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Adélie penguins on top of an ice flow near the Antarctic Peninsula. © Jo Crebbin/Shutterstock

Climate Change and Southern Ocean Resilience

REPORT FROM AN INTERDISCIPLINARY SCIENTIFIC WORKSHOP, MARCH 30, 2021

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I. INTRODUCTION *BY EVAN T. BLOOM* [vii]

As the world prepares for the Glasgow Climate Change Conference in November 2021, there is considerable focus on the Southern Ocean. The international community has come to realize that the polar regions hold many of the keys to unlocking our understanding of climate-related phenomena - and thus polar science will influence policy decisions on which our collective futures depend.

Global sea-level rise is linked to future melting of the Antarctic ice sheets and shelves. New research on the Antarctic Ice Sheet indicates that rapid sea-level rise from Antarctica will be triggered if Paris Agreement targets (2°C warming in the twenty-first century) are exceeded. A recent article notes that if current emissions rates continue and put the world on course towards 3°C warming, this tipping point will be reached by 2060, and no human intervention, including geoengineering, would be able to stop 17 to 21 centimeters (cm) of sea-level rise from Antarctic ice melt alone by 2100.[1]

Antarctica's main diplomatic fora, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and the Antarctic Treaty Consultative Meeting (ATCM), have both had climate change on their respective agendas for years and have taken substantial actions to boost Southern Ocean resilience, such as designating the Ross Sea region Marine Protected Area. Even so, the level of attention on the issue of climate change is increasing. On March 30, 2021, the Wilson Center's Polar Institute and The Pew Charitable Trusts brought together leading scientists for virtual discussions about the relationship between climate change and the Southern Ocean. The scientists were asked to discuss why policymakers should care about the Southern Ocean, considering two questions: what are the discrete management actions that CCAMLR can take in the next four-to-eight years to address climate impacts in the Southern Ocean? And how does what is happening in the Southern Ocean – both in terms of climate impacts and management action – affect broader global climate, human, and ecological systems?

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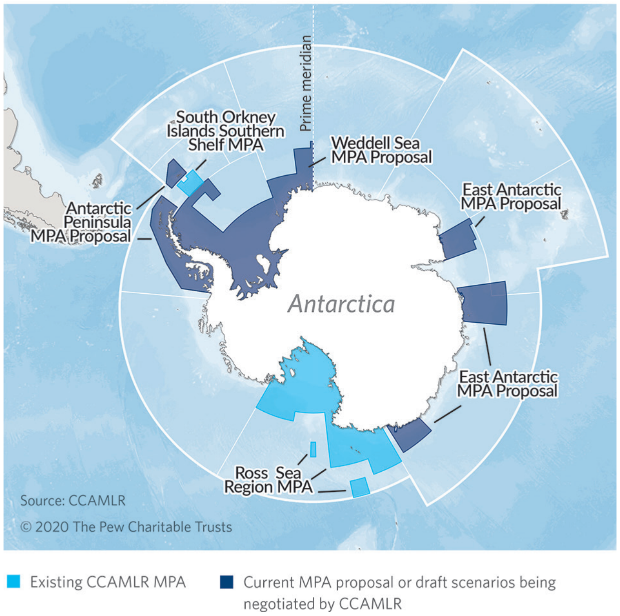
Fig 1: Southern Ocean regions proposed for protection

A network of MPAs could allow for conservation of distinct areas, each representing unique ecosystems



The report below provides a number of responses to these important questions and makes a compelling case for the parties at both CCAMLR and the ATCM to incorporate climate considerations into their work.

It is clear that Marine Protected Areas (MPAs) can play an important role in climate policy, and CCAMLR is already committed to establishing a representative system of MPAs, with three major proposals before the Commission requiring final negotiation. Given its size and the relative lack of human activity there, the Southern Ocean is a favorable location for establishing large-scale MPAs. In turn, MPAs generate benefits for fisheries and biodiversity by protecting key habitats, while delivering significant climate resilience gains. MPAs can also serve as climate reference areas; the relatively undisturbed Southern Ocean provides a natural laboratory for studying complex ecosystem responses to climate change impacts, such as warming and acidification, and how to best manage the ocean for climate mitigation, adaptation, and conservation potential. The Ross Sea region MPA, for example, holds the potential to promote climate science by allowing scientists to assess climate impacts on fished, unfished and, in some cases, more lightly fished areas.

CCAMLR and its Scientific Committee also need to prioritize the wider integration of climate into management and decision-making; the previously proposed Climate Change Response Work Program lays out many of these opportunities to boost Southern Ocean resilience. Similarly, the ATCM and Committee for Environmental Protection within the Antarctic Treaty System should strengthen efforts to integrate climate considerations into their work. All these organizations pride themselves on acting on the basis of best available science, and that science has to take into account climate considerations.

I trust that the Members of CCAMLR and the Antarctic Treaty Consultative Parties will find this report helpful in their coming deliberations.

Close-up of an Antarctic iceberg. Iceberg calving is increasing as climate change destabilizes ice regimes in the region.
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II. EXECUTIVE SUMMARY

The Antarctic has long been seen as an untouchable wilderness where few venture beyond scientists at remote research bases, scattered fishing vessels, and a limited number of well-heeled tourists. Yet shifts in Antarctic processes, driven by human-caused climate change, are impacting wider earth systems, with profound implications for human and ecological communities far from the icy continent. The Wilson Center's Polar Institute and The Pew Charitable Trusts co-convened an *ad hoc* Expert Working Group of leading Antarctic scientists globally[viii] to discuss climate-driven changes to the Southern Ocean around Antarctica. Key considerations were how these changes impact global marine, climate, and human systems, and how management actions taken through the Antarctic Treaty System, in particular CCAMLR, can build resilience to these changes in the Southern Ocean.

The Expert Working Group identified key interconnected Southern Ocean processes that are being impacted by climate change, and which will cumulatively result in widespread changes well beyond the Antarctic region. Five of these were highlighted as priority topics for conservation and management: shifts in sea ice and ice sheet dynamics; changes in ocean chemistry; increases in ocean temperatures; changes to the biological carbon pump; and alterations to ecosystems and species. The report details how some of these processes are moving towards tipping points - critical thresholds to irreversible, rapid, and substantial change - that can have devastating impacts on regional ecosystems and on far-flung human communities. In addressing these challenges, the Expert Working Group considered how CCAMLR could take concrete climate change-related actions by 2030, including expanding habitat protections, re-evaluating existing fisheries management, leveraging precautionary and ecosystem-based management approaches, and adopting a comprehensive work plan that considers climate change effects in all its conservation measures.

As Southern Ocean dynamics play a major role in global climate regulation and broader marine ecosystems, collective action to protect and enhance its resilience to climate change can benefit societies and economies around the world. Building this resilience requires additional actions,

viii. Participants of the workshop held on March 30, 2021 included, inter alia: Viviana Alder; Andrea Capurro; Rachel Cavanagh; Florence Colleoni; Sylvia Earle; Alexey Ekaykin; Susie Grant; Eileen Hofmann; Bettina Meyer; Jessica O'Reilly; Evgeny Pakhomov; Jean-Baptiste Sallée; Mercedes Santos; Fokje Schaafsma; and Bert Wouters.

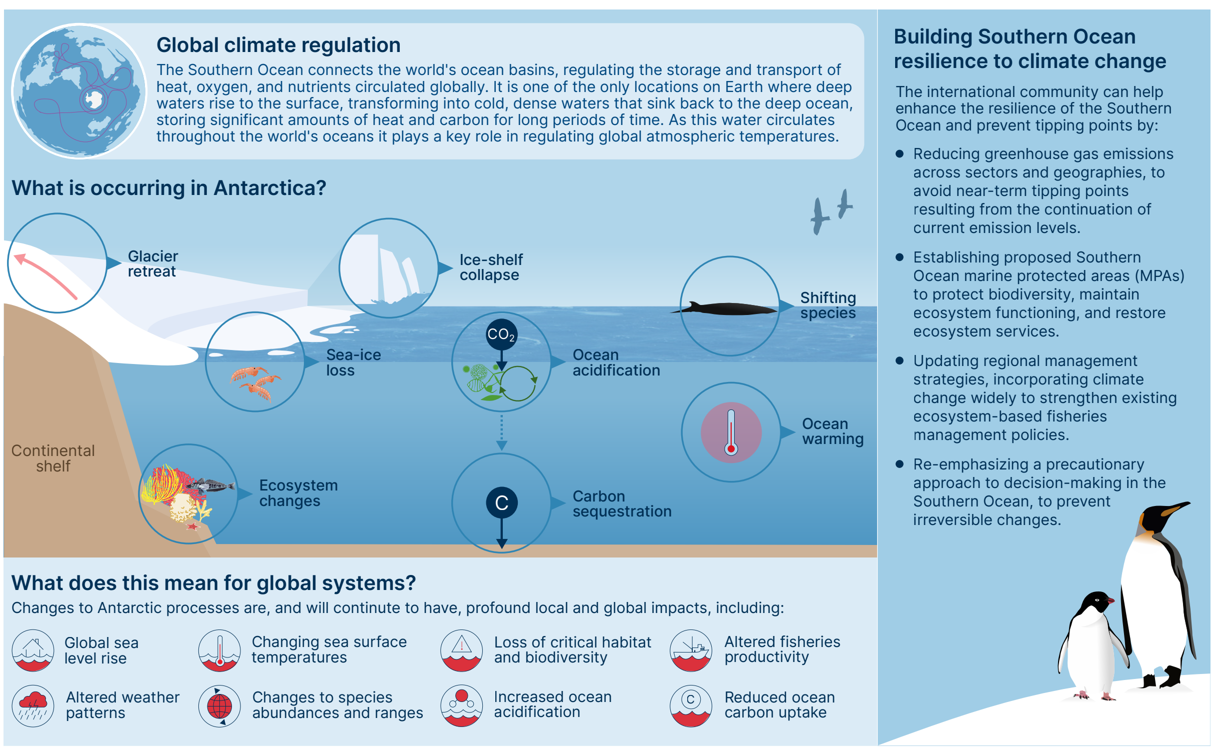
Chinstrap penguins in Antarctica. Penguin population structures are shifting as prey species, ice regimes, and weather patterns change in the Southern Ocean. © SZakharov/Shutterstock.com beyond CCAMLR, that recognize mandates and interconnections within and between regions. Importantly, these actions by the international community must include immediate and significant cuts to greenhouse gas emissions across sectors and geographies to avoid tipping points to physical processes in the Antarctic, as well as the wider suite of dire impacts predicted under future emissions scenarios.

The early success of the Antarctic Treaty led to it being seen as a global model for multilateral regional governance, as countries came together to manage the Antarctic for peace and science and the framework became a platform to launch robust scientific partnerships. CCAMLR, in particular, has an important role in the conservation of Southern Ocean marine life and in leading research that underpins decision making. As climate change effects challenge the Antarctic Treaty System, and nations cope with a dizzying array of global-level crises, stronger collaborations and coordinated work are needed within the Antarctic realm.

This Expert Working Group has demonstrated the value of these international idea exchanges to help expand our understanding of the importance of research and governance in this remote, yet vital, region. By drawing greater awareness to climate impacts within the Southern Ocean and highlighting its connection to global systems, this report can help policymakers elevate the governance dialogue around Antarctica and the Southern Ocean and bring the challenges of this distant region closer to home.

Fig.2 Climate Change and Southern Ocean Resilience

Global human-caused climate pressures are rapidly changing Antarctic processes, with profound implications for human and ecological systems around the world. Of particular concern is evidence which suggests the approach of imminent **tipping points**, which may set in motion irreversible, rapid, and substantial change to Antarctica's biogeochemical cycles and its role in regulating global climate.



Graphical summary illustrating climate change impacts on the Southern Ocean and global systems, and the potential actions to building resilience in the Southern Ocean. Source: Visual Knowledge, www.visualknowledge.design

III. CLIMATE CHANGE AND SOUTHERN OCEAN RESILIENCE

This report is guided by current scientific research and reflects the diverse array of topics discussed during the Expert Working Group's workshop. It does not represent or espouse the views of any one individual or organization, and not all ideas contained herein reflect consensus amongst all participants.

A. CLIMATE CHANGE AND THE SOUTHERN OCEAN

Oceans provide a wide range of vital ecosystem services to human populations, including regulation of the global climate, nutrient recycling and oxygen production, protection from extreme weather events, food security, transportation, and cultural uses.[2] These services are directly and indirectly affected by climate change, which alters the physical, chemical, and biological properties of the ocean. Anthropogenic greenhouse gas emissions are now higher than at any previous point in time, with major consequences for the climate system and life as we know it. Levels of atmospheric carbon dioxide are increasing fourfold faster than five decades ago,[3] contributing to global warming that is likely to exceed 1.5°C in the next few years. The last time carbon dioxide levels were as high as today (over 400 parts per million) was three million years ago when global sea level was 16-25 meters (m) higher.[4] The global ocean has taken up more than 90% of the excess heat and absorbed up to 40% of carbon from human activities.[5] The current rates of ocean warming, acidification, and deoxygenation can trigger both catastrophic events and gradual changes,[6] with global implications that can last for decades to centuries, or longer.

Disproportionate Southern Ocean impacts

The polar regions are showing the most rapid and uneven responses to climate change.[7–9] In recent years, the Southern Ocean has made the largest contribution to the increase in global ocean heat content in the upper 2000 m and has been warming

Glaciers are retreating in Antarctica, and calving along the Antarctic coastline is increasing, precipitating changes in regional ecosystems. © Denis Burdin/Shutterstock.com

Ice provides habitat to numerous species in the Southern Ocean, including penguins, seals, and krill larvae. © Jo Crebbin/Shutterstock.com

to a greater depth than the global average. In addition, the Southern Ocean has taken up to 40% of the total oceanic carbon uptake, a disproportionate magnitude considering its relatively small size.[7,10] The heat uptake of the ocean has, thus far, buffered human communities from experiencing the full impacts of our greenhouse gas emissions, however it has increased and accelerated ocean acidification (see below[11]) among other factors altering marine systems.

While these changes result in fundamental shifts in Southern Ocean processes and habitats, of particular concern is evidence that suggests imminent tipping points – critical thresholds to irreversible, rapid, and substantial change. Warm waters around Antarctica may be triggering the onset of irreversible ice shelf instability that could initiate a collapse of the Antarctic Ice Sheet. This would contribute to accelerated sea-level rise with devastating consequences for coastal regions worldwide.[1,12–16] New estimates reveal that sea-level rise and coastal flooding this century could be up to threefold greater than anticipated, threatening one billion people.[17] Tipping points may also be reached for ocean acidification with significant implications for the entire ecosystem,[11,18] including the potential collapse of the Antarctic krill population,[19] a keystone species in the Southern Ocean.

International Climate Collaboration

Given the disproportionate influence of the Southern Ocean on global climate dynamics, this remote place needs to be examined intimately, but also put into a global context.[28] While understanding local processes is critical, integrating this knowledge into broader systems can help policymakers and practitioners better understand the importance of the region. To this aim, a collaborative Expert Working Group, representing a diverse suite of disciplines including social sciences, governance, biogeography, oceanography, and biology, undertook a creative discussion process to contribute to improving management decisions in a changing Southern Ocean.

B. CONNECTION OF REGIONAL SOUTHERN OCEAN PROCESS TO GLOBAL SYSTEMS

The climate impacts experienced in the Southern Ocean have far-reaching impacts on global climate regulation, marine ecosystems, and human communities. The Southern Ocean is interlinked to northern regions by oceanic, atmospheric, and cryosphere coupling, connecting the global ocean basins and the deep and shallow layers of the oceans. In the Southern Ocean, deep waters rise to the surface where they transform into cold, dense waters that sink back to the deep ocean, storing significant amounts of human-produced heat and carbon for decades to centuries. Through this process, the Southern Ocean helps slow the rate of global warming in the atmosphere.[20]

As the surface of the Southern Ocean warms, the overturning circulation - a system of surface and deep currents around the globe - transports heat to deeper layers and northwards, increasing the ocean's temperature further north. Warmer deep waters in the Southern Ocean induce iceberg calving and melting at the base of ice shelves, which contributes to an accelerated mass loss from the Antarctic Ice Sheet. This, in turn, reduces albedo, releases fresh water into the ocean, reduces ocean salinity, and substantially contributes to global sea-level rise.[7] In addition, melting from icebergs and ice shelves influences ocean circulation, sea ice extent, and the rate of global temperature rise.[21] Melting is also closely related to meridional wind trends[22,23] that are linked to Pacific sea surface temperature variability;[24–26] in recent years, an extensive and prolonged surface melting from the West Antarctic Ice Sheet was linked to the horizontal transport of warm marine air transported from the tropical Pacific to the continent, likely influenced by El Niño. As extreme weather events are projected to increase around the world during the rest of the century, these global feedbacks, along with a warmer atmosphere,[27] could expose the West Antarctic Ice Sheet to more frequent major melt events with cascading physical, ecological, and global repercussions.

The Southern Ocean is also linked to global systems through nutrient cycling. Surface waters, rich in oxygen and organic matter, sink to ventilate the deep ocean, while upwelling transfers nutrients from

Adélie penguins, *pygoscelis adeliae*, leaping into the water at Paulet Island, Antarctica. Adélie penguin habitat is strongly determined by sea ice conditions. © slowmotiongli/Shutterstock.com deep to surface layers. The upwelling and export of nutrients in the Southern Ocean, strongly influenced by the overturning circulation and mediated by the biological carbon pump, support up to three-quarters of global marine primary production.[28,29] Climate-driven changes in the Southern Ocean, including retreating glaciers, sea-ice changes, and ocean acidification (described below), are altering phytoplankton communities.[30] This has cascading biological effects and modifies the ranges and abundance of ecologically important species, both regionally[31,32] and in distant ecosystems. The resultant declines in global primary production and global changes in marine species distribution may challenge the sustained provision of fisheries productivity, affecting food security and other ecosystem services[5,33–35] outside the Antarctic.

C. UNDERSTANDING PROCESS CHANGES IN THE SOUTHERN OCEAN

Climate change is altering the Southern Ocean's physical, chemical, and biological processes in numerous, cumulative, and iterative ways. One task of the Expert Working Group was to discuss how regional changes in the Southern Ocean affect global systems. It was clear during discussions that greater awareness is needed to advance understanding that impacts are not static in time; they are dynamic in nature and, subsequently, affect other systems. Experts described five primary process shifts that lead to changes in global climate regulation, broader marine ecosystems, and human climate resilience.

Shifts in sea ice and ice sheet dynamics

Ice is the defining feature of the Antarctic. Sea ice, which expands the footprint of the continent over sevenfold every winter, is formed when seawater freezes on the ocean surface and is further thickened by snow accumulation. Ice sheets and glaciers are dynamic, land-based ice formations that are built up by accumulating snowfall on their surface. The Antarctic Ice Sheet, which covers the continent, is 2.1 kilometers (km) thick on average and holds 70% of the world's fresh water. If it melted, it would raise global sea levels by almost 58 m.[36] Ice shelves - extensions of ice sheets and glaciers that float in the surrounding ocean - cover more than 1.5 million km^2 and are Antarctica's primary connection between its ice sheet and the Southern Ocean.[16]

Underwater ecosystem, Antarctica. © Ivan Hoermann/Shutterstock.com

Changes to ice regimes can, therefore, profoundly alter the entire region. Climate-driven shifts in sea-ice dynamics in the Southern Ocean, both in extent and duration, follow regional, interannual, and seasonal variability, with some areas losing and others gaining ice in the same period.[7,9,37,38] The last few years have shown a strong decrease in annual mean ice cover, largely driven by warmer atmospheric circulation and warmer water closer to the ice edge,[39–42] linked to increases in greenhouse gas emissions.[43]

Ice loss trends extend inland to the Antarctic Ice Sheet. In recent years, mass loss from this ice sheet has tripled, mostly due to rapid thinning and the retreat of major outlet glaciers draining the West and East Antarctic Ice Sheet,[44–47] caused by oceanic warming (e.g.[48–51]). The future dynamic response of the Antarctic Ice Sheet to warming will largely be determined by the thinning or collapse of ice shelves, which will reduce their buttressing or capacity to stabilize the associated ice sheet.[7,52,53] It is projected that this destabilization, or marine ice sheet instability, could cause 4-5 m of sea-level rise by 2300 under high emissions scenarios (e.g.[1,52,54]).

Changes in ocean chemistry

The ocean absorbs up to a quarter of carbon released from human activities, which in surface layers dissolves and forms carbonic acid, lowering the ocean's pH, a process known as ocean acidification.[5] This process can alter marine ecosystems and potentially impact commercially targeted species.[8,55–58] The Southern Ocean already has a significant vulnerability to undersaturation of aragonite (a form of calcium carbonate)[58,59] and coastal areas, which are already more acidic during winter, have an increased exposure to ocean acidification[60] that is predicted to intensify.[61

The vast Antarctic Ice Sheet is believed to be an important source of iron in biogeochemical cycling

Cape Petrels near South Shetland Islands, Antarctica.

in the Southern Ocean.[62] Iron fertilization from an increased melt of ice shelves, icebergs, and glacial meltwater[63] is predicted to increase primary productivity (see below) in some areas, particularly in ice-dominant regions. As the climate warms, nutrient cycling close to ice sheets is likely to increase due to the exposure of nutrient-laden glacial sediments,[64] but also to reduce from upwelling and icebergs.[65] These changes in iron supply in Southern Ocean waters are likely to additionally impact carbon sequestration (see below).

Increases in ocean temperatures

The rate of global ocean warming and, thus, heat uptake has more than doubled since 1993, attributed to greenhouse gases and ozone depletion.[7,66–69] The Southern Ocean has warmed both on the surface and in the deep ocean, with regional and decadal variability, largely influenced by air-sea flux, wind-forced changes, and overturning circulation.[70,71] From the surface to 2000 m, the Southern Ocean increased its share of heat uptake up to 45%-62% in 2005-2017,[7] and the deep Southern Ocean below 2000 m has stored a large fraction - up to one third - of the total anthropogenic heat excess since 1992.[72,73] These Southern Ocean warming trends, documented over the last century, are projected to continue, leading to 1°C–3°C warming by 2100.[74,75]

Changes to the biological carbon pump

The marine biological pump sequesters carbon from the atmosphere into deep ocean waters and sediments,[76] constituting one of Earth's most valuable ecosystem services.[77] At the air-water interface, inorganic carbon from the atmosphere is transformed into particulate organic matter by photosynthesis, which in turn is consumed and respired by surface-dwelling marine animals (such as fish larvae) and life on the continental shelf seafloor. As organic matter sinks, it can be remineralized (reconverted to inorganic carbon) and recycled through scavenging and/or solubilization (dissolution of particulate matter).[78] Only about one third of the carbon that reaches depths beyond the 'photic' zone - where light penetrates - is transported to the deepest ocean waters, and then usually only 1% of it is buried in sediment.[78] The most productive areas are typically the Antarctic continental shelves, which may accumulate over 60 million tonnes (Mt) of carbon per year.[79]

Tabular icebergs in the Weddell Sea, Antarctica. © Robert McGillivray/Shutterstock.com

The functioning of the biological carbon pump is shifting due to a host of factors, and the effects of climate change on it are complex.[35 (and references therein)] Ocean warming reduces the pump's efficiency in the Southern Ocean by promoting shallower remineralization and decreasing the overall carbon storage, reducing the available food to midwater and seafloor communities.[76] While increases in iron, light availability from ice loss, and near-surface stratification are likely to enhance primary production and carbon export in the near future,[8,80] increased ocean temperatures, acidification, and freshening from melting ice in the long run are expected to reduce the downward flux of carbon in the Southern Ocean.[81] Marine ice losses have led to new and longer phytoplankton blooms[82] and increased secondary production, storage and sequestration. The largest component to this negative (mitigating) feedback on climate change is sea-ice losses, which have doubled Antarctic continental carbon stocks in the last 25 years.[83] Ice shelf losses are also important;[84] a giant iceberg of approximately 5000 km^2 may generate 10[6] Mt of carbon.[79] Finally, the emergence of fjords from retreating glaciers is generating new small carbon sinks, which could be very important sites of higher sequestration.[85]

Changes to ecosystems and species

The changes described are impacting Southern Ocean species, food webs and ecosystems in both direct and indirect ways. While one of the most visible and widely reported impacts of climate change in the Southern Ocean are changes to its iconic wildlife population, there are a range of complex changes to species interactions and biological feedbacks within ecosystems that are less well understood. The data increasingly indicates that these processes, which underpin Southern Ocean and broader marine ecosystems, are under threat.

Plankton and pelagic primary productivity

Primary productivity - the rate at which carbon dioxide is converted into organic matter through photosynthesis - plays a key role in the biological carbon pump and the production of oxygen. It is strongly mediated by micronutrient availability (especially iron), temperature, carbonate chemistry, light, deep vertical mixing, seasonal fluctuations in solar radiation, and sea-ice cover.[86,87] Ice shelf collapses, such as the collapse of Larsen A and B in 1995 and 2002 which received global media attention, have led to increases in primary productivity on the newly exposed pelagic areas and polynyas,[ix] [16,88] which is predicted to benefit macroalgae and zooplankton.[7] Ocean acidification alters these processes and can lead to cascading negative effects across multiple trophic levels of Antarctic food webs.[8,89–91]

Southern Ocean primary productivity supports Antarctic krill, which make up the largest krill population globally, estimated at 400 Mt. These small shrimplike crustaceans play a key role in Antarctic food webs both as grazers and as prey[92,93]. Krill is a critical energy conduit between primary producers and top predators,[94,95] such as the endangered blue whale which can eat up to four tonnes of krill per day. Increasing water temperature, ocean acidification, and reduction in the sea-ice coverage, as well as productivity, may negatively affect the Antarctic krill population.[7,19,96–99]

ix. Antarctic coastal polynyas (areas of open water surrounded by sea ice) are biological hotspots that support high rates of primary productivity due to a combination of both high light and high nutrient levels, especially iron[7 (and references therein)].

As a consequence of these changes, Antarctic krill may have already shifted its distribution southward,[7,100] modifying species dominance and prey abundances, and forcing predators to shift their ranges.[7,100–103]

Benthic communities

Benthic communities - marine fauna that live on the seafloor and are largely composed of worms, crustaceans, and shellfish (mollusks) - play a vital role in maintaining sediments and water quality. In the Southern Ocean, sea ice decreases and glacial retreat have modified benthic communities through changes in habitat, freshening from melting glaciers, sedimentation, temperature, and productivity.[83,104,105] Ocean acidification has direct consequences on benthic organisms with carbonate skeletons and shells as well, ultimately reducing benthic diversity.[105] Climate change is expected to have a great impact on endemic benthic species found nowhere else on Earth; around 80% will lose habitat due to increases in temperatures by 2100,[106] with greater risks around the Antarctic Peninsula and Scotia Arc. A warmer ocean is likely to influence many cold-adapted benthic organisms, allowing the colonization of non-native species.[105]

Humpback whales migrate to the Southern Ocean from other ocean basins, and are an important part of the biological carbon pump.

Fish and apex predators

Much attention is paid to how climate change is altering the abundance and resilience of the Southern Ocean's iconic and endemic wildlife. Antarctic fish play a central role in the regional marine food web[31] and are well adapted to live in the frigid Southern Ocean waters, in part thanks to their antifreeze proteins. However, they have a very narrow thermal tolerance,[5] which makes them vulnerable to warming conditions. Increasing temperatures and loss of ice in the Southern Ocean can affect fish physiological functions, modify dispersal, stymie overfished stock recovery, reduce habitat, and alter food webs.[107–111]

Changes in fish and krill populations impact marine predators, such as penguins, flying seabirds, seals, and whales, which play an important role in connecting pelagic marine food webs in the Southern Ocean[32] and beyond. Most of these species can be directly or indirectly affected by climate change, mainly through alterations in habitat and food availability.[7,32,112–118] The impact of ice loss is species-specific depending on their affinity for sea ice; population responses may also vary around Antarctica.[32,89] In terms of food availability, the changes to krill and fish populations described above, compounded by direct climate stresses on predators, may result in reduced survival and breeding failures,[32] drastically reducing predator populations. These changes are accentuated by additional human pressures. Whales, seals, and seabirds were heavily affected by hunting and long-line operations until as recently as 1997.[32, 119] For example, it is estimated that in the early and mid-twentieth century, over two million whales and nearly three million seals were taken from the Southern Ocean.[120,121] Furthermore, as many as 25,000 seabirds were killed per year as bycatch (or incidental mortality) in toothfish fisheries by the late 1990s. Many of their populations are currently recovering from this over-exploitation, while coping with climate change and current fisheries pressures.

Uncertainties and the need for long-term research

Although the research is clear that climate change is fundamentally altering the Southern Ocean, uncertainties remain over how it affects most Antarctic processes.[20] For example, most

Antarctic krill, a keystone species, in the water near the Antarctic Peninsula. © Tarpan/Shutterstock.com of the regional changes in sea ice, including interannual variability, are not well captured by current models[7,97,122] The magnitude of climate-driven changes to species and ecosystems, including ocean acidification, is difficult to assess due to knowledge gaps in biodiversity estimates, ecosystem interactions, and population trends for many keystone species. There is also a lack of understanding related to the links between physical variables and ecological processes,[20,35] and the confounding effects with other causative mechanisms, such as fishing.[32] However, technological advances in both observing instruments and computational models are improving, allowing a better understanding of the complexity of the Southern Ocean. This points to the need for sustained funding and internationally collaborative research into Southern Ocean processes, including for improving observational records, extending time series, and gathering data on different spatial scales to continue informing management and governance decision-making.

D. ANTARCTIC GOVERNANCE AND DECISION MAKING

Policymakers can work through several multilateral governance frameworks to address climate change in the Southern Ocean. Parties to the Antarctic Treaty (which was signed in 1959 and came into force in 1961) are responsible for the preservation and conservation of living resources in Antarctica.[x] To act on this responsibility with respect to the terrestrial and marine environments, they subsequently negotiated and adopted several separate international instruments.[123–126] Together, the Antarctic Treaty, CCAMLR (which was signed in 1980 and came into force 1982) and the Environment Protocol to the Antarctic Treaty (which was signed in 1991 and came into force in 1998), form the main elements of the Antarctic Treaty System.

x. Antarctic Treaty, Article IX, paragraph 1(f).

A Weddell seal swims among ice near the shore of Ross Island, Antarctica. © Brian L Stetson/Shutterstock.com

Convention for the Conservation of Antarctic Marine Living Resources

Given the history of overexploitation of seals, whales, and some fish species during the nineteenth and twentieth centuries, increasing concern over the over-exploitation of Antarctic krill led to the formation of CCAMLR.[127] The fora pioneered the use of an ecosystem-based and precautionary approach for fisheries management, following conservation principles[xi] to maintain ecological relationships between species and prevent irreversible changes to the marine ecosystem.[127,128] This approach requires management that is responsive and adaptive, but also proactive in terms of environmental uncertainty, in that actions are not delayed for definitive attribution of the causes of change.[129]

Currently, CCAMLR builds ecosystem resilience to climate-driven change by, *inter alia*, robust stock assessments, large MPAs, and scientific monitoring programs. These existing tools and measures can be enhanced to improve the capacity of the ecosystem to cope with the effects of climate change.[130] Resilience actions that account for the spatio-temporal variability of Southern Ocean processes and risks can preserve connectivity and representativeness of habitat types, biodiversity, and ecosystem functions that support a wide range of species and food webs.

xi. CCAMLR, Article II (iii).

A group of emperor penguins on the sea ice in the Ross Sea, where a large-scale marine protected area was established in 2016. © Brian L Stetson/Shutterstock.com

Fisheries (for toothfish, icefish, and krill) currently operate under decision rules based on stock assessments[129] that have no explicit considerations of climate change in the legally binding measures. Furthermore, current fishery regulations apply to areas much bigger than the effective area where the fishery operates.[129] This means that local fishing pressures may be considerable. For instance, a catch level considered precautionary for the krill may not be precautionary for its predators, such as penguins, whales, and seals, given the spatio-temporal concentration of the fishery.[131] These risks are likely to be exacerbated in climate adverse conditions (e.g.[117,131–133]), and challenge the precautionary approach as it stands.

MPAs can play a key role in the adaptation to, and reduction of, climate change risks (e.g.[134–137]) by maintaining spatial connectivity and limiting additional non-climate stressors on the marine ecosystem, such as fishing. In 2011, CCAMLR committed to establishing a circumpolar representative system (or network) of MPAs. While CCAMLR has made significant progress towards this goal, including the adoption of the South Orkney Islands Southern Shelf MPA in 2009, and the Ross Sea region MPA in 2016, these areas alone cannot preserve habitat connectivity and representativeness across the Southern Ocean[138,139]. Three other large MPA proposals in East Antarctica, the Weddell Sea and the West Antarctic Peninsula (or Domain 1) are currently being discussed at CCAMLR, and their adoption would substantially improve representation.[139]

While CCAMLR has recognized climate change as one of the greatest challenges facing the Southern Ocean,[xii] its effective incorporation into binding management decisions more than ten years later remains limited. The proposed Climate Change Response Work Program aims to better incorporate climate change into CCAMLR's scientific framework and management decisions and set the path towards more climate-centric management. Although this program has not yet been adopted, it cuts across most – if not all – of the issues discussed by the Expert Working Group participants, highlighting its potential for building Southern Ocean resilience if implemented.

xii. CCAMLR Resolution 30/XXVIII (2009).

Antarctic Treaty Consultative Meeting

Apart from CCAMLR, the effect of anthropogenic climate change on the Antarctic environment has increasingly become a top priority for other Antarctic Treaty System bodies. Following an Antarctic Treaty Meeting of Experts in 2010, Parties adopted a Climate Change Response Work Program[xiii] which provides a mechanism to build resilience to climate change and address the associated governance and management implications for Antarctica.[140] In addition, Antarctic Treaty System bodies contribute to climate resilience by working across governance and research frameworks, conducting joint workshops, and engaging with experts from other Antarctic organizations and global programs.[xiv]

Global Frameworks

At a global scale, the current biodiversity and climate crises have stoked international calls for expanding the network of terrestrial and MPAs.[2,7,141] CCAMLR's current and proposed MPAs, in tandem with additional conservation measures in territorial waters and on the high seas, can contribute greatly to global targets and the ultimate goal of sustainable management. While recognizing each entities' mandate and governance, a globally coordinated effort is believed to be more efficient to simultaneously protect biodiversity, boost the yields of fisheries, and secure carbon stocks. This could be achieved by prioritizing regions for protection, such as the biogeographically unique area of the Antarctic Peninsula.[142]

Avoiding the worst-case climate impact scenarios in the Southern Ocean requires immediate and significant greenhouse gas emissions reductions across sectors and nations. The United Nations Framework Convention on Climate Change (UNFCCC) provides the framework for nations to limit further emissions through their Nationally Determined Contributions (NDCs), as well as to address climate impacts through adaptation measures. It notes that ocean-based solutions need to gain greater attention in NDCs, and that the ocean's role in absorbing human-caused heat has resulted in climate change impacts. To address these impacts, a recent report[xv] highlights that "adaptation and mitigation measures for ocean systems should be aligned with ongoing action on measures and policies under other multilateral agreements", including the Antarctic Treaty System. Therefore, while it is unlikely the world will meet the Paris Agreement's goal of holding twenty-first century warming to 2°C above pre-industrial levels,[143] CCAMLR and other frameworks must continue to address climate impacts to preserve Southern Ocean ecosystems and build resilience to change, alongside these vital emissions reductions.

Paradise Bay, Antarctica Peninsula. © Marc Andre LeTourneux/ Shutterstock.com

xiii. ATCM Resolution 4 (2015).
xiv. Including, *inter alia*, the Scientific Committee for Antarctic Research (SCAR) (and its associated groups, programs and initiatives), and global organizations or initiatives such as IPCC, IMO, IWC, the Agreement on the Conservation of Albatrosses and Petrels (ACAP), and IUCN.

xv. UNFCCC Subsidiary Body for Scientific and Technological Advice, p. 22.

E. CONCLUSION

The world has long valued Antarctica and the Southern Ocean as a vast wilderness, home to charismatic wildlife and the setting for scientific discoveries. Governments enshrined these values through the Antarctic Treaty System, to preserve the Antarctic for peace and science. The wisdom of this decision is increasingly clear; as climate change impacts are global in nature, climate-driven changes in the Southern Ocean are affecting marine systems and communities far beyond the Antarctic. The Southern Ocean is a key component of the Earth's system, redistributing heat, salt, fresh water, and nutrients to all the ocean basins in the world. In brief, a resilient Southern Ocean can benefit communities far from Antarctica.

Five key Southern Ocean processes are at risk due to climate change impacts – increases in ocean temperatures, shifts in sea-ice and ice-shelf dynamics, changes in ocean chemistry, changes to the biological carbon pump, and shifting ecosystems and species dynamics. These changes are already having cascading effects at regional and global scales and will continue to do so, with widespread socioeconomic consequences.

In the Southern Ocean, immediate actions by CCAMLR can help build ecosystem resilience to climate change. In particular, establishing MPAs can build climate resilience by maintaining spatial connectivity and reducing additional non-climate stressors, such as fishing. In addition, updating krill and fisheries management strategies, and incorporating climate change widely into conservation measures, can strengthen the ecosystem-based and precautionary approach under environmental uncertainty. Alongside these actions, sustained funding for long-term, wide-scope climate-based research programs and fostering international collaborations may reduce uncertainties in projections, ultimately improving adaptation and mitigation measures for future climate change scenarios.

Humpback whale, Antarctica. © MZPHOTO.CZ/Shutterstock.com

The extent to which Southern Ocean processes influence global changes largely depends on our ability to reduce global anthropogenic greenhouse gas emissions and therefore emissions reductions must be at the core of any strategy to address climate impacts.

The combined ecological and governance importance of the Antarctic will only be upheld through strong government action and commitment to preserve this region, not only because the Southern Ocean and its marine life help protect human communities globally from increasing climate impacts, but because Antarctica is a unique place where governments work together in favor of peace, science, and international cooperation.

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