Marine Policy 131 (2021) 104589

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Utilising IPCC assessments to support the ecosystem approach to fisheries management within a warming Southern Ocean

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A R T I C L E I N F O

Keywords:
IPCC
Southern Ocean
CCAMLR
Climate change
Antarctic krill
Ecosystem approach to management

A B S T R A C T

Southern Ocean marine ecosystems are highly vulnerable to climate-driven change, the impacts of which must be factored into conservation and management. The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) is aware of the urgent need to develop climate-responsive options within its ecosystem approach to management. However, limited capacity as well as political differences have meant that little progress has been made. Strengthening scientific information flow to inform CCAMLR's decision-making on climate change may help to remove some of these barriers. On this basis, this study encourages the utilisation of outputs from the United Nations' Intergovernmental Panel on Climate Change (IPCC). The IPCC's 2019 Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) constitutes the most rigorous and up-to-date assessment of how oceans and the cryosphere are changing, how they are projected to change, and the consequences of those changes, together with a range of response options. To assist CCAMLR to focus on what is most useful from this extensive global report, SROCC findings that have specific relevance to the management of Southern Ocean ecosystems are extracted and summarised here. These findings are translated into recommendations to CCAMLR, emphasising the need to reduce and manage the risks that climate change presents to harvested species and the wider ecosystem of which they are part. Improved linkages between IPCC, CCAMLR and other relevant bodies may help overcome existing impediments to progress, enabling climate change to become fully integrated into CCAMLR's policy and decision-making.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC), the United Nations (UN) body for assessing the science related to climate change, was created in 1988 to provide policymakers with timely scientific assessments on climate change, its implications and potential future risks, and to put forward adaptation and mitigation options. The IPCC's comprehensive Assessment Reports synthesise knowledge on climate change, its causes, potential impacts and response options, and aim to identify, through agreed and specific terminology, where there is agreement in the scientific community, where scientific consensus has not been established, and where further research is needed. The fifth Assessment Report (AR5) was published in 2014 [46], and following that, the IPCC Special Report on Global Warming of 1.5 °C (SR1.5; [47]) which outlined the projected risks of further warming. More recently, the IPCC Special Report on the Ocean and Cryosphere in a Changing

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https://doi.org/10.1016/j.marpol.2021.104589
Received 22 February 2021; Received in revised form 13 May 2021; Accepted 13 May 2021
Available online 25 May 2021

Climate (SROCC) was approved by the 195 UN member governments [48]. SROCC draws together the best available current knowledge on climate change with respect to the ocean and cryosphere, and, as with all IPCC assessments, underwent extensive community, specialist and government review. This generated 31,176 comments across three rounds of review, with each comment explicitly addressed. SROCC builds on and extends AR5 and SR1.5; its assessment of 6981 primary studies constitutes the most rigorous and up-to-date assessment of how the ocean and cryosphere are changing, how they are projected to change in the future under different climate scenarios, the consequences of those changes, together with a range of response options. It highlights the urgency of prioritising timely, ambitious and coordinated action to minimise and prepare for the impacts of these changes (Box 1).

A key message from AR5 was that polar ecosystems are highly vulnerable to climate-driven change [46]. SROCC builds on this in its polar regions chapter (Chapter 3, [58]), assessing the state of physical, biological and social knowledge concerning the polar oceans and cryosphere, how they are affected by climate change, and how they may evolve in the future. Concurrently, it assesses the local, regional and global consequences and impacts of individual and interacting polar system changes, and response options to reduce risk and build resilience in the polar regions.

The focus of this paper is the Southern Ocean, which falls within the management purview of the Convention for the Conservation of Antarctic Marine Living Resources (hereafter the Convention) (Fig. 1) which provides the framework for conservation and the management of fisheries and related activities. In response to a history of over-exploitation of several other marine living resources in the Southern Ocean and increasing commercial interest in fishing for Antarctic krill, *Euphausia superba,* a key component of the Antarctic marine ecosystem, the Convention entered into force in 1982, with the objective of conserving Antarctic marine life, establishing the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR, or the Commission hereafter) as its decision-making body. As a conservation-focused body and an integral part of the Antarctic Treaty System (ATS), CCAMLR differs from Regional Fisheries Management Organisations (RFMOs) in that it is able to address broader objectives of ecosystem conservation, including provisions in the Convention that bind Contracting Parties to a range of obligations in the Antarctic Treaty (Article III, Article IV.1, and Article V). The Convention's principles of conservation (Article II of the Convention) include preventing a decrease of harvested populations below levels that ensure their stable recruitment; restoration of depleted populations; maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources; and prevention of changes in the marine ecosystem that are not potentially reversible over two or three decades. This emphasis on ecological relationships and resilience was a significant departure from the previous established focus of fisheries management and conservation on specific species. The Convention predated the widespread use of the terms "ecosystem approach" and "ecosystem based management" from the late 1980s onwards but both terms have been retrospectively applied to CCAMLR's approach [26,34]. Here we follow Constable [26] in using the term "ecosystem approach". This is consistent with the definition of the term in the 1992 UN Convention on Biological Diversity, which

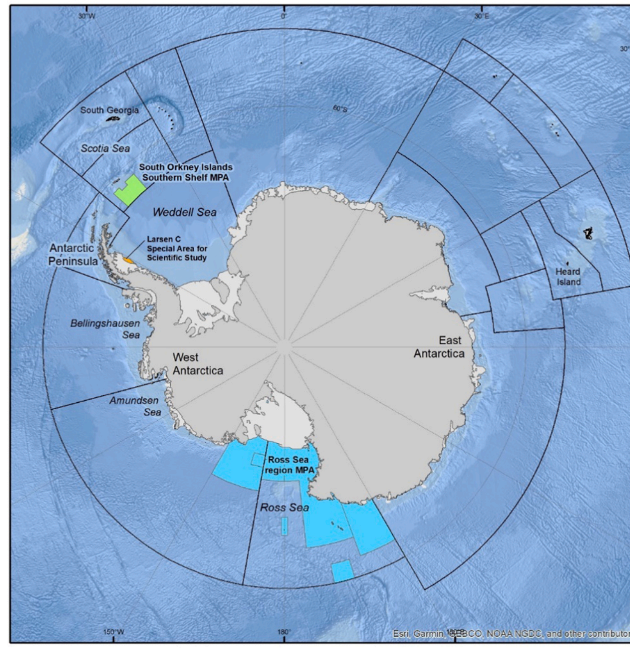

Fig. 1. Map showing locations referred to in the text. The Convention Area (heavy black line) is divided into statistical areas and subareas for reporting and management. The Antarctic Treaty covers the area south of 60°S. CCAMLR has designated two MPAs (see [11]), the first in 2009 at the South Orkney Islands Southern Shelf (green; [79]) and the second in 2016 in the Ross Sea region (blue), as well as the Larsen C Special Area for Scientific Study, designated in 2017 (orange). Data from http://gis.ccamlr.org.
Base map sources: ESRI, Garmin, GEBCO, NOAA and others.

emphasises "maintaining … ecological processes necessary to sustain the composition, structure and function of the … ecosystems concerned". In practice CCAMLR has focused on precautionary measures to prevent disproportionate impacts on the predators of fished species [26,34], where "precautionary" effectively means "setting low catch limits and protecting areas from fishing" [42].

Under the Convention, the Scientific Committee was established as an independent body to provide advice to the Commission in relation to these conservation principles, based on the best available scientific information, and drawing on the outcomes of research from Members. Currently 25 states and the European Union are Members of the Commission, with a further 10 states having acceded to the Convention. The Commission makes legally binding decisions about the formulation and implementation of regulations, known as Conservation Measures, through consensus. Working Groups assist in formulating scientific advice on key areas, with further input provided by Observers and invited experts. There are currently four Working Groups: Ecosystem Monitoring and Management (WG-EMM), Fish Stock Assessment (WG-FSA), Statistics, Assessments and Modelling (WG-SAM), and Acoustics, Survey and Analysis Methods (WG-ASAM). The expertise within the

Box 1
SROCC includes a brief synopsis with three key summary points that inform global responses to polar ocean and cryosphere change (Chapter 3, [58]):

- Climate-induced changes in the ocean and cryosphere are having significant impacts both locally and globally – everyone is affected.
- Across many aspects, the ocean and cryosphere regions of the future will appear significantly different from those of today.
- Choices are available that will influence the nature and magnitude of changes, potentially limiting their impacts and increasing the effectiveness of adaptation actions.

Working Groups consists predominantly of ecologists, fishery scientists and ecological modellers. The Scientific Committee established the CCAMLR Ecosystem Monitoring Programme (CEMP) in 1985 as part of the ecosystem approach, to detect possible effects of krill fishing on the performance of krill-dependent predators, such as albatrosses, petrels, penguins and fur seals [2].

CCAMLR currently oversees fisheries for four different species. Antarctic krill accounts for more than 90% of the catch by weight (~450,000 t in 2019/20) in the Convention Area. This fishery is currently concentrated in the Southwest Atlantic sector of the Southern Ocean although it has previously operated in the seas off East Antarctica, which remain open to fishing [50]. Patagonian and Antarctic toothfish (*Dissostichus eleginoides* and *D. mawsoni*) are high value species caught by longline fisheries in multiple deep-water locations throughout the Southern Ocean [24,39]. Finally, mackerel icefish, *Champsocephalus gunnari* are caught in low volumes (<3000 t yr^{-1}) by trawl fisheries operating in shelf areas around subantarctic islands (currently only South Georgia and Heard Island).

The Commission was not established to specifically manage the impacts of climate change, and the expertise within its Working Groups focuses upon harvested species, selected dependent predators, and changes in the ecosystem. However, within its ecosystem approach and under Article II of the Convention, CCAMLR is required to take into account the effects of environmental changes, a prescient consideration back in the early 1980 s. In recent years, information on the impacts of climate-driven change on Southern Ocean ecosystems has become increasingly important for CCAMLR and the wider ATS [35,44,76]. The Southern Ocean is amongst the most rapidly changing oceans of the world [54,58,80], with physical changes affecting ecosystem structure and processes (Box 2). It is therefore imperative that climate-driven ecosystem change, as well as the demand for fishery resources, is factored into the conservation and management of Southern Ocean species and ecosystems (e.g., [13,14,20,21,61,62,70,68,76,82]).

In 2008, the Scientific Committee recognised that climate change may be important for management and asked its Working Groups to further consider the issue. It was agreed that there were three key areas of work required to enable the Scientific Committee to provide specific advice to the Commission on appropriate management responses to climate change ([71], paragraph 7.14), that would ensure the objectives of the Convention are met. These are:

(i) "to examine the robustness of the scientific advice provided by the Scientific Committee and the stock assessments prepared by its Working Groups in the face of increasing uncertainty accompanying climate change, particularly in relation to predictions of future population responses and recruitment levels;
(ii) to examine the need for, and implement as appropriate, improvements to current monitoring programmes of harvested species and dependent and related species to provide robust and timely indicators of climate change impacts;
(iii) to determine whether CCAMLR's management objectives and performance indicators require modification to remain appropriate in the face of climate change uncertainty."

Subsequently, the Commission also recognised the urgency of appropriate management responses to climate change, including adopting a Climate Change Resolution in 2009 [15]. This Resolution recognised that global climate change is one of the greatest challenges facing the Southern Ocean and urges increased consideration of climate change impacts to better inform CCAMLR management decisions. For

Box 2
Summary of processes by which environmental change can impact Southern Ocean ecosystems.

Antarctic biota is highly specialised and adapted to the polar environment and seasonality over long evolutionary timescales [3,22,38]. The species and the ecosystems of which they are a part are strongly influenced by a range of physical drivers that interact and exert complex multi-directional effects throughout the food web, modifying structure and processes such as productivity, species distribution and connectivity [27,59,60,78,37,13,55].

Temperature.

Atmospheric temperatures affect heat input to the ocean and influence meltwater. Species vary in their thermal tolerance, and temperature has a major role in polar ecological processes, including primary productivity, growth, metabolism, thermoregulation, life cycles, reproductive success, species assemblages and distribution [65].

Ocean acidification.

At high latitudes, the cold surface ocean absorbs more CO_2 from the atmosphere. Increased CO_2 uptake causes acidification and conditions can become corrosive for calcium carbonate shell-producing organisms, with associated impacts on marine organisms and ecosystems [31,40].

Wind.

Wind velocities, strength and position influence circulation, stratification, mixed layer depth (MLD), nutrient transport, oceanic carbon and oxygen uptake and storage, sea surface temperature and sea ice, all of which have ecological importance. For example, the effects of winds on MLD have been linked to major changes in phytoplankton biomass and community composition [30]. Wind also directly influences the distribution of species such as oceanic seabirds that rely on it to move between breeding and foraging sites [83].

Ocean circulation.

The Antarctic Circumpolar Current (ACC) and its frontal systems, including circulating bodies of water known as eddies and gyres, has a key role in ecological processes such as nutrient cycling and primary production (e.g., eddies and gyres concentrate productivity in particular areas). It also influences species' distributions (e.g., larval dispersal) and foraging strategies for some species are associated with frontal dynamics [7,81].

Sea ice, retreating glaciers, ice sheets and ice shelf loss.

The annual seasonal advance and retreat of Antarctic sea ice influences physical conditions including the release of freshwater, ocean stratification, light availability, vertical mixing and temperature. It also provides crucial habitat for many species [53]. Carbon uptake and storage by Antarctic benthic communities is predicted to increase with sea ice losses [4,5]. Changes to glaciers, ice sheets, and ice shelves are also important, e.g., iceberg calving can create new habitats for biological colonisation [9,49], as well as scouring of the seabed [45]. Furthermore, both glacial ice and sea ice can form a physical barrier, either allowing or restricting the movement and access of species.

over a decade now, CCAMLR has recognised the importance of integrating relevant climate change research into its work (e.g., see [15,72], paragraphs 8.1–8.24). This recognition has been greatly influenced by the increasing body of research undertaken in this area by national and international programmes, including the Scientific Committee on Antarctic Research (SCAR), e.g., SCAR's Southern Ocean Observing System (SOOS; also overseen by the Scientific Committee on Oceanic Research (SCOR)), and the Integrated Climate and Ecosystem Dynamics in the Southern Ocean (ICED) programme (co-sponsored by SCAR and the Integrated Marine Biosphere Research (IMBeR) programme) [57,63]. These programmes have endeavoured to link closely with the Scientific Committee in this regard (e.g. [35,62]). Moreover, much of this research contributed to the syntheses and assessments in recent IPCC reports, including the SROCC [46,48].

However, despite the wealth of research that has been undertaken and the recognition of its importance, very little progress has been made to integrate climate change into CCAMLR's decision-making, and in recent years discussions have stalled [32,84]. There is a pressing need to ensure that not only does climate change remain on the agenda, but that it becomes a major factor underpinning policy making and decisions, as required in the Convention text. Challenges for CCAMLR include the need to inform (i) how projected environmental changes may affect future fisheries and management practices [20,41,62,66,68,76,82]; (ii) principles and methodology for monitoring both change and the efficacy of management measures [8,28]; (iii) existing fishery management measures based on assessments of current and potential future climate-driven change [77]; (iv) development of spatial management tools, such as climate-smart Marine Protected Areas (MPAs) with associated Research and Monitoring Plans [43,75,85]; and (v) development of a revised krill fishery management strategy [19].

Acknowledging that SROCC was commissioned by UN governments (which includes all CCAMLR Member governments) to provide the rigorous scientific basis upon which informed policy decisions could be made, and recognising that its findings will be useful in informing CCAMLR's discussion of possible future monitoring and management actions in the context of climate change impacts, the relevant findings of SROCC for CCAMLR are extracted and summarised here. In line with the ecosystem approach, the focus is on harvested species, including Antarctic krill and toothfish, as well as associated and dependent species, in terms of environmental changes, observed and projected ecological impacts of these changes, and management response options. In addition, acknowledging that IPCC assessments cannot provide policy advice (only the scientific advice upon which policy can be made), the findings are used to provide recommendations to CCAMLR, with the aim of ensuring that management becomes proactive and responsive to the effects of climate change.

2. Materials and methods

Within its ecosystem approach to management, it is important for CCAMLR to understand how climate-driven change will affect harvested, dependent and related populations, and what this will mean for the fisheries that target these species and how they are managed. Key findings to help inform CCAMLR in this regard were extracted from SROCC (see Supplementary Material, Table S1), particularly Chapter 3 on the Polar Regions [58]. The information extracted was based on questions identified by CCAMLR's Working Groups (see Supplementary Material, Table S2) with the following criteria: (i) geographical (Antarctic information, with a particular focus on the Convention Area); (ii) key drivers of change (sea ice, ocean temperature, acidification, winds and circulation, see Box 2); (iii) key species (mainly harvested and CEMP species, see above and Supplementary Material, Table S3); (iv) response options relevant to the management of Southern Ocean fisheries and ecosystems. Refer to Table S1 for these extracted statements, noting that those of particular importance with respect to the above criteria are highlighted in bold. For ease of reference, the information in Table S1 is organised as overarching statements; Antarctic fish; Antarctic krill; CEMP species and other higher predators; and additional information from SROCC Chapter 5 on Changing Ocean, Marine Ecosystems, and Dependent Communities [6] and Chapter 6 on Extremes, Abrupt Changes and Managing Risk [25]. Statements that refer to the polar regions more generally, or to a combination of Arctic and Antarctic information, have been edited to remove Arctic-specific information where possible. Each statement in Table S1 has a cross-reference to the exact section of SROCC wherein further information and associated references can be found. A summary narrative drawing on these statements, and particularly those highlighted in bold, is provided in Section 3, summarising drivers of change; the effects of these on the marine ecosystem; and management responses. The wording in the summary narrative has been minimally edited from how the information is reported in SROCC, and only so that it works as a narrative. To aid cross-referencing, each of the statements in Table S1 are numbered, and these numbers are then referred to in brackets throughout the main text of the paper, enabling the reader to find the relevant statements and associated links to SROCC. It is acknowledged that many of the summary statements included in Table S1 and Section 3 mask the detailed temporal and spatial changes that have been observed over recent decades; that not all of the literature cited within SROCC is cited in this paper; and that information of broader relevance, on which we place less emphasis in this study, is included within SROCC, e.g. change in regions adjacent and connected to the Convention Area, and information about ecosystem services such as the blue carbon pathway. Therefore SROCC and associated literature should be consulted for more information. Supplementary Material Table S3 defines Representative Concentration Pathways (RCPs), which are the atmospheric carbon dioxide scenarios used by IPCC to investigate future climate change and its impacts. Table S3 also provides an explanation of IPCC confidence statements which are italicised throughout this paper. SROCC discusses knowledge gaps and uncertainty [1,58], as such the strongest conclusions can be drawn with regard to those statements assigned *high confidence* whereas those assigned *low confidence* require careful interpretation and further work. The IPCC is now developing its Sixth Assessment Report (AR6), due for release in 2022, and many of these issues will be progressed through this therefore continuing to engage with the IPCC process is key (Box 3).

3. Key information provided by SROCC of particular relevance to CCAMLR

SROCC is an extensive report; even the information of most relevance to CCAMLR's ecosystem approach is substantial and is therefore presented separately in Table S1 with a summary narrative provided here, capturing the main points on key drivers of change, the effects of these on the marine ecosystem, and management responses (see Section 2). It should be noted that references to Table S1 in this section, and throughout the rest of the paper, are references to specific statements from SROCC (see Section 2).

3.1. Summary of key environmental changes assessed in SROCC of particular relevance to CCAMLR

The polar regions are losing ice, and their oceans are changing rapidly (Table S1, a). The Antarctic ice sheet is losing mass, accelerating global sea level rise (Table S1, Statement 6). Overall, Antarctic sea ice cover exhibits no significant trend over the period of satellite observations (1979–2018). However, there has been considerable regional variability in trends, with a large decrease in sea ice in the Amundsen and Bellingshausen seas compensated to a degree by ice gain in the Weddell and Ross seas. Because Antarctic sea ice extent has remained below climatological values since 2016, there is still potential for longer-term changes to emerge (Table S1, Statement 5). There is *low confidence* in projections of Antarctic sea ice because of multiple anthropogenic

Box 3
Recommendations.

CCAMLR is encouraged to continue working towards including climate change considerations in developing its management procedures, and to accelerate the pace of this work to ensure that management is responsive to the effects of change, thereby reducing the risks of additional negative ecosystem impacts. To enhance the scientific foundation for decision-making with specific relevance to climate change, it is recommended that CCAMLR:

Assesses the risks climate change presents to its objectives using available information sources:

- Improves mechanisms to coordinate and undertake targeted activities in support of identifying and integrating relevant scientific research outputs on climate change into the work of the Scientific Committee and its Working Groups.
- Invites contributions from external experts to ensure access to additional relevant expertise as appropriate.
- Further develops mechanisms to ensure that CCAMLR is well informed about climate change research, particularly as the UN IPCC process continues to develop relevant outputs, including AR6 and all subsequent reports. This could involve the establishment of a standing Working Group on Climate Change that reports directly to the Scientific Committee.
- Encourages input by its Members to the IPCC process as authors and reviewers, as well as through contributions to the published literature.

Identifies the most important risks and aims to understand, reduce and manage these risks:

- Encourages research focused on the continued conservation of Southern Ocean ecosystems in a changing climate by facilitating relevant data collection and responding appropriately to relevant findings.
- Actively engages with SCAR, SOOS, ICED and other relevant bodies to develop priorities for scientific research (Fig. 3).
- Actively engages with organisations or others that manage vessels or assets that might increase opportunities for collection of relevant information, e.g., International Association of Antarctica Tour Operators (IAATO) and Association of Responsible Krill harvesting companies (ARK).
- Actively engages with diverse stakeholders to facilitate knowledge-exchange and consider stakeholder values in decision-making processes related to climate change and ecosystem based management.

Ensures timely responses to information about these risks, including what action will be taken:

- Develops a work programme with the specific aim of ensuring that the management of all CCAMLR managed fisheries incorporates planning and adaptation pathways that include short-, medium- and longer-term actions to minimise climate change impacts on harvested species and the ecosystem.

forcing (ozone and greenhouse gases) and complex processes involving the ocean, atmosphere, and adjacent ice sheet (Table S1, Statement 11).

There is *high confidence* that the Southern Ocean has continued to warm in recent years, being disproportionately and increasingly important in global ocean heat increase. In contrast to the Arctic, the Antarctic continent has seen less uniform temperature changes over the past 30–50 years, with warming over parts of West Antarctica and no significant overall change over East Antarctica, though there is *low confidence* in these changes given the sparse in situ records and large interannual to interdecadal variability (Table S1, Statement 2). Coupled Model Intercomparison Project Phase 5 (CMIP5, managed by the World Climate Research Programme) projections indicate that observed Southern Ocean warming trends will continue under RCP4.5 and RCP8.5 scenarios (see Table S3 for information on the different RCPs), leading to 1–3 °C warming by 2100 mostly in the upper ocean (Table S1, Statement 10).

The Southern Ocean is continuing to remove CO_2 from the atmosphere and to acidify (Table S1, Statement 1), and it is *very likely* that the Southern Ocean will experience year-round conditions of surface water undersaturation for mineral forms of calcium carbonate by 2100 under RCP8.5; under RCP2.6 the extent of undersaturated waters are reduced markedly. Imperfect representation of local processes and sea ice interaction in global climate models limit the ability to project the response of specific polar areas and the precise timing of undersaturation at seasonal scales (Table S1, Statement 13).

Circumpolar winds have strengthened in recent decades, but the ACC has shown minimal change in transport and position. However, the Southern Ocean eddy field has intensified, with current loops and vortices becoming stronger (Table S1, Statement 9). These trends are set to continue (Table S1, Statement 50); however, *low confidence* is ascribed to the CMIP5-based model projections of future Southern Ocean circulation and water mass properties. In terms of oxygen decline, the Southern Ocean (and the north Pacific) have shown the largest overall declines across the global oceans (*medium confidence*) (Table S1, Statement 51). Significant wave heights (the average height from trough to crest of the highest one-third of waves) are projected to increase across the Southern Ocean (*high confidence*), and extreme waves are projected to increase under RCP4.5 and RCP8.5 (*high confidence*) (Table S1, Statements 52,53).

3.2. Summary of key ecological changes assessed in SROCC of particular relevance to CCAMLR

Fig. 2 provides a visual summary of key drivers that are causing or projected to cause direct effects on Southern Ocean marine ecosystems. Climate-induced changes in ocean and sea ice have contracted the range of polar fish and ice-associated species (*high confidence*), e.g., there has been a southward shift in the distribution of Antarctic krill in the South Atlantic, the main area for the krill fishery (*medium confidence*) (Table S1, Statement 4). Although some recent analyses have not detected trends in long-term Antarctic krill abundance in parts of the South Atlantic sector, the spatial distribution and size composition of krill in this sector may already have changed in association with change in the sea ice environment (*medium confidence*) and may result in different regional trends in numerical krill abundance (*medium confidence*) (Table S1, Statement 31). Since AR5, there has been an increasing body of evidence of climate-induced changes in populations of some Antarctic higher predators such as seabirds and marine mammals. These changes vary between different regions of the Southern Ocean and reflect differences in key drivers, particularly sea ice extent and food

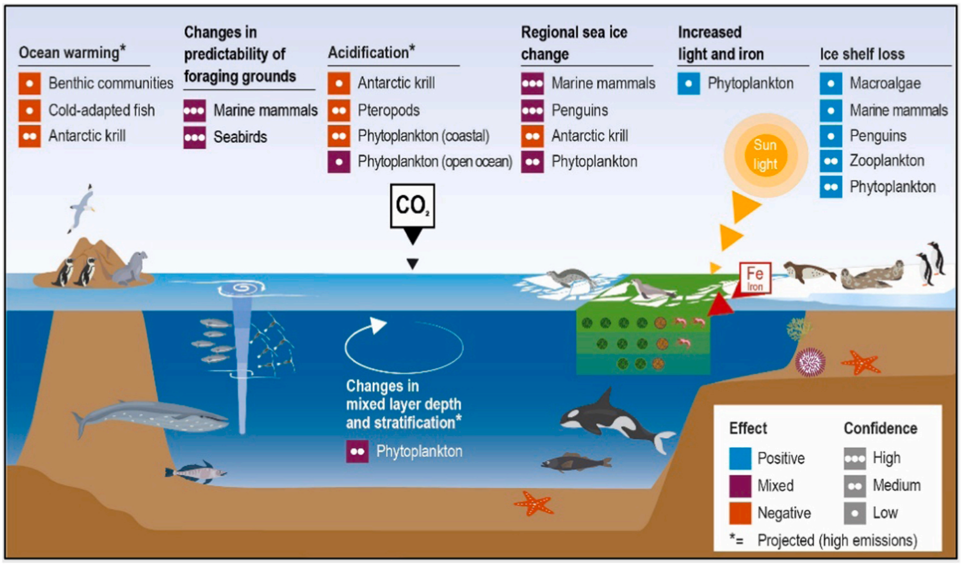

Fig. 2. Schematic summary of key drivers that are causing or are projected to cause direct effects on Southern Ocean marine ecosystems. Projected changes (indicated by an asterisk) are for high emissions scenarios. The cross-sectional view of the Southern Ocean ecosystem shows the association of key functional groups (marine mammals, birds, fish, zooplankton, phytoplankton and benthic assemblages) with Southern Ocean habitats.
(Source: Figure 3.6, [58]).

availability (*high confidence*) across regions (Table S1, Statements 35–43). In addition to these direct effects on krill, fish and higher predator species, there are numerous indirect effects, for example, observed changes in seasonal sea ice extent and thickness and ocean stratification are altering marine primary production (*high confidence*) with impacts on ecosystems (*medium confidence*). Changes in the timing, duration and intensity of primary production have occurred in both polar oceans, with marked regional or local variability (*high confidence*). In the Antarctic, such changes have been associated with locally rapid environmental change, including retreating glaciers and sea ice change (*medium confidence*) (Table S1, Statement 3). Rates of calcification (by which marine organisms form hard skeletons and shells) declined in the Southern Ocean by $3.9 \pm 1.3\%$ between 1998 and 2014 (Table S1, Statement 1). Differences in sensitivity and the scope for adaptation to projected levels of ocean acidification exist across a broad range of marine species groups. (Table S1, Statement 13).

Future climate-induced changes in the Southern Ocean will drive habitat and biome shifts, with associated changes in the ranges and abundance of ecologically important species (*medium confidence*). Projected shifts include further habitat contraction and changes in species abundance, including marine mammals, birds, fish, and Antarctic krill (*medium confidence*) (Table S1, Statement 14). The distribution of Antarctic krill is expected to change under future climate change because of changes in the location of the optimum conditions for growth and recruitment. The optimum conditions for krill are predicted to move southwards (*medium confidence*). The greatest projected reductions in krill due to the effects of warming and ocean acidification are predicted for the Southwest Atlantic/Weddell Sea region (*low confidence*), which is the area of highest current krill concentrations, contains important foraging grounds for krill predators, and is also the main area of operation of the krill fishery (Table S1, Statement 32). Ecosystem model results suggest that the effects of warming on krill growth off the Antarctic Peninsula and in the Scotia Sea translate to increased risks of declines in krill predator populations, particularly penguins, under both RCP2.6 and RCP8.5. (Table S1, Statement 47). Future warming may reduce the planktonic duration and increase egg and larval mortality for fish species. This is predicted to affect dispersal patterns, with potential consequences such as reduced population connectivity, which may in turn affect the ability of fish species to adapt to ongoing environmental change (Table S1, Statement 23–27). Given differences in temperature tolerances for Patagonian toothfish (with a wide temperature tolerance) and Antarctic toothfish (limited by a low tolerance for water temperatures above 2 °C), the latter may be faced with reduced habitat and potential competition with southward-moving Patagonian toothfish under climate change (*very low confidence*) (Table S1, Statement 28). These differences in temperature tolerance of toothfish may have implications for future fisheries, for example if changes in species distribution occur or recruitment is affected (Table S1, Statement 29).

3.3. *Information provided by SROCC on Southern Ocean ecosystem management*

SROCC notes that the principles of the ecosystem approach to fisheries management are embedded within the CCAMLR Convention (Table S1, Statement 19), and that innovative tools and practices in polar resource management and planning show strong potential in improving capacity to respond to climate change (*high confidence*). (Table S1, Statement 17). These include adaptive management that combines annual measures and within-season provisions informed by assessments of future ecosystem trends to reduce the risks of negative climate change impacts on polar fisheries (*medium confidence*) (Table S1, Statement 15), and CEMP, which aims to monitor important land-based krill predators to detect the effects of the krill fishery on the ecosystem. Currently, there is no formal mechanism for choosing which data are needed in a management procedure for krill or how to include such data. However, this information will be important in enabling CCAMLR fisheries management to respond to the effects of climate change on krill and krill predators in the future (Table S1, Statement 19); and developing pathways for spatial resilience involving systematic planning and designating networks of protected areas to protect connected tracts of representative habitats, and biologically and ecologically significant features. Protected area networks that combine both spatially rigid and spatially flexible regimes with climate refugia can support ecological resilience to climate change by maintaining connectivity of populations, food webs, and the flow of genes across scales. This approach reduces direct pressures on biodiversity, and thus gives biological communities, populations and ecosystems the space to adapt (*medium confidence*). The planning of protected area networks is currently an active topic of international collaboration in both polar regions (Table S1, Statement 21).

Furthermore, commercial fisheries management responses to climate change impacts in the Southern Ocean may need to address the displacement of fishing effort due to poleward shifts in species distribution (*low confidence*). Fisheries in the Southern Ocean are relatively mobile and are potentially able to respond to range shifts in target species. Management responses will also need to adapt to the effects of future changes in sea ice extent and duration on the spatial distribution of fishing operations (Table S1, Statement 20), and to the effects of changing wave intensity on the safety and feasibility of fishing operations (Table S1, Statements 52,53).

4. Discussion and recommendations

SROCC can be used by CCAMLR as a compendium of peer-reviewed and robust scientific information and understanding about climate change, and its impact on the ecosystem that CCAMLR is tasked by international agreement to conserve and manage. However, SROCC is an assessment and does not replace the detailed scientific research and activities undertaken by the wider scientific community (Fig. 3). While it is imperative that the information in SROCC is understood and acted upon by decision-makers, this undoubtedly remains a challenge for CCAMLR. It is likely that bodies with responsibilities for managing fishery resources in other regions of the world, with their proliferating remits and limited capacity, will also find this challenging.

SROCC, as with all IPCC assessments, is prohibited from being policy prescriptive. As such it cannot advise policymakers on what they should do and can only comment on potential outcomes of different policy decisions. Therefore, in summarising relevant information from SROCC and translating this into recommendations to CCAMLR, this paper helps bridge this gap to effective policymaking and policy implementation in the context of climate change impacts on Southern Ocean ecosystems and fisheries. This approach could be replicated for other regional marine resource management bodies to help maximise the impact of IPCC assessments in supporting decision-making and management for marine systems around the world.

The relevance of SROCC findings to CCAMLR's ecosystem approach to management are clear. The ecological effects of climate-driven change include alterations to key ecosystem structure and processes, including primary production (*high confidence*) (Table S1, Statement 3); range contractions of polar fish and ice-associated species (*high confidence*) (Table S1, Statement 4); and changes to life history traits, morphological, physiological and behavioural characteristics of top predators, as well as their patterns of activity (migration, distribution, foraging and reproduction) (*high confidence*) (Table S1, Statement 38). Furthermore, changes such as projected increases in wave heights and extreme waves (*high confidence*) will need to be factored into risk assessments of future fishery operations (Table S1, Statements 52,53). SROCC emphasises that the projected effects of climate-induced stressors on polar marine ecosystems present risks for commercial fisheries with implications for economies and the global supply of fish and Antarctic krill (*high confidence*) (Table S1, Statement 15, see also Fig. S1). Specific impacts will depend on both the nature and effects of future climate change and on the strategies employed to manage the effects on harvested species and the ecosystems that support them (*medium confidence*) (Table S1, Statement 15).

Key advice from SROCC is that actions to prepare for, and minimise the negative impacts of climate change are more likely to be successful if they include (i) flexible policies for adaptive ecosystem governance, that allow adjusting responses to complex ecosystem impacts caused by different climate change scenarios and extreme events; (ii) short-term risk reduction (adaptation) concurrent with long-term planning to build resilience to address expected and unexpected impacts; and (iii) enhanced systems to monitor key processes and changes, to inform/update flexible policies.

CCAMLR has several existing tools and strategies that have the potential to address the above three points; some of these are mentioned in SROCC (Section 3.3 above). To support the development and implementation of these management tools, CCAMLR is able to draw upon a broad range of research and advice via the Scientific Committee and its Working Groups. This advice is typically contributed by its Members, and increasingly involves collaborative and international science programmes such as SCAR, ICED and SOOS. Interactions between CCAMLR and relevant science bodies, as well as with the IPCC, can help to define priorities for further work (Fig. 3), and development of these relationships will continue to benefit management.

In terms of flexible policies that allow adjusting responses to ecosystem impacts, CCAMLR's framework of Conservation Measures provides for new management measures to be implemented or revised by the Commission on a regular basis, based on advice from the Scientific Committee and its Working Groups. Such measures can include the definition of catch limits or closed areas as well as the spatial distribution of catches within larger areas, and further use of these tools could contribute to short-term risk reduction and adaptation, if based on scientific evidence available at the appropriate temporal and spatial scales. A recent agreement to provide interim protection for marine areas exposed by ice shelf retreat or collapse is also designed to facilitate scientific study in these areas in the short term, which may inform additional protection and help further understanding of the ecological implications of climate change impacts [77]. Longer-term planning to

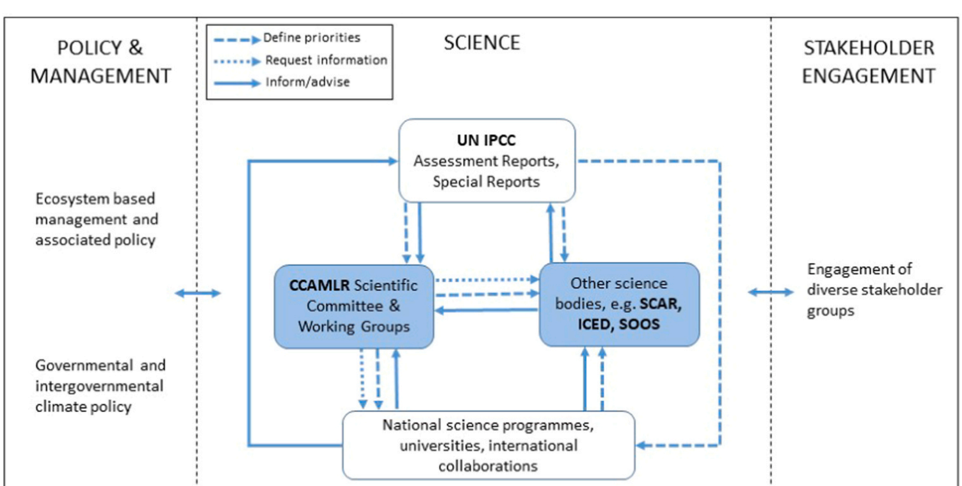

Fig. 3. Interactions between CCAMLR, other science bodies and the IPCC, including iterative processes where requests for information result in the provision of advice. IPCC assessments and special reports, including SROCC, do not replace the detailed scientific research and activities undertaken by CCAMLR and the Southern Ocean research community; rather SROCC has assimilated their findings to provide a state-of-the-art assessment that can inform their ongoing activities as well as influencing policy. Further development of the relationships between these bodies and the IPCC, and improved mechanisms for communication and the flow of information, will continue to enhance Southern Ocean management. Side boxes on policy & management and on stakeholder engagement show the connections of this system for scientific assessment to decision making and to diverse stakeholder groups beyond the scientific community, including industry, conservation organisations and the wider public.

build resilience includes the establishment of MPAs, as recognised by the objectives for MPAs set out by CCAMLR which include "the protection of areas to maintain resilience or the ability to adapt to the effects of climate change" (CCAMLR Conservation Measure 91–04, [17]). CCAMLR's implementation of the ecosystem approach to date has focused mainly on the trophic relationships between predators and prey [26], while work towards a representative network of MPAs [11] indicates a recognition that spatial processes are also important. The degree of spatial connectivity within and between ecosystems is a major influence on their resilience to impacts ([29]; see also Table S1, Statement 21). Positive and negative effects of connectivity are both possible. Examples of positive effects include the ability of connected populations to recolonise impacted habitats, as Antarctic fur seals recolonised South Georgia following over exploitation [64]. Examples of negative effects include the rapid spread of invasive species or disease. Understanding of the spatial structure and connectivity of Southern Ocean ecosystems is incomplete. For example, for the purposes of management and many ecological studies, the circumpolar population of Antarctic krill is divided into broad longitudinal sectors [50,86], whereas genomic studies suggest a homogenous circumpolar population and bacterial epibiont communities suggest a high level suggest a high level of spatial structure at the scale of a few hundred kilometres [23]. In projection models, krill population connectivity mediates the propagation of climate change effects through the foodweb such that impacts on krill in one location affect predators in other locations [51]. Improved understanding of key aspects of connectivity, including beyond the Convention Area, and how they contribute to resilience should be a research priority [63].

CCAMLR has agreed two MPAs to date, at the South Orkney Islands (CCAMLR Conservation Measure 91–03, [16]) and the Ross Sea region (CCAMLR Conservation Measure 91–05, [18]) (Fig. 1), and proposals for new MPAs in the Weddell Sea, the Antarctic Peninsula and East Antarctica are under discussion. In particular, the proposed Antarctic Peninsula MPA is designed to protect key life-history stages of various species, including under climate change scenarios, and aims to establish scientific reference areas to evaluate the potential impacts of climate change on the marine ecosystem [74].

The process for reviewing and revising MPAs, including with the use of scientific reference areas, is critical to ensuring their effectiveness, particularly in response to the impacts of a changing climate. Well-designed MPA Research and Monitoring Plans provide a framework for the collection and analysis of new information, assessment of specific threats to biodiversity and evaluation of change, including with the use of relevant baseline data and indicators where possible. Indicators can be based on metrics that assess aspects such as recruitment and recovery, as well as adaptive capacity, and should be specific to the objectives of a particular MPA [56,85]. MPA review processes can therefore use this information to develop enhanced and responsive management, which may include the consideration of revised boundaries to ensure that features associated with specific objectives remain adequately protected into the future.

Other localised actions can complement MPAs, such as the designation of Vulnerable Marine Ecosystems (VMEs), increasing resilience by reducing or removing the negative impact from other drivers [9,36]. In response to a United Nations General Assembly Resolution to close areas to bottom fisheries until appropriate measures have been put in place to prevent significant adverse impacts on VMEs, a suite of measures was adopted by CCAMLR [69]. There are now over 50 registered VMEs across the Convention Area [36], and VME indicator taxa include those with high carbon storage potential, such as cold water corals [9]. The prohibition of all bottom trawling activities in the Convention Area reduces impacts on benthic ecosystems, bringing a range of benefits including protection of biodiversity which in turn plays a role in climate regulation via the blue carbon pathway [4,5,14,33].

CCAMLR also has other systems in place that can be used to monitor change and deliver the scientific information required to inform and update flexible policies. For example, CEMP was established to monitor ecosystem change and help identify the ecosystem effects of krill fishing, and stock assessment models are regularly updated with new information to set catch limits for the toothfish fishery. Enhancement of these systems to consider the impacts of climate change would be beneficial in providing further support to adaptive decision-making. A review of CEMP (as recently proposed by Members) would provide a timely opportunity to ensure that its remit expands to include detection and attribution of climate change effects on the ecosystem.

In 2019, CCAMLR agreed a new framework for managing the fishery for Antarctic krill, which includes the use of a risk-based approach [19]. As it develops, the new framework will need to evaluate not only risks to the fishery and to the krill stock itself, but also to krill-dependent predators and other ecosystem components. Importantly, however, it will also need to integrate considerations related to marine spatial planning, recovery of previously over-exploited taxa, and climate change. The initial work to implement the new framework will therefore need to expand in scope, moving towards true ecosystem-based fisheries management (sensu [52]). In time, appropriate spatial management (i.e., open and closed areas) must be fully integrated with CCAMLR's krill management framework to adequately protect and conserve the marine ecosystem. Further, as spatial management can also facilitate the designation of scientific research, or reference areas, such areas will be important in disentangling harvesting and climate change as drivers of ecological change.

SROCC states that the capacity of governance systems in polar regions to respond to climate change has strengthened recently, but that the development of these systems is not sufficiently rapid or robust to address the challenges and risks to societies posed by projected changes (*high confidence*) (Table S1, Statement 18). While CCAMLR's existing management framework includes a range of tools providing the capacity to respond to climate change [67], further work is needed to ensure that this becomes fully operationalised [32]. CCAMLR has a substantial workload, and although climate change has been identified as a specific item in its meeting agendas for more than a decade, there is often limited time for detailed discussion, as well as a lack of relevant climate science expertise. Discussions on climate change in international fora have often stalled or been derailed for political reasons, with CCAMLR no exception [67,84]. However, efforts to improve the scientific background to these discussions, including through utilisation of IPCC output, may help to remove some of these obstacles, and would have significant benefits for management. Specific recommendations on how CCAMLR might achieve this in practice are provided below (Box 3).

Strengthening scientific information flow to inform CCAMLR's decision-making on climate change is an important step but is not the whole picture. Engaging with diverse stakeholder groups beyond the scientific community, including industry, conservation organisations and the wider public, is important to facilitate knowledge-exchange and action on climate change ([12,73]; Table S1, Statement 16). As human-driven pressures on the region increase [10,21,36], so too will the demand for, and importance of, Southern Ocean ecosystem services which provide a range of benefits to society [14,70]. While the management measures discussed above are important, e.g. MPAs can help to protect multiple ecosystem services such as harvested species, the blue carbon pathway and tourism, CCAMLR's actions alone cannot prevent climate-driven changes to Southern Ocean ecosystems. Integrated management across the ATS is needed, as well as cooperation between CCAMLR and neighbouring RFMOs, and with international conservation agreements [84]. Above all, global policy and action on climate change must be implemented.

In 2021, CCAMLR is set to convene its annual meetings prior to the 26th UN Climate Change Conference of the Parties (COP26) that will bring together heads of state, climate experts and campaigners to attempt to agree further coordinated action to tackle climate change. It is vital that CCAMLR, as an integral part of the ATS, demonstrates that it is addressing the implications of climate change on the conservation and protection of Antarctica. Having pioneered the ecosystem approach to fisheries management four decades ago, CCAMLR now has the potential to provide further leadership by integrating climate change into its management and policy-making.

CRediT authorship contribution statement

Rachel D. Cavanagh: Conceptualization, Methodology, Writing - original draft, Supervision. **Philip N. Trathan**: Conceptualization, Methodology, Writing - original draft. **Susie M. Grant**: Conceptualization, Methodology, Visualisation, Writing - original draft. All other authors: Writing - review & editing.

Acknowledgements

The British Antarctic Survey authors (RC, SG, PH, SH, EM, JT and PT) are supported by Natural Environment Research Council (NERC): NERC/BAS Ecosystems ALI-Science funding. The participation of MM was funded by NERC via award NE/N018095/1 and via the EU under grant agreement 821001.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2021.104589.

References

[1] N. Abram, J.-P. Gattuso, A. Prakash, L. Cheng, M.P. Chidichimo, S. Crate et al., Framing and Context of the Report. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E. et al. (eds.)], 2019. https://www.ipcc.ch/srocc/ (accessed February 2021).
[2] D.J. Agnew, The CCAMLR ecosystem monitoring programme, Ant. Sci. 9 (3) (1997) 235–242, https://doi.org/10.1017/S095410209700031X.
[3] D.K.A. Barnes, L.S. Peck, Vulnerability of Antarctic shelf biodiversity to predicted regional warming, Clim. Res. 37 (2008) 149–163, https://doi.org/10.3354/cr00760.
[4] D.K.A. Barnes, A. Fleming, C.J. Sands, M.L. Quartino, D. Deregibus, Icebergs, sea ice, blue carbon and Antarctic climate feedbacks, Philos. Trans. A Math. Phys. Eng. Sci. 376 (2018), 20170176, https://doi.org/10.1098/rsta.2017.0176.
[5] N. Bax, C.J. Sands, B. Gogarty, R.V. Downey, C.V.E. Moreau, B. Moreno, C. Held, M.L. Paulsen, J. McGee, M. Haward, D. Barnes, Perspective: Increasing blue carbon around Antarctica is an ecosystem service of considerable societal and economic value worth protecting, Glob. Change Biol. 27 (2021) 5–12, https://doi.org/10.1111/gcb.15392.
[6] N.L. Bindoff, W.W.L. Cheung, J.G. Kairo, J. Arístegui, V.A. Guinder, R. Hallberg et al., Changing Ocean, Marine Ecosystems, and Dependent Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E. et al. (eds.)], 2019. ⟨https://www.ipcc.ch/srocc/⟩ (accessed May 2021).
[7] C.A. Bost, C. Cotté, F. Bailleul, Y. Cherel, J.B. Charrassin, C. Guinet, D.G. Ainley, H. Weimerskirch, The importance of oceanographic fronts to marine birds and mammals of the Southern Oceans, J. Mar. Syst. 78 (2009) 363–376, https://doi.org/10.1016/j.jmarsys.2008.11.022.
[8] M.J. Brasier, A. Constable, J. Melbourne-Thomas, R. Trebilco, H. Griffiths, A. Van de Putte, M. Sumner, Observations and models to support the first Marine Ecosystem Assessment for the Southern Ocean (MEASO), J. Mar. Syst. 197 (2019), 103182.
[9] M.J. Brasier, D. Barnes, N. Bax, A. Brandt, A.B. Christianson, A.J. Constable, R. Downey, B. Figuerola, H. Griffiths, J. Gutt, S. Lockhart, S.A. Morley, A.L. Post, A. Van de Putte, H. Saeedi, J.S. Stark, M. Sumner, C.L. Waller, Responses of southern ocean seafloor habitats and communities to global and local drivers of change, Front. Mar. Sci. 8 (2021), https://doi.org/10.3389/fmars.2021.622721.
[10] S.T. Brooks, J. Jabour, J. van den Hoff, D.M. Bergman, Our footprint on Antarctica competes with nature for rare ice-free land, Nat. Sustain 2 (2019) 185–190, https://doi.org/10.1038/s41893-019-0237-y.
[11] C.M. Brooks, S.L. Chown, L.L. Douglass, B.P. Raymond, J.D. Shaw, Z.T. Sylvester, C.L. Torrens, Progress towards a representative network of Southern Ocean protected areas, PLoS One 15 (4) (2020), 0231361, https://doi.org/10.1371/journal.pone.0231361.
[12] R.D. Cavanagh, S.L. Hill, C.A. Knowland, S.M. Grant, Stakeholder perspectives on ecosystem-based management of the Antarctic krill fishery, Mar. Policy 68 (2016) 205–211, doi: 10.1016/j.marpol.2016.03.006.
[13] R.D. Cavanagh, E.J. Murphy, T.J. Bracegirdle, J. Turner, C.A. Knowland, S. P. Corney, W.O. Smith, C.M. Waluda, N.M. Johnston, R.G.J. Bellerby, A. J. Constable, D.P. Costa, E.E. Hofmann, J.A. Jackson, I.J. Staniland, D. Wolf-Gladrow, J.C. Xavier, A Synergistic approach for evaluating climate model output for ecological applications, Front. Mar. Sci. 4 (2017) 308, https://doi.org/10.3389/fmars.2017.00308.
[14] R.D. Cavanagh, J. Melbourne-Thomas, S.M. Grant, D.K.A. Barnes, K.A. Hughes, S. Halfter, M.P. Meredith, E.J. Murphy, R. Trebilco, S.L. Hill, Future risk for southern ocean ecosystem services under climate change, Front. Mar. Sci. 7 (2021), 615214, https://doi.org/10.3389/fmars.2020.615214.
[15] CCAMLR, Resolution 30/XXVIII. 2009. https://www.ccamlr.org/en/resolution-30/xxviii-2009 (accessed February 2021).
[16] CCAMLR, Protection of the South Orkney Islands southern shelf. CCAMLR Conservation Measure 91–03, 2009. https://www.ccamlr.org/sites/default/files/91–03_9.pdf (accessed February 2021).
[17] CCAMLR, General Framework for the Establishment of CCAMLR Marine Protected Areas. CCAMLR Conservation Measure 91–04, 2011. https://www.ccamlr.org/en/measure-91–04-2011 (accessed February 2021).
[18] CCAMLR, Ross Sea region marine protected area. CCAMLR Conservation Measure 91–05, 2016. https://www.ccamlr.org/sites/default/files/91–05_11.pdf (accessed February 2021).
[19] CCAMLR, Report of the Thirty-Eighth meeting of the Commission, CCCAMLR-38, paragraphs 5.17 to 5.20. CCAMLR, Hobart, Australia, 2019. ⟨https://www.ccamlr.org/en/system/files/e-cc-38_1.pdf⟩ (accessed February 2021).
[20] W.W.L. Cheung, V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, D. Zeller, D. Pauly, Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change, Glob. Change Biol. 16 (2010) 24–35, https://doi.org/10.1111/j.1365-2486.2009.01995.x.
[21] S.L. Chown, C.M. Brooks, The state and future of Antarctic environments in a global context, Annu. Rev. Environ. Resour. 44 (2019) 1–30, https://doi.org/10.1146/annurev-environ-101718-033236.
[22] A. Clarke, N.M. Johnston, E.J. Murphy, A.D. Rogers, Introduction. Antarctic ecology from genes to ecosystems: the impact of climate change and the importance of scale, Philos. Trans. R. Soc. Lond. B. Biol. Sci. 362 (2007) 5–9, https://doi.org/10.1098/rstb.2006.1943.
[23] L.J. Clarke, L. Suter, R. King, A. Bisset, S. Bestley, B.E. Deagle, Bacterial epibiont communities of panmictic Antarctic krill are spatially structured (doi.org/), Mol. Ecol. 30 (2021) 1042–1052, https://doi.org/10.1111/mec.15771.
[24] M.A. Collins, P. Brickle, J. Brown, M. Belchier, The Patagonian toothfish: biology, ecology and fishery, Adv. Mar. Biol. 58 (2010) 227–300, https://doi.org/10.1016/B978-0-12-381015-1.00004-6.
[25] M. Collins, M. Sutherland, L. Bouwer, S.-M. Cheong, T. Frölicher, H. Jacot Des Combes et al., Extremes, Abrupt Changes and Managing Risk. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E. et al. (eds.)], 2019. ⟨https://www.ipcc.ch/srocc/⟩ (accessed May 2021).
[26] A.J. Constable, Lessons from CCAMLR on the implementation of the ecosystem approach to managing fisheries, Fish Fish. 12 (2011) 138–151, https://doi.org/10.1111/j.1467-2979.2011.00410.x.
[27] A.J. Constable, J. Melbourne-Thomas, S.P. Corney, K.R. Arrigo, C. Barbraud, D. K. Barnes, N.L. Bindoff, P.W. Boyd, A. Brandt, D.P. Costa, A.T. Davidson, H. W. Ducklow, L. Emmerson, M. Fukuchi, J. Gutt, M.A. Hindell, E.E. Hofmann, G. W. Hosie, T. Iida, S. Jacob, N.M. Johnston, S. Kawaguchi, N. Kokubun, P. Koubbi, M.A. Lea, A. Makhado, R.A. Massom, K. Meiners, M.P. Meredith, E.J. Murphy, S. Nicol, K. Reid, K. Richerson, M.J. Riddle, S.R. Rintoul, Jr Smith WO, C. Southwell, J.S. Stark, M. Sumner, K.M. Swadling, K.T. Takahashi, P.N. Trathan, D.C. Welsford, H. Weimerskirch, K.J. Westwood, B.C. Wienecke, D. Wolf-Gladrow, S.W. Wright, J.C. Xavier, P. Ziegler, Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota, Glob. Change Biol. 20 (2014) 3004–3025, https://doi.org/10.1111/gcb.12623.
[28] A.J. Constable, D.P. Costa, O. Schofield, L. Newman, E.R. Urban, E.A. Fulton, J. Melbourne-Thomas, T. Ballerini, P.W. Boyd, A. Brandt, W.K. de la Mare, M. Edwards, M. Eléaume, L. Emmerson, K. Fennel, S. Fielding, H. Griffiths, J. Gutt, M.A. Hindell, E.E. Hofmann, S. Jennings, H.S. La, A. McCurdy, B.G. Mitchell, T. Moltmann, M. Muelbert, E. Murphy, A.J. Press, B. Raymond, K. Reid, C. Reiss, J. Rice, I. Salter, D.C. Smith, S. Song, C. Southwell, K.M. Swadling, A. Van de Putte, Z. Willis, Developing priority variables ("ecosystem Essential Ocean Variables" — eEOVs) for observing dynamics and change in Southern Ocean ecosystems, J. Mar. Syst. 161 (2016) 26–41, https://doi.org/10.1016/j.jmarsys.2016.05.003.
[29] V. Dakos, A. Quinlan, J.A. Baggio, E. Bennett, O. Bodin, S. Burnsilver, Principle 2 – manage connectivity. Principles for Building Resilience: Sustaining Ecosystem Services in Social-Ecological Systems, Cambridge University Press, Cambridge, UK, 2019, pp. 80–104.
[30] S.L. Deppeler, A.T. Davidson, Southern ocean phytoplankton in a changing climate, Front. Mar. Sci. 4 (2017) 40, https://doi.org/10.3389/fmars.2017.00040.
[31] B. Figuerola, A.M. Hancock, N. Bax, V.J. Cummings, R. Downey, H.J. Griffiths, J. Smith, J.S. Stark, A review and meta-analysis of potential impacts of ocean acidification on marine calcifiers from the Southern Ocean, Front. Mar. Sci. 8 (2021) 22, https://doi.org/10.3389/fmars.2021.584445.
[32] L. Goldsworthy, E. Brennan, Climate change in the Southern Ocean: is the Commission for the Convention for the Conservation of Antarctic Marine Living Resources doing enough? Mar. Policy 130 (2021), 104549 https://doi.org/10.1016/j.marpol.2021.104549.
[33] B. Gogarty, J. McGee, D.K.A. Barnes, C.J. Sands, N. Bax, M. Haward, R. Downey, C. Moreau, B. Moreno, C. Held, M.L. Paulsen, Protecting Antarctic blue carbon: as marine ice retreats can the law fill the gap? Clim. Policy 20 (2020) 149–162, https://doi.org/10.1080/14693062.2019.1694482.

[34] S.M. Grant, S.L. Hill, P.N. Trathan, E.J. Murphy, Ecosystem services of the Southern Ocean: trade-offs in decision-making, Antarct. Sci. 25 (2013) 603–617, https://doi.org/10.1017/S0954102013000308.
[35] S.M. Grant, and P.A. Penhale, Conveners' Report of the Joint CEP/SC-CAMLR Workshop on Climate Change and Monitoring. SC-CAMLR-XXXV/07. SC-CAMLR XXXV, Hobart, Australia, 2016.
[36] Grant, S.M., Waller, C.L., Morley, S.A., Barnes, D.K.A., Brasier, M.J., Double, M.C., et al. (in press). Local drivers of change in Southern Ocean ecosystems: human activities and policy implications. Front. Mar. Sci.
[37] J. Gutt, N. Bertler, T.J. Bracegirdle, A. Buschmann, J. Comiso, G. Hosie, E. Isla, I. R. Schloss, C.R. Smith, J. Tournadre, J.C. Xavier, The Southern Ocean ecosystem under multiple climate change stresses–an integrated circumpolar assessment, Glob. Change Biol. 21 (2015) 1434–1453, https://doi.org/10.1111/gcb.12794 (in review). Local drivers of change in Southern Ocean ecosystems: human activities and policy implications. Front. Mar. Sci. Gutt, J., Bertler, N., Bracegirdle, T. J., Buschmann, A., Comiso, J., Hosie, G., et al.
[38] J. Gutt, E. Isla, J.C. Xavier, B.J. Adams, I.Y. Ahn, C.C. Cheng, C. Colesie, V. J. Cummings, G. di Prisco, H. Griffiths, I. Hawes, I. Hogg, T. McIntyre, K. M. Meiners, D.A. Pearce, L. Peck, D. Piepenburg, R.R. Reisinger, G.K. Saba, I. R. Schloss, C.N. Signori, C.R. Smith, M. Vacchi, C. Verde, D.H. Wall, Antarctic ecosystems in transition – life between stresses and opportunities, Biol. Rev. Camb. Philos. Soc. 96 (2021) 798–821, https://doi.org/10.1111/brv.12679.
[39] S. Hanchet, A. Dunn, S. Parker, P. Horn, D. Stevens, S. Mormede, The Antarctic toothfish (Dissostichus mawsoni): biology, ecology, and life history in the Ross Sea region, Hydrobiologia 761 (2015) 397–414, https://doi.org/10.1007/s10750-015-2435-6.
[40] S.F. Henley, E.L. Cavan, S.E. Fawcett, R. Kerr, T. Monteiro, R.M. Sherrell, A. R. Bowie, P.W. Boyd, D.K.A. Barnes, I.R. Schloss, T. Marshall, R. Flynn, S. Smith, Changing biogeochemistry of the Southern Ocean and its ecosystem implications, Front. Mar. Sci. 7 (2020) 581, https://doi.org/10.3389/fmars.2020.00581.
[41] R. Hilborn, T.P. Quinn, D.E. Schindler, D.E. Rogers, Biocomplexity and fisheries sustainability, Proc. Natl. Acad. Sci. U. S. A. 100 (11) (2003) 6564–6568, https://doi.org/10.1073/pnas.1037274100.
[42] S. Hill, From strategic ambiguity to technical reference points in the Antarctic krill fishery: the worst journey in the world, Environ. Conserv. 40 (2013) 394–504, https://doi.org/10.1017/S0376892913000088.
[43] M.A. Hindell, R.R. Reisinger, Y. Ropert-Coudert, L.A. Hückstädt, P.N. Trathan, H. Bornemann, J.B. Charrassin, S.L. Chown, D.P. Costa, B. Danis, M.A. Lea, D. Thompson, L.G. Torres, A.P. Van de Putte, R. Alderman, V. Andrews-Goff, B. Arthur, G. Ballard, J. Bengtson, M.N. Bester, A.S. Blix, L. Boehme, C.A. Bost, P. Boveng, J. Cleeland, R. Constantine, S. Corney, R. Crawford, L. Dalla Rosa, P. de Bruyn, K. Delord, S. Descamps, M. Double, L. Emmerson, M. Fedak, A. Friedlaender, N. Gales, M.E. Goebel, K.T. Goetz, C. Guinet, S.D. Goldsworthy, R. Harcourt, J.T. Hinke, K. Jerosch, A. Kato, K.R. Kerry, R. Kirkwood, G. L. Kooyman, K.M. Kovacs, K. Lawton, A.D. Lowther, C. Lydersen, P.O. Lyver, A. B. Makhado, M. Márquez, B.I. McDonald, C.R. McMahon, M. Muelbert, D. Nachtsheim, K.W. Nicholls, E.S. Nordøy, S. Olmastroni, R.A. Phillips, P. Pistorius, J. Plötz, K. Pütz, N. Ratcliffe, P.G. Ryan, M. Santos, C. Southwell, I. Staniland, A. Takahashi, A. Tarroux, W. Trivelpiece, E. Wakefield, H. Weimerskirch, B. Wienecke, J.C. Xavier, S. Wotherspoon, I.D. Jonsen, B. Raymond, Tracking of marine predators to protect Southern Ocean ecosystems, Nature 580 (2020) 87–92, https://doi.org/10.1038/s41586-020-2126-y.
[44] K.A. Hughes, A. Constable, Y. Frenot, J. López-Martínez, E. McIvor, B. Njåstad, A. Terauds, D. Liggett, G. Roldan, A. Wilmotte, J.C. Xavier, Antarctic environmental protection: strengthening the links between science and governance, Environ. Sci. Policy 83 (2018) 86–95, https://doi.org/10.1016/j.envsci.2018.02.006.
[45] J. Ingels, R.B. Aronson, C.R. Smith, A. Baco, H.M. Bik, J.A. Blake, et al., Erratum: Borderud SP, Li Y, Burkhalter JE, Sheffer CE and Ostroff JS. Electronic cigarette use among patients with cancer: characteristics of electronic cigarette users and their smoking cessation outcomes, Cancer 121 (2015) 800, https://doi.org/10.1002/wcc.682.
[46] IPCC, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K. and Meyer, L.A. (eds.)]. IPCC, Geneva, Switzerland, 2014; 151 pp. ⟨https://www.ipcc.ch/report/ar5/syr/⟩ (accessed February 2021).
[47] IPCC, Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P.R. et al. (eds.)]. IPCC, Geneva, Switzerland. 2018. https://www.ipcc.ch/sr15/ (accessed February 2021).
[48] IPCC, IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H.-O., Roberts D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E. et al. (eds.)]. IPCC, Geneva, Switzerland, 2019. ⟨https://www.ipcc.ch/srocc/⟩ (accessed February 2021).
[49] S. Kaiser, S.N. Brandão, S. Brix, D.K.A. Barnes, D.A. Bowden, J. Ingels, F. Leese, S. Schiaparelli, C.P. Arango, R. Badhe, N. Bax, M. Blazewicz-Paszkowycz, A. Brandt, N. Brenke, A.I. Catarino, B. David, C. De Ridder, P. Dubois, K. E. Ellingsen, A.G. Glover, H.J. Griffiths, J. Gutt, K.M. Halanych, C. Havermans, C. Held, D. Janussen, A.N. Lörz, D.A. Pearce, B. Pierrat, T. Riehl, A. Rose, C. J. Sands, A. Soler-Membrives, M. Schüller, J.M. Strugnell, A. Vanreusel, G. Veit-Köhler, N.G. Wilson, M. Yasuhara, Patterns, processes and vulnerability of Southern Ocean benthos: a decadal leap in knowledge and understanding, Mar. Biol. 160 (2013) 2295–2317, https://doi.org/10.1007/s00227-013-2232-6.
[50] S. Kawaguchi, S. Nicol, in: G. Lovrich, M. Thiel (Eds.), Fisheries and Aquaculture, Vol. 9, Oxford University Press, UK, 2020, pp. 137–158, https://doi.org/10.1093/oso/9780190865627.003.0006.
[51] E.S. Klein, S.L. Hill, J.T. Hinke, T. Phillips, G.M. Watters, Impacts of rising sea temperature on krill increase risks for predators in the Scotia Sea, PLoS One 13 (2018) 0191011, https://doi.org/10.1371/journal.pone.0191011.
[52] J.S. Link, H.I. Browman, Integrating what? Levels of marine ecosystem-based assessment and management, ICES J. Mar. Sci. 71 (5) (2014) 1170–1173, https://doi.org/10.1093/icesjms/fsu026.
[53] R.A. Massom, S.E. Stammerjohn, Antarctic sea ice change and variability – physical and ecological implications, Pol. Sci. 4 (2010) 149–186, https://doi.org/10.1016/j.polar.2010.05.001.
[54] P.A. Mayewski, M.P. Meredith, C.P. Summerhayes, J. Turner, A. Worby, P. J. Barrett, G. Casassa, N.A.N. Bertler, T. Bracegirdle, A.C. Naveira Garabato, D. Bromwich, H. Campbell, G.S. Hamilton, W.B. Lyons, K.A. Maasch, S. Aoki, C. Xiao, T. van Ommen, State of the Antarctic and Southern Ocean climate system, Rev. Geophys. 47 (2009) RG1003, https://doi.org/10.1029/2007RG000231.
[55] S.A. McCormack, J. Melbourne-Thomas, R. Trebilco, J.L. Blanchard, and A. Constable, Simplification of complex ecological networks - species aggregation in Antarctic food web models. In: MODSIM2017, 22nd International Congress on Modelling and Simulation, December 2017, Hobart, Tasmania, Australia [Syme, G., Hatton MacDonald, D., Fulton, E. and Piantadosi, J. (eds.)], Modelling and Simulation Society of Australia and New Zealand, 2017; 264–270.
[56] E. Mcleod, K. Anthony, P.J. Mumby, J. Maynard, R. Beeden, N. Graham, S. F. Heron, O. Hoegh-Guldberg, S. Jupiter, P. MacGowan, S. Mangubhai, N. Marshall, P.A. Marshall, T.R. McClanahan, K. Mcleod, M. Nyström, D. Obura, B. Parker, H.P. Possingham, R.V. Salm, J. Tamelander, The future of resilience-based management in coral reef ecosystems, J. Environ. Manag. 233 (2019) 291–301, https://doi.org/10.1016/j.jenvman.2018.11.034.
[57] M.P. Meredith, O. Schofield, L. Newman, E. Urban, M. Sparrow, The vision for a Southern Ocean Observing System, Curr. Opin. Environ. Sust. 5 (2013) 306–313, https://doi.org/10.1016/j.cosust.2013.03.002.
[58] M. Meredith, M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed et al., Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [Pörtner, H.-O., Roberts D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E. et al. (eds.)]. IPCC, Geneva, Switzerland, 2019. https://www.ipcc.ch/srocc/ (accessed February 2021).
[59] E.J. Murphy, P.N. Trathan, J.L. Watkins, K. Reid, M.P. Meredith, J. Thorpe, S. E. Johnston, N.M. Rothery, P. Forcada, Climatically driven fluctuations in Southern Ocean ecosystems, Proc. Roy. Soc. B 274 (1629) (2007) 3057–3067, https://doi.org/10.1098/rspb.2007.1180.
[60] E.J. Murphy, J.L. Watkins, P.N. Trathan, K. Reid, M.P. Meredith, S.E. Thorpe, N. M. Johnston, A. Clarke, G.A. Tarling, M.A. Collins, J. Forcada, R.S. Shreeve, A. Atkinson, R. Korb, M.J. Whitehouse, P. Ward, P.G. Rodhouse, P. Enderlein, A. G. Hirst, A.R. Martin, S.L. Hill, I.J. Staniland, D.W. Pond, D.R. Briggs, N. J. Cunningham, A.H. Fleming, Spatial and temporal operation of the Scotia Sea ecosystem: a review of large-scale links in a krill centred food web, Philos. Trans. R. Soc. B. Lond. Biol. Sci. 362 (2007) 113–148, https://doi.org/10.1098/rstb.2006.1957.
[61] E.J. Murphy, R.D. Cavanagh, N.M. Johnston, K. Reid, and E.E. Hofmann, Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) Science Plan and Implementation Strategy. Plymouth; Bergen: GLOBEC; IMBER, 2008. https://www.iced.ac.uk/documents/Finaltoprint.pdf (accessed February 2021).
[62] E.J. Murphy, N.M. Johnston, S. Corney, K. Reid, Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) programme: Report of the ICED–CCAMLR Projections Workshop, 5–7 April 2018. In paper SC-CAMLR-XXXVII/BG/16. SC-CAMLR XXXVII, Hobart, Australia, 2018.
[63] E.J. Murphy, N.M. Johnston, E.E. Hofmann, R.A. Phillips, J.A. Jackson, A.J. Constable et al., Global connectivity of Southern Ocean ecosystems. Front. Ecol. Evol., in review.
[64] M.R. Payne, Growth of a fur seal population, Philos. Trans. R. Soc. Lond. B 279 (1977) 67–79, https://doi.org/10.1098/rstb.1977.0072.
[65] L.S. Peck, Antarctic marine biodiversity: adaptations, environments and responses to change, in: S.J. Hawkins, A.J. Evans, A.C. Dale, L.B. Firth, I.P. Smith (Eds.), Oceanography and Marine Biology, Taylor & Francis, Milton Park, 2018, https://doi.org/10.1201/9780429454455-3.
[66] A.L. Perry, P.J. Low, J.R. Ellis, J.D. Reynolds, Climate change and distribution shifts in marine fishes, Science 308 (5730) (2005) 1912–1915, https://doi.org/10.1126/science.1111322.
[67] B. Pentz, N. Klenk, S. Ogle, J.A. Fisher, Can regional fisheries management organizations (RFMOs) manage resources effectively during climate change? Mar. Pol. 92 (2018) 13–20, https://doi.org/10.1016/j.marpol.2018.01.011.
[68] M.L. Pinsky, G. Reygondeau, R. Caddell, J. Palacios-Abrantes, J. Spijkers, W.W. L. Cheung, Preparing ocean governance for species on the move, Science 360 (2018) 1189–1191, https://doi.org/10.1126/science.aat2360.
[69] K. Reid, Conserving Antarctica from the Bottom Up: Implementing UN General Assembly Resolution 61/105 in the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), Ocean Yearb. 25 (2011) 131–139.
[70] A.D. Rogers, B. Frinault, D. Barnes, N.L. Bindoff, R. Downie, H.W. Ducklow, A. S. Friedlaender, T. Hart, S.L. Hill, E.E. Hofmann, K. Linse, C.R. McMahon, E. J. Murphy, E.A. Pakhomov, G. Reygondeau, I.J. Staniland, D.A. Wolf-Gladrow, R. M. Wright, Antarctic futures: an assessment of climate driven changes in ecosystem structure, function, and service provisioning in the Southern Ocean, Annu. Rev.

Mar. Sci. 12 (2020) 87–120, https://doi.org/10.1146/annurevmarine-010419-011028.
[71] SC-CAMLR, Report of the Twenty-Seventh Meeting of the Scientific Committee, SC-CAMLR-XXVII, Hobart, Australia, 2008.
[72] SC-CAMLR, Report of the Thirty-Fifth Meeting of the Scientific Committee, SC-CAMLR-XXXV, Hobart, Australia, 2016.
[73] J. Solomonsz, J. Melbourne-Thomas, A.J. Constable, R. Trebilco, E.I. van Putten, L. Goldsworthy, Stakeholder engagement in decision making and pathways of influence for Southern Ocean ecosystem services, Front. Mar. Sci. 8 (2021), https://doi.org/10.3389/fmars.2021.623733.
[74] Z.T. Sylvester, C.M. Brooks, Protecting Antarctica through co-production of actionable science: lessons from the CCAMLR marine protected area process, J. Mar. Pol. (2019) 111, https://doi.org/10.1016/j.marpol.2019.103720.
[75] D.P. Tittensor, M. Beger, K. Boerder, D.G. Boyce, R.D. Cavanagh, A. Cosandey-Godin, G.O. Crespo, D.C. Dunn, W. Ghiffary, S.M. Grant, L. Hannah, P.N. Halpin, M. Harfoot, S.G. Heaslip, N.W. Jeffery, N. Kingston, H.K. Lotze, J. McGowan, E. McLeod, C.J. McOwen, B.C. O'Leary, L. Schiller, R. Stanley, M. Westhead, K. L. Wilson, B. Worm, Integrating climate adaptation and biodiversity conservation in the global ocean, Sci. Adv. 5 (11) (2019) 9969, https://doi.org/10.1126/sciadv.aay9969.
[76] P.N. Trathan, D. Agnew, Climate change and the Antarctic marine ecosystem: an essay on management implications, Ant. Sci. 22 (2010) 387–398, https://doi.org/10.1017/S0954102010000222.
[77] P.N. Trathan, S.M. Grant, V. Siegel, K.-H. Kock, Precautionary spatial protection to facilitate the scientific study of habitats and communities under ice shelves in the context of recent, rapid, regional climate change, CCAMLR Sci. 20 (2013) 139–151.
[78] P.N. Trathan, J. Forcada, E.J. Murphy, Environmental Forcing and Southern Ocean marine predator populations: effects of climate change and variability, Philos. Trans. Roy. Soc. 362 (2007) 2351–2365.
[79] P.N. Trathan, S.M. Grant, The South Orkney Islands Southern Shelf Marine Protected Area: towards the establishment of marine spatial protection within international waters in the Southern Ocean, in: J. Humphreys, R.W.E. Clark (Eds.), Marine Protected Areas: Science, Policy and Management, Elsevier, Oxford, UK, 2019.
[80] J. Turner, N.E. Barrand, T.J. Bracegirdle, P. Convey, D.A. Hodgson, M. Jarvis, et al., Antarctic climate change and the environment: an update, Pol. Rec. 50 (2014) 237–259, https://doi.org/10.1017/S0032247413000296.
[81] H. Venables, M.P. Meredith, A. Atkinson, P. Ward, Fronts and habitat zones in the Scotia Sea, Deep Sea Res. Part II Top. Stud. Oceanogr. 59–60 (2012) 14–24, https://doi.org/10.1016/j.dsr2.2011.08.012.
[82] G.M. Watters, J.T. Hinke, C.S. Reiss, Long-term observations from Antarctica demonstrate that mismatched scales of fisheries management and predator-prey interaction lead to erroneous conclusions about precaution, Sci. Rep. 10 (2020) 1–9, https://doi.org/10.1038/s41598-020-59223-9.
[83] H. Weimerskirch, M. Louzao, S. de Grissac, K. Delord, Changes in wind pattern alter albatross distribution and life-history traits, Science 335 (2012) 211–214, https://doi.org/10.1126/science.1210270.
[84] M.R. Wendebourg, Southern Ocean fishery management – is CCAMLR addressing the challenges posed by a changing climate? Mar. Policy 118 (2020), 103847 https://doi.org/10.1016/j.marpol.2020.103847.
[85] K.L. Wilson, D.P. Tittensor, B. Worm, H.K. Lotze, Incorporating climate change adaptation in into marine protected area planning, Glob. Change Biol. 2020 (2020) 1–17, https://doi.org/10.1111/gcb.15094.
[86] G. Yang, A. Atkinson, S.L. Hill, L. Guglielmo, A. Granata, Changing circumpolar distributions and isoscapes of Antarctic krill: indo-Pacific habitat refuges counter long-term degradation of the Atlantic sector, Limnol. Oeanogr. 9999 (2020) 1–16, https://doi.org/10.1002/lno.11603.