that organisms are able to deal with (8). Indeed, it appears that future changes to temperature, sea-ice extent, iceberg size and number, and nutrient availability will initially overshadow acidification effects. For pelagic species, substantial effects of acidification have been demonstrated experimentally at high CO₂ partial pressures such as those likely to be realized by 2100, but these depend on life stage (142, 143). For pteropods (pelagic molluscs also known as sea butterflies) (144), dissolution of their shells has been attributed to current acidification, yet the extent to which they are able to deal with such effects appears to be greater than originally anticipated (145). Nonetheless, juvenile life stages may well be at greatest risk (146). Overall, the likely effects of acidification on Southern Ocean species and ecosystems is still uncertain, although some species may have better capacities to respond than originally anticipated.

Several suggestions have been made that Southern Ocean ecosystems will become more susceptible to marine biological invasions, with potentially devastating consequences (147). Although the extent to which this will be the case for crabs remains a matter of discussion (147, 148), modeling work on other groups such as sea stars (149), along with clear demonstrations of the efficacy of shipping for such transfers (150), suggests that concerns about future invasions of a range of species are warranted. A particular difficulty of managing such transfers, however, will be distinguishing them from natural colonization events, which are more common than has previously been thought (151).

4.2. The Antarctic Continent

Most of the change expected as a result of anthropogenic climate change will play out on the Antarctic Peninsula (130). The fastest rate of growth of human impacts is also expected here, given its popularity for science and for tourism (11, 55). Rising temperatures are expected to result in an increase in the ice-free area available for terrestrial life (130), along with increasing biological rates, which are likely to benefit most species (17). These benefits extend also to nonindigenous species, and forecasts are that a suite of species will be capable of establishing on the Peninsula (152, 153). Indeed, this process may well be underway with new species now turning up regularly in the region (154). Effective biosecurity, addressing entrainment areas (those where visitors and vehicles depart from), invasion pathways, species, and the most favorable sites of establishment could readily reduce risks (57), but such biosecurity requires rigorous implementation across all Antarctic activity if it is to be effective.

Elsewhere on the continent, the likely future effects of climate change have not been especially well explored, although the already realized effects of drying (90) and extreme events (91) suggest expectations for the future. Somewhat curiously, species distribution models [either mechanistic or based on climate matching (155)] that have proven so useful elsewhere for developing testable hypotheses about species responses to environmental change have not yet been deployed in the Antarctic to any great extent. Nonetheless, lessons from elsewhere suggest that the faster climates change on the continent, the greater the impacts will be.

Increasing human interest in the continent will likely also increase local human impacts through habitat change (e.g., for station building or tourist camps), pollution, and the diminishing wilderness of the continent (53, 123). Just how these impacts will play out is difficult to foresee, although they may well compromise the ability of science to fully understand the history

and future of life on the continent, especially if traffic among the ACBRs increases faster than a focus on biosecurity protocols, thus preventing human transfer of indigenous species from being distinguished from natural range change (17).

4.3. The Sub-Antarctic Islands

These islands encompass a wide range of geological and climatological settings, located as they are around the Antarctic between approximately 40°S and 56°S (37). Some of the islands are unoccupied, whereas others have permanent research stations. In consequence, knowledge of the changes to these islands varies considerably. Many of them are showing signs of substantial warming, with glacial retreat on islands such as South Georgia in the Atlantic and Heard Island in the Indian Ocean. On others, such as Marion and Kerguelen Islands in the Indian Ocean, the warming has been accompanied by substantial declines (as much as 50%) in total annual precipitation (124, 156) or substantial changes in water availability (40).

These changing abiotic environmental circumstances related to global climate change, although likely not via southward frontal shifts (21), have had three major classes of impact on the biotas of the islands. First, indigenous species have moved upward in elevation (43) or have shown some form of threshold-level effect with declines in populations (40). Second, the changes seem to be benefitting invasive alien species over their indigenous counterparts (57, 156). Third, the impacts of invasive alien species on indigenous species and ecosystems are being exacerbated by climate change (56, 124, 156). Although these impacts are not being measured on all of the sub-Antarctic islands, and abiotic changes are not taking place in the same ways across them, the expectation is that future change will play out in similar ways across the islands. Such change will depend on the invasive species present and the climatic circumstances of the island's location (157, 158).

4.4. Global Implications of Sea-Level Change

Changes to the Antarctic and Southern Ocean environments are of perhaps the most profound concern globally because of the role of the Southern Ocean in global ocean uptake of carbon (10) and of the Antarctic ice sheets in global sea-level change (159). Both processes will affect the future of all species and environments on Earth. The signal from species on the move in response to anthropogenic greenhouse gas-driven environmental change is clear already (160). Less commonly investigated is the extent to which rising sea levels will alter not only species occurrences, but also the efficacy of conservation areas and the extent to which low-lying agricultural land will have to be abandoned and replaced by other areas, much of which are marginal or are currently protected for biodiversity conservation (161, 162). Even with climate mitigation, sea-level rise and its associated hazards to humans will continue, although aggressive mitigation will have the most benefit. With no mitigation (and no human population growth after 2100), the expectation is that >5% of the global population will be exposed to sea-level rise (162). Loss of agricultural land, displaced human populations, and adaptation to changes by society will have growing negative effects on biodiversity (160), which is already under significant pressure from human activity (112, 163, 164).

5. EVOLVING REGULATORY REGIMES

The Antarctic Treaty System's environmental regime, or suite of regulatory agreements, includes the Antarctic Treaty itself (5), agreements that set restrictions on harvesting seals (the Convention on the Conservation of Antarctic Seals) and that seek to conserve Antarctic marine living resources (the CAMLR Convention), and the Protocol on Environmental Protection to the Antarctic Treaty (165). The Protocol prohibits mineral resource activities except for scientific research (Article 7),

Discernment

hysteresis: the difference in rates and their overall form between the acquisition of understanding of the value of scientific evidence and expertise, and the loss of that understanding

commits the Antarctic Treaty Parties to the comprehensive protection of the Antarctic environment, and designates Antarctica as a natural reserve, devoted to peace and science.

Given the focus on peace, science and environmental protection, the ATS is considered by many to be among the most successful international environmental regulatory regimes, particularly on the governance of international common pool resources (e.g., 18, 165). The efficacy of the regime has, however, come under increasing scrutiny in recent years for reasons that include (a) growing membership numbers, (b) changing and conflicting perceptions of the purpose of the agreements, (c) ineffectiveness (including budget commitment) in dealing with mounting environmental problems, (d) neglect of scientific evidence highly relevant to management, (e) slow decision making, (f) unwillingness to engage with other international agreements, (g) and the lack of new agreements within the ATS to manage environmental challenges (the last major agreement being the Protocol more than 25 years ago) (9, 12, 19, 117, 166–171).

By contrast, a persistent theme emerging from current assessments of Antarctic environments is that their future, and as a consequence their influence on global society, is entirely dependent on political decision making that must take place over the next 10 to 20 years (15, 131), and on effective engagement with other international agreements that concern global environmental concerns, perhaps best summarized as ensuring the success of the Sustainable Development Goals (9, 17, 172). Thus, current ineffectiveness in the ATS must urgently be overcome. Indeed, in very much the same way that other international agreements must become more rapidly effective to avoid future planetary conditions of a form unknown in the evolutionary history of humans and with negative consequences for both us and the Earth's other species and environments (132, 173).

These concurrent and similar requirements to improve the pace and effectiveness of decision making within both the ATS and other international agreements mean that substantial scope for colearning exists between them. Thus, rather than insisting that “[f]rom a legal-political aspect, even though the Antarctic Treaty promotes cooperation with the specialized agencies of the UN, it is clear that the regulatory framework for the Antarctic Treaty area is the Antarctic Treaty” (6), the Parties to the ATS agreements might instead seek to adopt a more collaborative approach and to reap the benefits of cooperation among environmental regimes, including careful assessments of the reasons for difficulties and the consideration of alternative strategies (13, 174). These benefits have been secured elsewhere (14). Moreover, the ATS not only has much to offer other agreements, given its successes (165), but also has much to gain from the considerable thinking, critique, and use of evidence invested in the development and refinement of other agreements (163, 175).

In this process, much advantage can be gained from research strategies that enable both practitioners within the ATS and academics to engage in a dialogue that maximizes the effectiveness of the agreements within the ATS. A substantial literature exists on how this may be done (e.g., 174, 176–178), and one that also deals with the specifics of the ATS (179). Providing an overview of this literature, even if brief, is beyond the scope of this current work. Nonetheless, in the context of modern politics, it is worth recognizing the likely difficulties to be encountered (178). These include those resulting from the urgency required of current decision making (17, 131), the ways in which evidence is being discounted (180), and growing neglect of the very norms that make engaged debate successful (181, 182). Although we have no ready solution to these difficulties, we think it useful to recognize the landscape over which evidence and policy making interact at present (**Figure 5**). Critically, the available analysis (180, 182) suggests that this landscape has an asymmetry at its foundation (we call it discernment hysteresis), which means that the current rapid path of decline in the appreciation of evidence and expertise cannot be matched by an equally rapid recovery thereof (**Figure 5**). Prevention is thus better than cure.

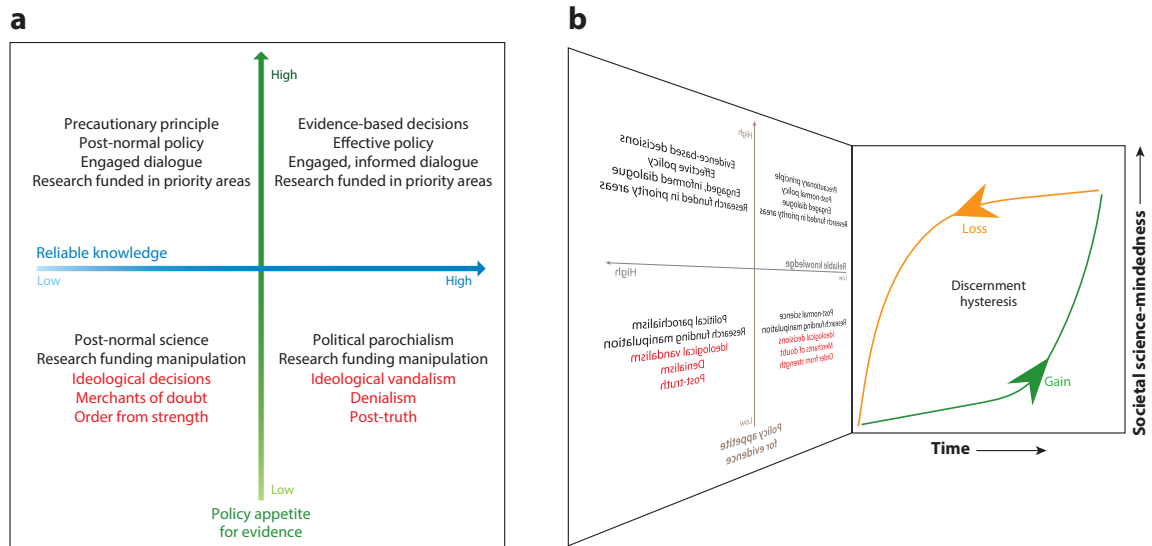


Figure 5

The modern science-policy landscape. (a) Reliable knowledge refers to well-supported scientific evidence (176), whereas policy appetite indicates the inclination to use that evidence (174, 180). Text within the boxes suggests what the outcomes [or desired outcomes of those with vested interests (*red text*)] might be when different portions of the landscape are occupied. (b) Underlying this relationship is the extent to which society might be considered science-minded or appreciative of the value of established knowledge (180). Discernment hysteresis refers to the difference in rates and their overall form between the acquisition of understanding of the value of scientific evidence and expertise (*green line*), and the loss of that understanding (*orange line*).

6. CONCLUSIONS

Antarctica and the Southern Ocean are integral, influential, and extraordinary components of the Earth System. Although some still consider the region's environments to be isolated, and others think that its environmental regime should remain similarly set apart from other international agreements, neither position is tenable. Maintaining them will have negative consequences not only for Antarctic environments and biodiversity, but also for the rest of the planet and for society that is so dependent on a system that resembles the one within which it evolved. Embracing the value to be had from whole-of-system dialogue and accepting the fundamental challenges of the Anthropocene (178, 183, 184), engaging with controversial suggestions for reform (170), and admitting that the limited time left for important decisions has changed the global environmental regulatory stage offer means to avert the worst elements of these consequences. The Antarctic Treaty System not only should but also has the means to show leadership in doing so. Moreover, its practitioners, and researchers conducting work in, on, and about the Antarctic and Southern Ocean are among the few who could readily implement the regional requirements to address ambitious calls, such as those of the Half-Earth Project (185), to secure a sustainable future for our planet.

SUMMARY POINTS

1. Antarctica and the Southern Ocean encompass a range of diverse and increasingly well-characterized environments.

2. The current state of these environments, despite their isolation, is, on average, no better than many of those elsewhere on the planet.
3. Information on key species, such as Antarctic krill, seabirds, and seals, and on key ecosystems, such as those of the West Antarctic Peninsula, remains inadequate to fully understand their dynamics. Additional long-term monitoring is essential for effective management.
4. Climate change and increasing local human impacts are key future environmental threats.
5. Much change is needed in the implementation of the Antarctic Treaty System's environmental regimes if it is to remain successful.
6. Co-learning among international environmental regimes, their practitioners, and the researchers contributing evidence to them is essential.

FUTURE ISSUES

1. Antarctica's wilderness is often assumed, but seldom formally examined, yet it appears to be in decline owing to rapidly rising use of the region.
2. Integrated management and monitoring of activities such as science, tourism, and fishing will require better development using modern tools because of growing human use and change across the region.
3. Accelerating climate change, if mitigation of greenhouse gas emissions is ineffective, will pose considerable challenges to environmental management across the region.
4. Environmental degradation elsewhere will increase pressure for use of Antarctica and the Southern Ocean's resources.
5. Discord among state parties to other international regimes will increasingly impinge on the Antarctic Treaty System.

DISCLOSURE STATEMENT

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