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Choosing the future of Antarctica

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We present two narratives on the future of Antarctica and the Southern Ocean, from the perspective of an observer looking back from 2070. In the first scenario, greenhouse gas emissions remained unchecked, the climate continued to warm, and the policy response was ineffective; this had large ramifications in Antarctica and the Southern Ocean, with worldwide impacts. In the second scenario, ambitious action was taken to limit greenhouse gas emissions and to establish policies that reduced anthropogenic pressure on the environment, slowing the rate of change in Antarctica. Choices made in the next decade will determine what trajectory is realized.

Antarctica, the most remote region on Earth, is intimately coupled to the rest of the climate system. Atmospheric and oceanic teleconnections communicate climate variations at low latitude to Antarctica and the Southern Ocean, influencing the polar atmosphere, ocean, ice sheet, sea ice and biosphere. Likewise, Antarctica and the surrounding Southern Ocean affect the rest of the globe. The amount and rate of sea level rise in the coming centuries depends on the response of the Antarctic Ice Sheet to warming of the atmosphere and ocean[1]. The Southern Ocean takes up more anthropogenic heat and carbon than the oceans at other latitudes, helping to slow the pace of atmospheric warming[2,3]. The circulation of the Southern Ocean also sustains global marine productivity by returning nutrient-rich deep water to the surface and exporting nutrients to lower latitudes[4]. Given the profound influence of Antarctica and the Southern Ocean on sea level, climate, and marine ecosystems, change in the region will have widespread consequences for the Earth and humanity. From a political perspective, Antarctica and the Southern Ocean are among the largest shared spaces on Earth, regulated by the unique governance regime of the Antarctic Treaty System[5], and embedded within and connected to broader global decision-making[6,7].

We present, from the perspective of an observer in 2070, two narratives on 50 years of change in Antarctica. Each narrative highlights the long-term consequences of decisions made today. The 50-year timescale reflects a period over which substantial differences between the two scenarios will develop and is within the lifetime of today's children. In the first, no meaningful action was taken to mitigate greenhouse gas emissions and global warming continued unabated. In the second, aggressive measures were taken to limit emissions, restrict global warming and increase resilience. We consider the 'high emissions/weak action' and 'low emissions/strong action' narratives to be likely upper and lower bounds on the future trajectory of Antarctica and the Southern Ocean. The trajectory that plays out over the next 50 years depends on choices made today. Cumulative emissions of CO_2 largely determine global mean surface warming[1], so continued growth in emissions soon commits us to further unavoidable climate impacts, even if some of those impacts take decades or centuries to emerge fully[8]. Greenhouse gas emissions must start decreasing in the coming decade to have a realistic prospect of following the low emissions narrative[9].

We provide an integrated assessment of the associated trajectories for Antarctica and the Southern Ocean, spanning physical, biological and social dimensions. These trajectories describe plausible alternative futures rather than forecasts. Where possible, such as for some physical and chemical variables, we use quantitative projections from climate and ice sheet models. Where this is not possible (as for many biological and social systems), we anticipate future change using a heuristic approach based on process understanding and the known response to past changes (noting that the heuristic approach risks neglecting important nonlinearities or surprises in natural systems[10,11]).

Of necessity, we offer the perspective of a single observer on 50 years of change in Antarctica, but we acknowledge that given the global diversity of human experience and values, other observers would interpret these changes through a different lens. We do not assume that individuals, institutions or society will act in a certain way; rather, we assess the possible consequences of particular courses of action (or inaction). Our goal is to initiate discussion and consideration of options for Antarctica's future, and to highlight how the future of Antarctica is tied to that of the rest of the planet and human society.

Antarctica in 2070 under high emissions

Looking back from 2070, it is clear that the past 50 years have unfolded much as anticipated by the high emissions (Representative Concentration Pathway (RCP) 8.5) scenario used by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report[1] published more than half a century ago. Growth in energy and food demand by the increased global population, supplied predominantly by intensive agriculture supported by fossil fuel use and associated with deforestation, drove an ongoing acceleration of greenhouse gas concentrations in the atmosphere and an increase in effective radiative forcing of about 5 W m^{-2} compared to the pre-industrial period[1]. Lack of action to mitigate greenhouse gas emissions was accompanied by lack of regulation of the human presence in Antarctica. Both distant and local human activities have left an indelible footprint on the Antarctic and Southern Ocean environment (Fig. 1).

Change in the physical environment

After 50 years of continued high greenhouse gas emissions, global mean surface air temperatures over land are now more than 3.5 °C higher than observed in the late nineteenth century[1] (Fig. 2), well above the symbolic 'guardrail' of 2 °C introduced in international climate agreements

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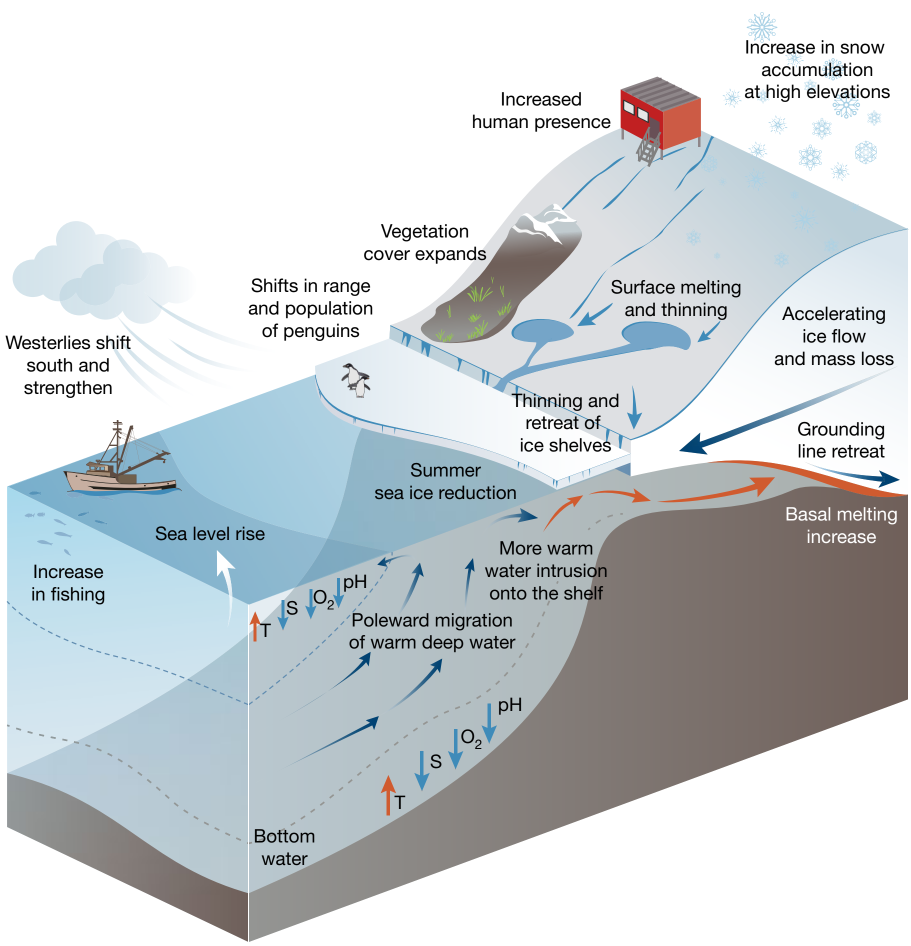

Fig. 1 | Schematic summary of impacts on Antarctica and the Southern Ocean in 2070, under a 'high emissions/low action' scenario. T, temperature; S, salinity; O_2, oxygen.

after the 2009 United Nations Framework Convention on Climate Change meeting in Copenhagen and reaffirmed by the nations of the world in a landmark agreement signed in Paris in December 2015.

Atmosphere. Air temperatures over Antarctica have warmed[1] by about 3 °C, well above the range of centennial variations of the current interglacial period[12]. In some low-lying regions of the continent, this increase in temperature has been sufficient to cause surface melt in summer. The increase in summer melt has had widespread impacts, contributing to the collapse of ice shelves, exposing new ice-free areas open to colonization by native and introduced plants, and altering the area suitable for nesting penguins and other birds.

During the 30 years between 2015 and 2045, recovery of the ozone hole tended to push the westerlies further north, while increases in greenhouse gas concentrations caused a shift to the south. As a result, spring and summer wind patterns changed little over this time period, in stark contrast to the strengthening and poleward shift of the westerlies seen in summer in previous decades[13]. During the winter season, when the ozone hole had little impact on the winds, the westerlies began to shift polewards and intensify after 2010 in response to increasing greenhouse gas concentrations in the atmosphere. By around 2045, greenhouse gases had won out over ozone recovery even in summer, forcing the westerlies to shift south and strengthen in all seasons[14].

Southern Ocean. Southern Ocean surface waters have warmed everywhere, reversing a slight cooling observed in the early twenty-first century at high latitudes, with an average increase[1] of 1.9 °C south of 50 °S. Surface waters have also freshened in response to increased precipitation and melt of sea ice and glacier ice[15–17]. Warming and freshening of surface waters have increased stratification and inhibited exchange with nutrient-rich deep waters. At 1,000 m depth, warming north of the Antarctic Circumpolar Current has exceeded ocean temperature rise observed at other latitudes, reflecting the efficient uptake of anthropogenic heat by the overturning circulation[3]. Antarctic Bottom Water, the volume of which had already contracted by 50% between 1970 and 2014[18], no longer exists. As a result of freshening, water sinking near Antarctica is no longer dense enough to qualify as Antarctic Bottom Water, although continued sinking of less-dense water maintains deep oxygen levels[19]. In response to ongoing changes in surface winds, the subtropical gyres have shifted polewards, effectively shrinking the Southern Ocean[20].

The combined impact of changes in winds, warming and freshening has slightly strengthened the upper limb of the Southern Ocean overturning circulation[21]. The Southern Ocean therefore continues to take up and export large amounts of heat and carbon dioxide, helping to slow the increase in global surface temperatures. Although uptake and export of heat by the overturning circulation initially delayed warming around Antarctica, surface sea and air temperatures in and around Antarctica are now warming at about the same rate as the global average, with larger warming in winter than in summer[1].

The chemistry of Southern Ocean waters continued to change in response to rising levels of atmospheric CO_2. The pH of surface waters south of 60° S decreased by 0.2 between 2017 and 2070, equivalent to a 50% decrease in the concentration of hydrogen ions since the pre-industrial period[1]. Southern Ocean surface waters south of 60° S became under-saturated with respect to aragonite in winter by 2040, and by 2070, >30% of the Southern Ocean surface waters south of 40° S had become under-saturated year-round[1,22]. Hence, waters have become corrosive to shells and other biological structures made of this form of calcium carbonate.

Ice shelves. Wind-driven changes in ocean currents resulted in an increase in ocean heat transport to the Amundsen Sea in the late twentieth and early twenty-first century[23]. Warmer ocean waters entering the cavities beneath floating ice shelves drove higher rates of basal melting, thinning of ice shelves, and a reduction in the back-stress on the grounded ice upstream. The reduced buttressing increased the flow of the ice streams feeding the ice shelves and led to the retreat of grounding lines, including runaway retreat of glaciers grounded on bedrock that deepened inland[24–27].

Although some ice shelves had supported extensive surface melting for decades[28], summer air temperatures are now high enough to increase surface melt on large areas of the floating ice shelves[29–31]. The increased volume of surface melt, coupled with an increase in the temperature of the surface firn due to persistent refreezing of meltwater and associated release of latent heat, has now led to the collapse of several ice shelves through hydrofracturing, a process first observed in Antarctica 70 years ago during the 2002 collapse of the Larsen B Ice Shelf[32]. The Larsen C Ice Shelf collapsed by hydrofracture in 2055[33] following several decades of thinning[34], and then several consecutive summers of excessive summer melting.

Most of the ice shelves in the Amundsen Sea have thinned at an accelerating rate owing to increased ocean temperatures that caused higher basal melt rates in the sub-ice cavities. The Venable, Crosson and Dotson ice shelves were all lost between 2040 and 2050, quickly followed by the Thwaites ice shelf in 2060, as anticipated in 2015 from trends measured by satellites between 1994 and 2012[34]. Nearly a quarter of the volume of Antarctica's ice shelves has been lost in the past 50 years[33]. Loss of sea ice also contributed to a decrease in buttressing of ice shelves[35]. Totten Glacier, an outlet for a large ice-sheet drainage basin in East Antarctica, has undergone thinning and retreat driven by warm water[36] accessing the grounding line. Changes in ocean currents have led to warmer ocean water entering ice shelf cavities (as predicted for the Filchner Ronne Ice Shelf[37]), causing ice-shelf thinning and the retreat of the grounding line across ice streams identified previously as being particularly vulnerable to such change in both the West[38] and East Antarctic[39] ice sheets.

The large number of icebergs produced by collapsing ice shelves all around Antarctica[40] is now carefully monitored to manage the risks to the greatly expanded fishing, tourism and commercial shipping fleets, and Antarctic operations by Antarctic Treaty nations.

Antarctic Ice Sheet and sea level. Fifty years ago, mass loss from the ice-sheet margins of West Antarctica was partially compensated by mass gain due to increased snowfall over East Antarctica[41,42], facilitated by more frequent intrusions of marine air as the westerlies shifted south[43]. However, the increase in ocean-driven melting could not be balanced by enhanced accumulation after 2020, leading to unequivocal loss of mass from the Antarctic Ice Sheet.

Observations of grounding line locations and ice stream velocities now confirm that the 'marine ice sheet instability' is well underway in West Antarctica, as first proposed in the 1970s[24] and supported by observations and modelling in 2014[25–27]. The loss of back-stress after the disappearance of ice shelves has led to increased flow of ice from the ice sheet to the ocean in both East and West Antarctica. Tall, unstable[44] ice cliffs have begun to appear in places around the marine-terminating ice sheet margin, where ice shelves and glacier tongues that were more than 750 m thick at their grounding zones have been lost. Further collapse of the West Antarctic Ice Sheet is now irreversible[26,27], mainly through the rapidly retreating, 120-km-wide Thwaites Glacier. Mass loss from the Antarctic Ice Sheet has contributed more than 27 cm of global sea level rise since 2000, as predicted decades earlier[33,45]. The rate of mass loss from Antarctica now exceeds 5 mm yr^{-1} (in sea level equivalent terms) and continues to accelerate. Antarctica now makes the largest contribution to the rise in global mean sea level, exceeding the contribution from thermal expansion, the retreat of mountain glaciers and melting of the Greenland Ice Sheet. The total rate of sea level rise is similar to rates during the last deglaciation (averaging 10–15 mm yr^{-1})[1]. A commitment to multiple metres of sea level rise in the longer term is now irreversible, consistent with early ice sheet model projections[33,45–47] and sea-level reconstructions of past warmer worlds[48], including the Pliocene (3 million years ago, when atmospheric CO_2 concentrations were only 400 parts per million by volume), and the most recent interglacial period (125 thousand years ago). High emissions over the past 50 years have already committed us to more than 10 m of sea level rise in the longer term (that is, >3,000 years); if emissions continue on the present trajectory to a total of 5,120 Pg of carbon, we are committed to more than 50 m of sea level rise in 10,000 years, 80% of which will be contributed by the Antarctic Ice Sheet[49]. Economic losses from the flooding of coastal cities already exceed US$1 trillion per year[50] as a result of the sea level rise of less than half a metre that occurred between 2000 and 2070[1,33].

Sea ice

Slow expansion of Antarctic sea ice in the decades preceding 2016 encouraged, in some, a sense of complacency about the stability of Antarctic sea ice. Record low sea ice extent in 2016 served as a cautionary reminder that this past stability could not be taken for granted. Indeed, by 2045 Antarctic sea ice was in clear and sustained retreat. Winter sea ice extent has reduced by 40%, more than twice the retreat projected for 2070 by climate models[1], consistent with the large sensitivity of winter sea ice extent to Antarctic warming inferred from palaeoclimate information[51]. Summer sea ice extent has decreased by almost half and most of the continental margin is now regularly free of sea ice in February, enabling access by ship to previously inaccessible regions, increasing fishing activity and tourism.

Change in biology and ecosystems

Fisheries. As access to the Antarctic coast has become easier, Antarctic marine systems are being exploited by fisheries from many nations, with stocks in decline around the continent. While initial conservation actions, including new marine protected areas, provided some respite for toothfish (*Dissostichus eleginoides* and *Dissostichus mawsoni*)[7], their long life cycles[52], illegal and unregulated practices[53], and increased interest in the species because of fishery collapses elsewhere[54] quickly depleted their populations. Interest in the Antarctic krill *Euphausia superba* fishery has seen profound growth because of new technologies for product processing, and resource depletion elsewhere[55]. Coupled with growing impacts of acidification on juvenile stages[56], replacement of Antarctic krill by salps in many areas owing to sea ice changes[57], and a rise in the number of baleen whales[58] the fishery has substantially reduced stocks, at least as far as assessments show, though these have been compromised by the absence of an extensive research-based assessment[59]. In the ensuing scramble to make use of resources, the evidence-based management approaches implemented successfully by the Commission on the Conservation of Antarctic Marine Living resources (CCAMLR) were overwhelmed[58,60].

Predators. The decline of exploited fish and krill stocks affected the populations of predators, including declines of several populations of penguin species[61,62], though with complexity in some areas arising from declines in competition with exploited toothfish[63]. Some Antarctic krill predators, such as black-browed and grey-headed albatrosses, have shifted their diet from Antarctic krill to mesopelagic fish and squid in response[64], joining a large suite of myctophid feeders[65], including fur seals[66]. Fishery-related mortality of seabirds and seals has increased because of growth in mesopelagic fish and squid fisheries[67–69]. Overall, Southern Ocean fisheries are declining in value and their regulation is increasingly contentious, reflecting problems encountered globally in fisheries during the twentieth and twenty-first centuries.

Community structure. Warming has also led to substantial changes in the composition of marine communities. In the decades following 2017, regional trends of increase in some species and declines in others continued[70,71]. More recently, unexpected regime shifts occurred,

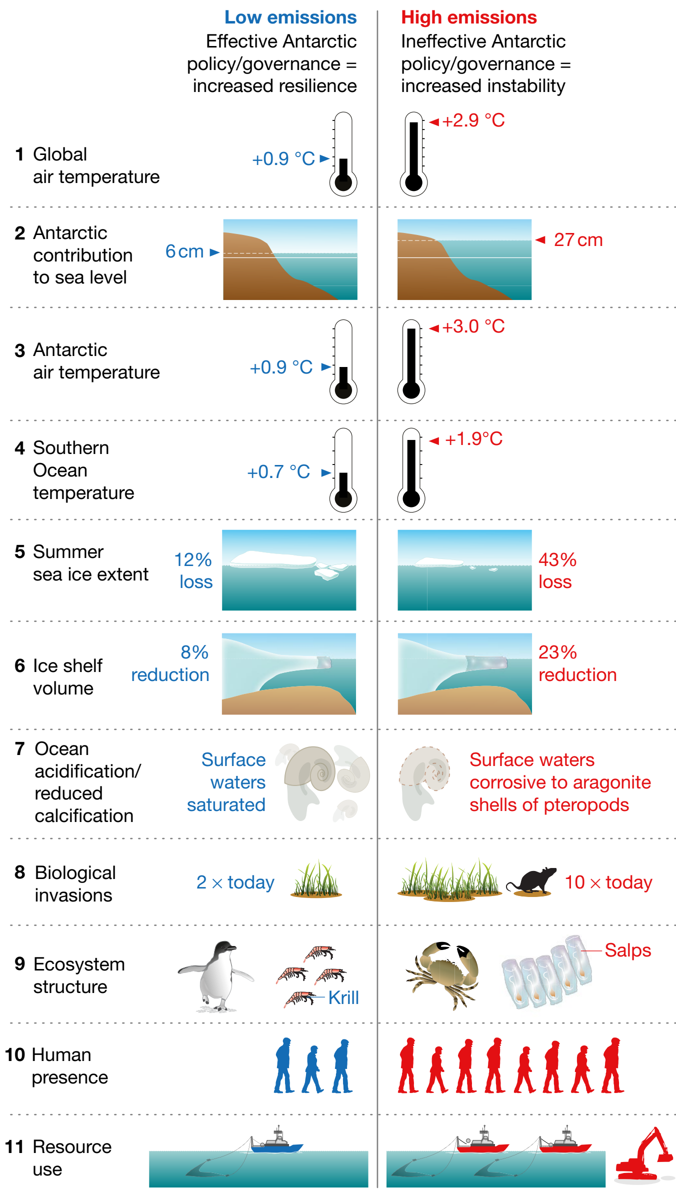

Fig. 2 | Antarctica and the Southern Ocean in 2070, under 'low emissions/high action' (left) and 'high emissions/low action' (right) scenarios. Differences are relative to a 1986–2005 reference period. Differences (1) to (6) are atmosphere–ocean–ice differences, taken from model projections following low- and high-emissions scenarios, respectively. Data for differences (1), (3), (4) and (5) are from ref. [1]. Data for differences (2) and (6) are from ref. [33]. Differences (7) to (11) are differences in ecosystem states and pressures, with ecosystem structure changing from the current situation to one characterized by new species and interactions. Data for difference (7) is from refs [1] and [22]; for (8) from refs [82] and [83]; for (9) from refs [57,78] and [113]; for (10) from ref. [6] and for (11) from ref. [5]. The low-emissions scenario sees greenhouse gas mitigation adhered to, limiting global warming by 2070 to 0.9 °C above the 1986–2005 mean. The high-emissions scenario, in which no mitigation takes place, leads to 2.9 °C of global warming by 2070 relative to the 1986–2005 mean, or 3.5 °C relative to 1850–1900. The systems assessed are: (1) global average air temperature; (2) Antarctic contribution to global sea level; (3) Antarctic surface air temperature; (4) Southern Ocean surface temperature; (5) summer (February) sea ice extent; (6) Antarctic ice shelf volume; (7) ocean acidification (illustrated by a pteropod, a marine snail, with an aragonite shell subject to dissolution under acidic conditions); (8) level of alien species invasion; (9) ecosystem structure (under the low-emissions scenario the present ecosystem continues; under the high-emissions scenario some species, such as crabs, become established and other species shifts occur, such as from krill to salps, as the climate warms and sea ice retreats); (10) human presence; and (11) resource use. Each of these systems will continue to change after 2070, with the magnitude of the change to which we are committed being generally much larger than the change realized by 2070.

caused by changing interactions among key species (such as between Antarctic krill, penguins, seals and baleen whales), catastrophic declines in some species, and in response to new phenomena such as transport of soil particles to the ocean by increased run-off of ice melt from the continent[72,73]. Changes in resource availability further hastened Adelie and Chinstrap penguin range contractions[61,74]. Gentoo penguins benefited initially, as early assessments predicted[75], but warming to the north and fishery impacts have led to trailing-edge range contractions and the start of population declines in this species too. Ocean acidification further complicated community responses. While some species adapted to acidification (for example, Antarctic brachiopods[76]), others were less able to do so (for example, pteropods[77]), resulting in reorganization of communities[70], compounded by changing ocean and atmospheric conditions[78].

Terrestrial biota and invasive species. On land, melt and retreat of glaciers exposed new ice-free areas, particularly on the Antarctic Peninsula, the northernmost part of the continent[79]. Antarctica's only two native vascular plant species showed initial increases in populations and expanded their ranges widely on the peninsula, with Antarctic hair grass predominating[80]. By 2050 this vegetation had come to include many other species too. Some are recognizable as widespread Antarctic invaders, especially the annual bluegrass or *Poa annua*, already recorded from the peninsula in the early part of the century[81]. Others are species that had long been predicted to colonize on the basis of analyses of seeds carried to Antarctica by scientific and tourist operations[82]. For other species, provenance remains obscure: they could have colonized naturally or through human agency. Debate of this contentious point at the Antarctic Treaty's Committee for Environmental Protection (CEP) precluded action, resulting in their further spread. By 2070, many research stations and several new tourist hotels have, in consequence, developed manicured gardens. Settlements of permanent residents, including small numbers of migrants, have now become established to service the research and tourism industries[6], and to control invasive pests[83]. Invasive species management lessons learned in the late twentieth century from the sub-Antarctic islands seem to have been forgotten.

Elsewhere on the continent, non-indigenous species have yet to establish populations[82,83]. Yet, owing to discord in the CEP precipitated by rapidly changing conditions on the Antarctic Peninsula and many biotic invasions, attention to transfer of species among the continent's conservation biogeographic regions diminished[84,85]. Molecular phylogeographic studies of several groups, and especially the microbiota, were discontinued after investigations revealed that exchange of species and populations among Antarctic biogeographic regions had become virtually continuous after 2050[86].

Biodiversity conservation. Both in the Southern Ocean and on continental Antarctica, action early in the twenty-first century led to improvements in biodiversity conservation, especially after attention was drawn to the potential for effective management to deliver rapid improvements in Antarctic biodiversity[7]. By 2050, however, many gains had started to suffer attrition. Establishment of protected areas slowed after an increase in the first two decades of the century, and protected area management failed to keep up with threats from growing human activity and resource exploitation[60,87]. Moreover, funding of environmental protection to underpin decision-making declined owing to larger environmental degradation problems elsewhere, including those associated with rapidly rising sea levels[88]. Although the CEP continues to meet on an annual basis, its recommendations are generally ignored at meetings of the parties to the Antarctic Treaty, unless they are relevant to the dominant issues of resource apportionment and management of expanding ice-free areas and widespread, land-based tourism. The special meeting held 50 years ago at the 40th Antarctic Treaty Consultative Meeting entitled 'Our Antarctica: Protection and Utilization' presaged this change.

Change in human engagement with Antarctica

Perceptions of the priorities for and efficacy of the Antarctic governance regime and its global role varied widely among governments, NGOs and diverse members of civil society, and changed over time in concert with a rapidly changing global order. While the reaction of different actors to the growing evidence of dramatic change in the Antarctic environment therefore diversified, overall the past 50 years have been characterized by gradual erosion of the systems that safeguarded the Antarctic environment in the late twentieth and early twenty-first century[5].

Harvesting. Between 2017 and 2070, the global human population grew by >40%, from 7 billion to 10 billion[89]. Owing to tremendous pressure for resources to support this larger and more prosperous population, including a now overweight or obese majority[90], Antarctica and the Southern Ocean are now even more widely explored or exploited. Most exploitation has occurred in the Southern Ocean, with a diversity of marine species harvested. At the CCAMLR, discussions now focus on resource apportionment among nations, rather than on an ecosystem-based approach to conservation[60,91]. On the continent, harvesting is less noticeable. Ongoing legal battles over bioprospecting[7] continue, however. Much of the pharmaceutical prospecting interest lies in discovering products that may manipulate human metabolism.

Mining. In 2049, several nations attempted to rescind Article 7 of the Protocol on Environmental Protection to the Antarctic Treaty, which prohibits mineral resource exploitation. A majority of nations agreed, but the motion failed to obtain agreement of three-quarters of the states that were Antarctic Treaty Consultative Parties at the time of the adoption of the Environmental Protocol, a requirement of Article 25. Thus, the Environmental Protocol remained unchanged. The early, clear division between the parties espousing a research for use approach and those more concerned with conservation[5] largely disappeared after 2048. Many nations started investigating resource potential and extraction technologies, thinly veiled under the guise of scientific exploration. Much of this 'research' activity now verges on extraction, with little political will to challenge these actions because of likely interference with geo-political complexities elsewhere on the planet[6]. Rapid technological developments in the Arctic have made resource exploration more affordable in polar regions, and global shortages of key minerals have driven investment in what has now come to be called 'scientific exploration'.

Tourism. Although a visit to Antarctica still remains the privilege of a limited few compared with the global population, tourist numbers now exceed one million each year, reflecting rapid growth after an initial hiatus in the early twenty-first century[92]. For many nations, tourism revenue now provides the main source of funding for national Antarctic programmes, alongside partnerships with the fishing, pharmaceutical, food and minerals industries. Management of the Antarctic environment is now similar to that of national parks elsewhere, where managers strike an uneasy balance between revenue generation, tourist numbers and biodiversity protection. Most of the global population now lives in cities and is less connected with the importance and meaning of the natural world (an extinction of experience[93]), resulting in loss of commitment to environmental concerns, including Antarctica. In consequence, programmes focused on a distant continent rather than on immediate surroundings attract little media attention, apart from the wide concern about Antarctica's impact on global sea level rise. (A rearguard action to delay sea level rise by pumping seawater onto the Antarctic continent to be stored as ice, with power supplied by 850,000 1.5-MW wind turbines, fell well short of the scale needed to make much difference to sea level rise[94]). While the Antarctic Treaty System's various agreements remain in place, they have weakened, leaving them vulnerable to other actors on a stage marked by regional rivalry rather than international cooperation.

Antarctica in 2070 under low emissions

Although the prospects for effective global action to mitigate emissions looked grim in 2015, the subsequent ratification of the United Nations Paris climate agreement by 196 countries, including the USA after some delay, heralded a new era of international cooperation to reduce greenhouse gas emissions. The faster-than-anticipated decrease in renewable energy and battery costs triggered a rapid transition out of coal. An increase in the magnitude and frequency of extreme climate events affecting major populations and economies highlighted widespread vulnerability and convinced decision-makers to increase their ambition to reduce greenhouse gas emissions, with the strong involvement of cities, regions and business. As a result of these policies, amplifying carbon feedbacks were not triggered, and we are now on track to keep warming well below the 2 °C target. New financial pathways helped create a functional and equitable carbon market, which incentivized business to transition rapidly to a low-carbon economy. Business leaders and fund managers began to appreciate the financial opportunities and other co-benefits of the transition associated with de-carbonization, and new technologies allowed for safe and efficient sequestration and ultimately removal of greenhouse gases from the atmosphere. As a result, radiative forcing has more or less followed the so-called RCP2.6 scenario considered by the IPCC Fifth Assessment Report, with radiative forcing reaching a peak in about 2040 and with net fossil fuel emissions now negative[1]. Widespread recognition of the dangers of unrestricted use of fossil fuels inspired changes in consumption patterns in the developed world, including shifts to more sustainable plant-based diets and changes in agriculture and land-use practices. The availability of low-cost renewable energy enabled developing countries to provide affordable clean energy and alleviate poverty. Progress in meeting the challenge of climate change was accompanied by a renewed global commitment to the Sustainable Development Goals, most of which were achieved by 2035[95]. Early action to reduce emissions allowed some costly adaptation measures to be avoided (for example, the US$50 billion per year needed to protect coastal cities against flood losses[50]), freeing up funds for social goods such as improved healthcare and poverty reduction.

Change in the physical environment

The physical environment of Antarctica and the Southern Ocean remains similar in many respects to that of 50 years ago[1] (Fig. 2). Climate variability in Antarctica and the Southern Ocean continues to be dominated by the Southern Annular Mode, the high-latitude atmospheric response to ENSO[96], and interactions between the two[97].

Atmosphere. Atmospheric trends observed in the decades before 2017 were largely associated with changes in the Southern Annular Mode related to the ozone hole, in particular a southward shift and strengthening of the westerly winds over the Southern Ocean, particularly in summer[13]. Decreases in emissions of ozone-depleting substances as a result of the 1989 Montreal Protocol led to gradual repair of the ozone hole and ozone levels in the Antarctic stratosphere have now returned to the values of the 1960s[98]. Repair of the ozone hole and a stabilization of greenhouse gas concentrations in the atmosphere were accompanied by a gradual shift towards the Equator and weakening of the westerly winds in summer[99], returning to values typical of the twentieth century[14]. Surface air and sea temperatures warmed by less than 1 °C and precipitation slightly increased (<10%) over the ocean and interior of the Antarctic continent[1].

Southern Ocean and sea ice. Trends observed in temperature, salinity and circulation of the Southern Ocean in the late twentieth century and early twenty-first century slowed and ultimately reversed in the decades between 2020 and 2050. The return of the westerly winds to a position closer to the Equator was associated with a similar shift of the Antarctic Circumpolar Current and hence cooling in parts of the Southern Ocean. The overturning circulation continued to transfer anthropogenic heat and carbon dioxide effectively into the ocean interior. Changes in wind-driven ocean currents reduced the exposure of the floating ice shelves to basal melt by warm ocean waters. However, the reduction in ocean heat transport to the ice shelf cavities came too late to save some West Antarctic ice shelves and ice tongues. Sea ice extent declined slightly (<15%) in both summer and winter between 2015 and 2070[1].

Effective action to mitigate emissions has also slowed the rate of increase in acidity of the oceans. The pH of Southern Ocean surface waters stabilized in the 2040s at values about 0.15 below pre-industrial values, or 0.05 below values observed in 2015[1]. Southern Ocean surface waters remain super-saturated with respect to aragonite. The exposure of Southern Ocean biota to ocean acidification has therefore increased only marginally over the past 50 years.

Ice shelves. While some ice shelves in the Antarctic Peninsula and Amundsen Sea were lost, the thinning rates observed in the large ice shelves for the period 1994–2012 remained fairly steady through to 2070. The Totten, Amery and Larsen C ice shelves remain largely intact, undergoing normal retreat through several large iceberg calving events. The marine ice cliff instability[33,44], which glaciologists feared could become widespread by 2050, has mostly been limited to a few outlet glaciers in the Amundsen Sea sector of West Antarctica and has not reached East Antarctica. Persistence of pore space in the surface layer allowed more meltwater to be stored within the firn, decreasing the susceptibility to hydrofracture[100].

Antarctic Ice Sheet and sea level. Although dynamic ice loss from marine-based sectors of the ice sheet has occurred, the rate of change is much less than the worst-case projections because many ice shelves continue to provide back-stress on the grounded ice[33,45]. Mass loss from the Amundsen Sea sector of West Antarctica continued, contributing 6 cm of sea level rise between 2000 and 2070[33]. After retreating steadily until 2050, the grounding zone of the Thwaites Glacier re-stabilized on a topographic feature about 25 km landwards of its early twenty-first-century position[101], saving the West Antarctic Ice Sheet from further decay. In 2070, sea level rise continues to be dominated by contributions from ocean thermal expansion, glacier melt, and equal roles of the Greenland and west Antarctic ice sheets, as in the 2010s.

Change in biology and ecosystems

Value of Antarctica. Following the ratification of the United Nations Paris Climate Agreement, and the Santiago Declaration by the parties to the Antarctic Treaty[102] to improve Antarctic and Southern Ocean environmental management, a sea change swept across the Antarctic Treaty System. The CCAMLR embraced the reality that climate change and harvesting were simultaneously threatening the Antarctic ecosystem. In consequence, barriers to establishment of Marine Protected Areas[60] were dismantled. Systematic conservation planning[103], based on recognition of evolutionary potential and genetic connectivity, enabled a flexible approach to maintenance of populations and helped achieve the CCAMLR goal of conservation of the Southern Ocean ecosystem.

Marine ecosystems. Local change in the marine system continued along trajectories recorded early in the twenty-first century[72–75,78], with reversals of earlier trends recently becoming apparent. Widely forecast tipping points were averted. New monitoring approaches[104,105] provided opportunities to identify locations where such threshold shifts might be important and to design strategies to avert them, such as temporary ecosystem manipulation[106]. Although ocean acidification continued, the impacts stabilized following the decrease in atmospheric CO_2 levels after 2040. Some population declines were recorded in sensitive species[77], but others adapted, resulting in less change than was initially forecast[71]. Seal and seabird populations continued to show changes in their foraging range, and changes in body mass and breeding success[62,64]. However, stabilization of sea ice conditions, and a reduction in the frequency of the extreme events to which these species are sensitive[107], reduced the rate of change. For some species, such as wandering albatross *Diomedea exulans*, weakening in the strength of the westerlies reversed a trend of enhanced breeding success and larger body mass associated with the strengthening westerlies earlier in the century[108].

Terrestrial ecosystems. On land, spread of the two indigenous vascular plant species on the Antarctic Peninsula continued, but at a declining rate by the late 2060s. Changes predicted for the Dry Valleys associated with pulse events[109] continued, but with declining importance after 2060. The Long Term Ecological Research sites proved exceptionally important as a source of evidence to document climate-associated biodiversity responses. Rapid progress in remote sensing techniques[110], alongside adoption of a suite of essential biodiversity variables, enabled researchers to verify that changes in terrestrial ecosystems were within the bounds anticipated for the low-emissions scenario considered by the IPCC Fifth Assessment Report[1].

Invasive species. The introduction of invasive species along the Antarctic Peninsula initially continued as had been expected. However, none of the world's most invasive species have established, largely because the climate remained inhospitable[83]. Several European and sub-Antarctic species were able to gain a foothold and spread initially, as had been predicted from increasing human activity in the region[82]. Nonetheless, two developments reduced the magnitude of the problem. First, the CEP adopted a systematic, DNA barcoding and web-based surveillance system, which enabled rapid identification of 'unusual' species found by environmental managers, and appropriate action. Second, the parties to the Antarctic Treaty agreed two regulatory frameworks in quick succession in the years leading up to 2030. First, an agreement on the importance of Antarctic genetic resources and bioprospecting was put in place as a further Annex to the Environmental Protocol, thus resolving a decades-long impasse[7]. The renewed focus on the value of indigenous resources improved conservation actions to retain them, including the declaration of a suite of new terrestrial protected areas. Second, a Protocol on Tourism Regulation, initially proposed in the earlier years of the century[5] was eventually agreed as a further Annex to the Environmental Protocol. The Annex regulated all Antarctic activity, recognizing the similarity in impacts of science, tourism and resource extraction activities (the agreement excluded fishing). These developments also prompted further attention to components of diversity not frequently considered, yet of tremendous consequence in the Antarctic terrestrial system—the microbiota[111]. The parties to the Antarctic Treaty agreed by resolution to apply strict biosecurity measures on travel among the Antarctic Conservation Biogeographic Regions[86]. Thus, evolutionary biology continued to document the unusual nature of Antarctic systems and their evolutionary history. The outcomes of this work provided valuable insights into the microbial history of the planet and the way systems might evolve elsewhere. Moreover, bioprospecting activities delivered new products that improved the health and wellbeing of human populations.

Change in human engagement with Antarctica

Effective governance. Strong action by the international community to mitigate greenhouse gas emissions was echoed in Antarctica, where the parties to the Antarctic Treaty reversed decades of regulatory inaction[5]. Decisive steps were taken to limit the impact of increased human engagement with Antarctica. Motivated by a clearer appreciation of the threats to the region and the global value of better understanding Antarctica and its links to lower latitudes, the parties reaffirmed the commitment to maintain Antarctica as a natural reserve for peace and science[102] and, importantly, strengthened a variety of governance measures to ensure the commitment was put into practice. Although national implementation of measures remained variable, reflecting the complexity of interactions and feedbacks between international law and domestic legislation and politics[5], the tenor of the international governance conversation had changed.

International collaboration. Perhaps most important was the improved relationship between the Antarctic Treaty System and the United Nations, especially through its environment programme. The very cool relations sparked in the 1980s by the 'Question of Antarctica', which remained on the United Nations' General Assembly Agenda until 2005[112], started to thaw some two decades later. Chief among the catalysts was research showing that Antarctica and the Earth system are inseparable. Moreover, an increasing focus on truly global action to achieve the Sustainable Development Goals[95] helped improve collaboration. Warming relationships between international institutions were also reflected by better collaboration between CCAMLR and other regional fisheries management organizations[5], to the benefit of the latter. In consequence, regulatory activities across both marine and terrestrial environments improved and an integrated biodiversity strategy[7] facilitated holistic management of the region. These achievements by the Antarctic Treaty System have provided a compelling illustration of the power of effective management of shared international spaces. The governance of Antarctica is now taught in schools worldwide as an example of successful international cooperation in conservation and sustainable resource management.

Societal benefits. Human engagement in Antarctica continued to deliver societal benefits on a global scale. New compounds isolated from Antarctic biota are now used in a wide variety of industrial and medical applications (an advance made possible by the Environmental Protocol's new Annex to ensure fair and effective management of intellectual property associated with biological prospecting). The skills of weather, climate and sea level forecasts for the entire Southern Hemisphere now depend heavily on the automatic observing systems established in Antarctica and the Southern Ocean. Lessons learned in redesigning Antarctic bases and logistics to increase efficiency and minimize environmental impact helped accelerate progress to a low-carbon global economy. These advances included improvements in building efficiency, renewable energy and storage, electric vehicles, waste management and autonomous systems.

Conclusion

We have described two retrospective narratives for Antarctica set in the year 2070: one in which greenhouse gas emissions continued to increase rapidly and little policy action was taken to respond to environmental and social factors affecting Antarctica, and a second in which strong action was taken to reduce emissions and to put in place effective policies to enhance the resilience of Antarctica. The two scenarios are of course highly speculative and intended as counterfactual catalysts for discussion, rather than as predictions of the future. One thing is certain, however: the narrative that eventually plays out will depend substantially on choices made over the next decade[9].

Antarctica and the Southern Ocean are closely coupled to the rest of the globe. The Antarctic Ice Sheet is the largest and most uncertain potential contributor to future sea level rise. In addition, changes in high southern latitudes will also directly affect the energy budget of the Earth by altering the planetary albedo, the strength of the global overturning circulation, the amount of carbon dioxide in the atmosphere, and the availability of nutrients to support marine life.

Under the high-emissions scenario, Antarctica and the Southern Ocean undergo widespread and rapid change, with global consequences. But the environmental change realized by 2070 will be only a fraction of the change to which we are committed by choices made today, and the rate of change will have increased and continue to accelerate. For example, once initiated, the marine ice sheet instability will result in irreversible loss of large parts of the ice sheet resting on bedrock below sea level. Under the low-emissions scenario, in which global average temperatures remain within 2 °C of 1850 values, there is some chance that the buttressing ice shelves will survive and the Antarctic contribution to sea level rise will remain below 1 m. Under the high-emissions scenario, the ice shelves are lost and Antarctica contributes 0.6 m to 3 m of sea level rise by 2300, with an irreversible commitment[45] of 5 m to 9 m, or as much as[33] 15 m in the coming millennia.

Despite the challenges, actions can be taken now that will slow the rate of environmental change, increase the resilience of Antarctica, and reduce the risk of out-of-control consequences. An effective response to the challenges of a changing Antarctica can serve as an example of the power of peaceful international collaboration, as well as demonstrate how integration of physical, biological and social sciences can enable decision-making that is informed by the past and takes account of the long-term consequences of today's choices.

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Competing interests S.L.C. is President of the Scientific Committee on Antarctic Research.

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