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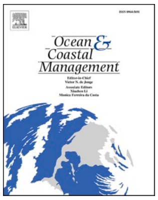

Managing for climate resilient fisheries: Applications to the Southern Ocean

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ABSTRACT

Climate change is having profound effects on populations of fished species and the ecosystems on which they depend, lending to a growing body of work that advocates for climate resilience to be a priority in fishery management. Here, we provide a comprehensive analysis of the tools needed to manage for climate resiliency. The Antarctic region is among the most vulnerable to climate change, and thus, we then consider climate resilient management tools utilized by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), the body responsible for the management of Antarctic marine living resources as part of the Antarctic Treaty System. We note progress, gaps, and opportunities for implementation. Across the literature, ecosystem-based management was cited as an appropriate tool for climate resilience of marine ecosystems, as was the use of climate model outputs (projections and simulations), marine protected areas (MPAs), and dynamic stock assessments. CCAMLR has a unique position where its Convention effectively mandates the principles of an ecosystem-based precautionary approach for managing fisheries, and many of its Member States have been advocating for climate initiatives within this approach. While CCAMLR has made limited overall progress towards ensuring climate resilience, it has advanced in some areas, such as MPA implementation, developing a risk assessment for krill, and including statements on climate change in fishery reports, although there is much work to be done. While climate change remains a worldwide issue that must be addressed on a global scale, CCAMLR holds the responsibility for adaptively managing Southern Ocean marine living resources for climate resilience.

1. Introduction

Across the world, climate change is dramatically altering marine systems and threatening fished populations as well as the livelihoods and the food security they provide (Boersma et al., 2016; Brown et al., 2010; Cheung et al., 2018; Miller et al., 2018). Warming temperatures have been correlated with an overall reduction in fisheries yield over the past 80 years (Bryndum-Buchholz et al., 2019; Freer et al., 2019). Global projections suggest this trend will continue with significant decreases in animal marine biomass by 2100 (Lotze et al., 2019). The Intergovernmental Panel on Climate Change (IPCC) has warned that by 2050, future shifts in fish distribution and decreases in their abundance will have profound effects on income, livelihoods, and food security (IPCC, 2019; Hannesson, 2007).

Climate change is currently impacting marine systems in a variety of ways, including increases in sea temperature, acidification, loss of oxygen, and changes in ocean currents; this in turn has caused shifts of species distributions, biodiversity declines, and loss of ecosystem integrity and function (Bijma et al., 2013; Brander, 2010; Frazão Santos et al., 2020; Funk and Brown, 2009; Hoegh-Guldberg and Bruno, 2010; IPBES et al., 2019; Meredith et al., 2019; Reid et al., 2010). Generally, marine species are responding to warming by shifting their geographic ranges both polewards and into deeper waters (Barhri et al., 2021; Mills et al., 2015; Pecl et al., 2017). Warming ocean temperatures are also

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linked to reductions in body size of marine species, and changes in reproduction and growth rates (Huang et al., 2021; Poloczanska et al., 2016). Earlier migrations have also been recorded in marine species as a response to changes in seasonality and sea temperature (Bell et al., 2020; Lennox et al., 2019, Mills et al., 2015). As warming continues, these shifts will become more common as species change their distribution patterns seeking an environment that suits their optimal thermal tolerance (McBride et al., 2021; Erauskin-Extramiana et al., 2019; Hobday et al., 2015; Poloczanska et al., 2016; Porter et al., 2015).

Southern Ocean ecosystems are globally important due to their influence on the Earth system and are among the most impacted by climate change (Murphy et al., 2021; Newman et al., 2019). Current climate change projections predict the Southern Ocean will experience the most pronounced warming at depths of 0–2,000m compared to other ocean bodies (Bindoff et al., 2022; Hoegh-Guldberg, 2018). More specifically, the western Antarctic Peninsula has been identified as being one of the most climatically sensitive regions on earth (Hendry et al., 2018; Meredith et al., 2019; Wang et al., 2021). The general prognosis for Southern Ocean systems is one of overall warming and freshening, increased acidification, strengthening of westerly winds, increase in ocean eddy activity, shifting currents, increased primary production in the water column and less in sea ice, and declines in sea ice extent; all these physical changes will have potentially dramatic impacts on Antarctic marine ecosystems (Bindoff et al., 2022; Chown and Brooks 2019; Collins et al., 2019; Constable et al., 2014; IPCC, 2021; Henley et al., 2020; Karp et al., 2019; Pinkerton et al., 2021; Rintoul et al., 2018; Rogers et al., 2019). Southern Ocean species can be especially vulnerable to climate change due to restricted ranges, thermal tolerances, and reliance on sea ice (Brasier et al., 2019, 2021; Constable et al., 2014; Peck, 2018). Further, climate change is also predicted to decrease the overall capacity of the Southern Ocean to supply globally important ecosystem services (Cavanagh et al., 2021a; Meredith et al., 2019). However, quantifying the effects of climate change on Southern Ocean ecosystems has been difficult and wrought with uncertainty (Abrams et al., 2016; Bestley et al., 2020; Cavanagh et al., 2017; Constable et al., 2016; Constable et al., 2017; Free et al., 2019; Goldsworthy and Brennan, 2021; Meyer et al., 2020; Press, 2021; Rayfuse, 2018; Watters et al., 2020).

Marine living resources in the region are managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Established in 1982, CCAMLR's objective is to carry forward the provisions of the Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention). The CAMLR Convention is one of the agreements that make up the Antarctic Treaty System, which comprehensively dedicates Antarctica as a shared international space committed to peace, science, and environmental protection (Berkman et al., 2011). This important context, along with the CAMLR Convention's conservation principles (see Box 1, Article II), sets CCAMLR apart from regional fisheries management organizations (RFMOs). CCAMLR currently has 26 Member States plus the European Union, and all substantive decisions require consensus.

CCAMLR's mandate is the conservation of Antarctic marine living resources. However, the Convention also allows for rational use, where commercial fishing is permitted, but must be in accordance with the conservation principles outlined in Article II following a precautionary and ecosystem-based approach, which is grounded in the best available science (Constable et al., 2000) (see Box 1). Maintaining ecological relationships and managing for the effects of environmental change are among these principles. Climate change presents an unprecedented ongoing challenge to CCAMLR, demanding new approaches to management to meet the ecosystem provisions of Article II. The recent 2022 IPCC report cross-chapter on Polar Regions clearly demonstrates the need for improved Southern Ocean management, with recommendations including: improved spatial management, ecosystem-based fishery management (EBFM), marine protected areas (MPAs), climate informed management, protection of prey fields, climate resilient infrastructure, and diversification of harvest portfolios (Constable et al., 2022). Similarly, Sustainable Development Goal 14 of the United Nations calls for enhancement of scientific research to build resilient infrastructure to minimize and address the impacts of climate change across all oceans (Bebianno et al., 2021). Aligned with recent IPCC recommendations (IPCC, 2021), and much of the scientific research and discussion to date, a recent report by the Scientific Committee on Antarctic Research (SCAR) recommends identifying which species and ecosystems are the most vulnerable to climate change, determining how fishing will affect the Southern Ocean food web, and further supporting research to reduce scientific uncertainty and understand the impacts of mitigation and adaptation responses (Chown et al., 2022).

1.1. *Managing for climate resilience*

Given the stressors posed by climate change on marine ecosystem worldwide, a growing body of work has advocated for climate resilience of ecosystems to be a priority in fishery management (Burden and Fujita, 2019; Busch et al., 2016; Free et al., 2020; Karp et al., 2019; Link et al., 2020; Mellin et al., 2016; Ojea et al., 2020; Pentz et al., 2018; Sekadende et al., 2020). In this paper, we use Holsman et al.'s (2019, pg. 1379) definition of climate resilient fisheries management as "precautionary, efficient, and responsive policies that address climate uncertainty, explicitly consider feedback within coupled marine social-ecological systems and integrate tools and politics at multiple spatiotemporal scales." The extent to which resilience can be operationalized in fisheries

Box 1
CAMLR Convention Article II (CCAMLR, 1980)

Article II

1. The objective of this Convention is the conservation of Antarctic marine living resources.
2. For the purposes of this Convention, the term 'conservation' includes rational use.
3. Any harvesting and associated activities in the area to which this Convention applies shall be conducted in accordance with the provisions of this Convention and with the following principles of conservation:

(a) prevention of decrease in the size of any harvested population to levels below those which ensure its stable recruitment. For this purpose, its size should not be allowed to fall below a level close to that which ensures the greatest net annual increment;
(b) maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources and the restoration of depleted populations to the levels defined in sub-paragraph (a) above; and
(c) prevention of changes or minimization of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades, taking into account the state of available knowledge of the direct and indirect impact of harvesting, the effect of the introduction of alien species, the effects of associated activities on the marine ecosystem and of the effects of environmental changes, with the aim of making possible the sustained conservation of Antarctic marine living resources.

as a complex social ecological system is still a key question due to gaps across (i) ecological, (ii) socio-economic and (iii) governance dimensions (Mason et al., 2021). Globally, managing for climate resilient fisheries has focused on building resistance to stressors and recovery from both ecosystem disturbances and pressures from social systems (Mason et al., 2021). However, in the Southern Ocean, where there are no resident social systems in place, building climate resilience is skewed towards the former (Press and Constable, 2022). This is further emphasized by the objective of the CAMLR Convention: conserving Antarctic marine living resources (CCAMLR, 1980, Article II).

Managing fisheries for climate change has been slow and difficult (Pinsky and Mantua, 2014; Bryndum-Buchholz et al., 2021; Holsman et al., 2020, 2019; Rudd et al., 2018; Skern-Mauritzen et al., 2016), and often applied reactively in response to extreme events rather than proactively (Barhri et al., 2021). This is in part because managing for climate resilience demands an increased understanding of population and community dynamics to predict the effects of climate change within a system (Murphy et al., 2021). And yet, there is inherent uncertainty about marine system predictions, and the tools for managing for climate change are still being developed (Skern-Mauritzen et al., 2016; Bryndum-Buchholz et al., 2021).

In this paper, we identified best practices for managing fisheries for climate resilience of ecosystems, and then assessed the application of these best practices to the Southern Ocean. First, we provided background on Southern Ocean fisheries, including climate change impacts to the ecosystem. Then we performed a review of the peer-reviewed literature focused on climate resilient fisheries management. The goal of our review was to be qualitative and descriptive (Xiao and Watson, 2019), rather than systematic or quantitative, and to derive common themes and tools that scholars and practitioners recommend for climate resilient fisheries management across scales, from local to global. Below we present and summarize these themes, offering examples where possible of the management tool in action. We then addressed these climate change management tools to CCAMLR's management practices, noting progress, challenges, gaps and opportunities for improvement. Further, we assessed CCAMLR's draft proposed Climate Change Response Work Plan (CCRWP) in the context of the literature, while noting that discussions on progressing this plan have not been undertaken since 2019 and would need to be updated to reflect current climate resilience literature. The CCRWP, however, provided a useful framework to assess CCAMLR's progress towards managing for climate change. While we aimed to be comprehensive in our review and assessment of CCAMLR, we acknowledge that some CCAMLR activities are not documented in the peer-reviewed literature or publicly available reports. We close with recommendations for CCAMLR to work towards improving climate resiliency of Southern Ocean fisheries and ecosystems.

2. Southern Ocean fisheries

Antarctic krill (*Euphausia superba*, hereafter krill), are one of two main fisheries in the CCAMLR area. Krill are a key prey species supporting the Southern Ocean food web and are particularly vulnerable to a changing climate (Atkinson et al., 2019; Flores et al., 2012; Johnston et al., 2022). The Antarctic Peninsula region, where 70% of the current population of krill is concentrated (Atkinson et al., 2008), is experiencing some of the most rapid warming in the Southern Ocean (Meredith et al., 2019). The current population center for krill extends from the South Sandwich Islands to the Antarctic Peninsula. However, empirical evidence has shown that there has been a southward contraction in the distribution of krill (Atkinson et al., 2019; Cooley et al., 2022; Trivelpiece et al., 2011; Watters et al., 2020). Modeling studies have also shown that as climate changes, the optimal conditions for krill are predicted to move poleward (Hill et al., 2013; Murphy et al., 2017; Veytia et al., 2020; Sylvester et al., 2021). Meanwhile, there is increasing pressure to expand krill fisheries in the Southern Ocean to meet the growing demand for nutraceutical products for krill oil (e.g., Omega-3 supplements) and for fishmeal and marine by-products (Meyer et al., 2020).

In addition to krill, and limited catch of Mackerel icefish (*Champsocephalus gunnari*), the other major fishery in the Southern Ocean is for Patagonian and Antarctic toothfish (*Dissostichus eleginoides* and *D. mawsoni*, respectively; hereafter toothfish), which are sold as the lucrative Chilean Sea Bass. Toothfish serve as the top fish predator, but also as an important prey species for seals and whales (Ainley and Ballard, 2012; Ainley and Siniff, 2009). Patagonian toothfish largely occupy the more northern subantarctic waters while Antarctic toothfish, which have antifreeze in their blood, occupy higher latitude waters further south (Caccavo et al., 2021). Like krill, much uncertainty remains around the projected impacts of climate change on Antarctic toothfish (Morley et al., 2020). For example, while one study emphasized the possible extinction of the Antarctic toothfish due to its restricted range and affinity to freezing temperatures (Cheung et al., 2008a), a later study instead argued that Antarctic toothfish may respond well to temperature and oceanographic changes due to their ability to thrive in various depths and locations (Constable et al., 2014). Although Antarctic toothfish are prevalent throughout Antarctic waters, many knowledge gaps remain. This includes uncertainty about their life history (e.g., spawning frequency), population status (e.g., virgin biomass), and connectivity (e.g., how many populations exist) (Abrams, 2014; Abrams et al., 2016; SC-CAMLR, 2018; Chown and Brooks, 2019), along with potential cumulative impacts from environmental change and fishing (Brooks et al., 2018). In addition to fishing, the direct and indirect effects of climate change on fish and wildlife populations in the Southern Ocean are further complicated by the cumulative pressures of pollution, and overall increased human activity, including tourism (Roberts et al., 2017; Tulloch et al., 2019; Wauchope et al., 2019; Grant et al., 2021).

3. Management tools for climate resilience

The peer reviewed literature on climate resilient fisheries primarily highlighted the need for EBFM (including precautionary, adaptive, and dynamic approaches), along with applying outputs from climate models in developing management measures, utilizing environmentally informed dynamic stock assessments, and implementing MPAs. These tools ideally work in tandem as part of EBFM. Climate model outputs provide a means for predicting future ecosystem and environmental scenarios which can be used, for example, to help inform a dynamic stock assessment or to guide where a network of MPAs might best be placed. Below we examine each of these tools including some of the key elements that support them.

3.1. Ecosystem-based fishery management

As a tool for climate resilience, EBFM provides an approach that integrates social, ecological, and economic factors to comprehensively manage the threats to an ecosystem. Unlike fixed management measures - which are only revisited periodically and are difficult to adjust - EBFM includes management measures that are able to adjust and respond to new conditions and new data, including ecosystem drivers, while also being forward-looking and proactive (Holsman et al., 2019; Hazen et al., 2018). EBFM inherently applies to managing not only the target species, but also the whole ecosystem. For the purposes of this paper, we use Pikitch et al.'s (2004) pillars for achieving EBFM. These include: (i) avoiding degradation of ecosystems, (ii) minimizing the risk of irreversible change to species and ecosystem processes, (iii) maintaining long-term socioeconomic benefits, and (iv) continue to generate knowledge of ecosystem processes under anthropogenic actions, with the acknowledgement that EBFM will look different given the community in question's specific needs and values. EBFM encompasses the wide diversity of services provided by marine ecosystems, the cumulative effects of anthropogenic activities on ecological systems, and the importance of working towards a common goal for all parties and across all sectors (McLead et al., 2009).

There are a number of tools that can work as part of an EBFM approach and have the potential to be used towards managing for climate resilience. These include: scenario planning (a method to help managers identify the most potentially detrimental drivers of change and enable them to plan around them), protecting key habitats and species, designating MPAs (elaborated on further below), applying outputs from climate models (also elaborated on below), and being dynamic and adaptive (Chavez et al., 2017). Within EBFM and in response to the intrinsic dynamic nature of oceans, researchers have advocated for management to be dynamic over static (Dunn et al., 2016). Thus far, frameworks for dynamic management tend to operate on smaller scales and focus on managing grid-based fisheries closures for conservation (Dunn et al., 2016).

Similarly, EBFM relies on adaptive management measures that center on developing management practices tailored to a wide range of outcomes within an ecosystem. Adaptive management is a structured approach to decision-making in the face of uncertainty that focuses on monitoring and forecasting environmental outcomes to reduce uncertainty and improve fisheries management (Chavez et al., 2017; McCarthy and Possingham, 2007; Sekadende et al., 2020; Williams et al., 2009). Similarly, adaptive fisheries management requires the regular adjustment of management measures based on ecosystem monitoring indices for stock assessments (Wang et al., 2021). Introducing adaptive management measures towards climate resilience can minimize the negative impacts of climate change on fisheries by aligning management practices with the spatial and temporal effects of climate change, ecosystem change, and socioeconomic responses (Free et al., 2019; Free et al., 2020; Kenny et al., 2018).

3.2. Climate models

The use of climate models in fisheries management can help guide decision-making regarding the biological implications of climate change (Hewitt et al., 2020; Quentin Grafton, 2010; Saba et al., 2014). Global climate models are a mathematical representation of the four major components of the earth system (atmosphere, land surface, ocean, and sea ice). When applied across a three dimensional gridded representation of the earth, climate models formulate a system that allows interaction between all major components. In doing so, climate model outputs provide a vast set of tools for understanding the complexities of how climate functions within the earth system. For example, data from climate model outputs can provide scenarios of environmental change, which then enables identification of sensitive areas, or provides a means by which ecological models can be projected in space and time to see what impacts climate change might have on the biosphere.

Data from climate model outputs can provide fishery managers with tools to envision and prepare for climate change and climate variability (Free et al., 2020; Hare et al., 2016; Lindegren and Brander, 2018). Climate models can be applied to decipher forecasts on regional ocean productivity trends (Stock et al., 2017) and to inform future environmental conditions to manage risk and account for variability (Hobday et al., 2018). Monitoring the effects of seasonal variability, spatial variability, and the long term impacts of climate change on fish populations and modeling them in climate models can help inform management decisions and determine species responses to climate induced changes (Bell et al., 2020; Goethel et al., 2021; Sekadende et al., 2020). For example, climate model outputs can be used in vulnerability analyses to help identify which species are at most risk from threats to an ecosystem, such as rising temperatures or increased ocean acidification. Climate model outputs can also be used in scenario planning (defined above), holistic ecosystem models (which connect the interactions of ecological systems to the socioeconomic systems) and climate vulnerability analyses (which combines the exposure and sensitivity of a species to a stressor to estimate overall vulnerability) (Free et al., 2020; Holsman et al., 2017; Metcalf et al., 2015; Moore et al., 2013). Using climate model data to aid decision-making can help managers respond to a wide range of potential outcomes to species and ecosystems at different spatial and temporal scales.

Recent technological advancements have increased capacity for incorporating climate model outputs into fisheries research and management (Bradley et al., 2019). One example is the development of dynamic bioclimatic envelope models (DBEM). These models process associations between climate and fish species to estimate the conditions that are suitable to maintain viable populations (Araujo and Peterson, 2012). One recent study used a DBEM approach to project species distributions in the Gulf of Maine and Pacific Northwest from 2015 to 2100 under specific IPCC climate change projections (IPCC Representative Concentration Pathways, RCP 2.6 & 8.5), along with potential fishery catches (Palacios-Abrantes et al., 2020). Another example is the Fisheries and Marine Ecosystem Model Intercomparison Project which uses climate models to investigate predicted impacts on fisheries and marine ecosystems under different climate change scenarios (Cooley et al., 2022). Building on previous studies (Cheung et al., 2008b, 2009), models such as the DBEM seek to estimate future productivity, distribution, movement, and other life history and population parameters of targeted fisheries.

3.3. Environmentally informed dynamic stock assessments

Stock assessments are the foundational tool for fisheries management and consist of a range of statistical methods used to estimate current population size for a targeted species. Managers use stock assessments to analyze biological and fisheries data to determine changes in fishery stocks in response to fishing, predict future changes in stock abundance, and ultimately set informed catch limits (Hilborn, 2003). Most stock assessments assume single-species, single-stock dynamics and employ limited use of environmental data, often due to limited data availability. Therefore, data availability along with model structure can influence how sustainable catch limits are defined (Punt et al., 2020).

As targeted species continue to shift their distribution under climate change, stock assessments need to innovate towards accounting for environmental change and uncertainty as well as ecosystem dynamics (Funk and Brown, 2009; Karp et al., 2019). A stronger understanding of how environmental variables drive productivity and trophic dynamics can facilitate the development of multispecies and ecosystem-based stock assessments (Thøgersen et al., 2015; Wang et al., 2021). Not only can climate change affect distribution and movement, but it can also lead to changes in recruitment, mortality rate, and productivity (Pankhurst and Munday, 2011; Portner and Peck, 2010). Failing to account for the impacts of climate change on species life history could lead to stock collapse from inaccurate fishing quotas (Jensen et al., 2020). Fishery managers have advocated for environmentally informed dynamic stock assessments which aim to incorporate environmental variables that account for the effects of climate on spawning and recruitment (Crone et al., 2019), as well as responding to data on ecosystem drivers (e.g., temperature, ice coverage, upwelling, primary production, predator-prey relationships) of stock productivity (Pankhurst and Munday, 2011; Portner and Peck, 2010; Skern-Mauritzen et al., 2016).

While moving towards ecologically informed stock assessments is a goal for many researchers and managers, currently, ecosystem drivers, ecological interactions, and the effects of climate change are rarely accounted for in fishery stock assessments (Skern-Mauritzen et al., 2016; Wang et al., 2021). Only 2% of global fisheries include ecosystem drivers of stock productivity in their management (Skern-Mauritzen et al., 2016), none of which are in the Southern Ocean. Applying this tool requires extensive data, computing power, and technical expertise to implement, and therefore remains out of reach for many fisheries (Burden and Fujita, 2019). This is particularly relevant in data-poor regions, where there is limited information on stock status and climate change (Cisneros-Mata et al., 2019; Punt et al., 2020; Van de Putte et al., 2021). Nonetheless, improving understanding of how spatial distributions correlate with environmental variables shows promise for improving accuracy of predictions of spatial shifts, and opportunities to link habitat selection models to climate projections for stock assessments (Tommasi et al., 2017; Wayte, 2013).

Another approach is to set aside some of the catch limit to account for potentially diminishing or stressed fish stocks due to climate change (Johnson and Welch, 2010). This climate change catch quota aims to build in more precaution because of the inherent uncertainties related to how climate change will affect key parameters in stock assessments (Johnson and Welch, 2010). This could in turn provide fisheries with greater resilience to climate and stock variability (Johnson and Welch, 2010). Long-term solutions to address fishery management under climate change will require extensive monitoring and updating of stock assessments in addition to refining data collection and sharing (Cvitanovic et al., 2015; Dunn et al., 2016; Frazão Santos et al., 2020). Setting climate informed quotas that include recent as well as historical observations, is an important step towards strengthening climate resilient fisheries (Bryndum-Buchholz et al., 2021; Tanaka, 2019).

3.4. Marine protected areas

MPAs, defined as regions of the ocean where human activities are restricted to promote conservation (Lubchenco et al., 2003), are emerging as an important tool to conserve biodiversity, and mitigate threats, including those posed by climate change (Browman and Stergiou, 2004; Cabral et al., 2020; Grorud-Colvert et al., 2021; Lubchenco and Grorud-Colvert, 2015; Pentz and Klenk, 2017; Wendebourg, 2020). Well-designed MPAs with strong levels of protection that encompass all trophic levels of an ecosystem have been shown to increase species and genetic diversity, thus enhancing resilience to environmental impacts (McLeod et al., 2009; Barnett and Baskett, 2015; Olds et al., 2014; Roberts et al., 2017; Jacquemont et al., 2022).

In terms of climate change, MPAs can be implemented specifically towards managing in a changing seascape and towards climate resilience. Wilson et al. (2020) presented a framework with four main steps. First, define clear conservation goals and objectives for the MPA, and adapt these specifically to the effects of climate change to the marine ecosystem. Second, use vulnerability assessments to evaluate how climate change will impact the stated conservation goals. Third, based on the vulnerability assessment, identify and incorporate adaptation strategies to mitigate climate change impacts. Fourth, monitor the MPA to gauge effectiveness in response to climate change and use monitoring results to guide adaptive management (Wilson et al., 2020). Wilson et al. (2020) further identified the range of climate adaptation strategies that can be utilized in MPA design and management (based on vulnerability assessments). These include (Wilson et al., 2020): encompassing climate refugia, increasing resilience, protecting future habitat, increasing heterogeneity (Jones et al., 2016), increasing connectivity, and reducing other stressors (Roberts et al., 2017). While there are many examples of MPA managers applying these adaptation strategies, the majority are in tropical coral reef systems (Wilson et al., 2020); yet the lessons could transfer globally. Finally, creating MPAs as a connected network can lead to enhanced ecosystem resilience (Engler, 2020; McLeod et al., 2009; Green et al., 2014) by protecting the critical life stages of species, from spawning aggregations and nursery or feeding grounds to migration corridors for highly mobile species (Grorud-Colvert et al., 2021).

4. Applying climate resilient management tools to CCAMLR

Below we consider the main tools for managing for climate resilience of ecosystems as applied to CCAMLR's current management practices. We further note potential gaps in implementation and areas for improvement towards climate resilient fisheries management.

4.1. Ecosystem based fishery management

While Article II of the CAMLR Convention encompasses the principles of EBFM (Article II (3) (b) and (c)), CCAMLR has grappled with effectively applying an ecosystem approach to the management of its fisheries (Constable et al., 2016), including under a changing climate. CCAMLR has led in some EBFM innovations, including the development of the CCAMLR Ecosystem Monitoring Program (CEMP). CEMP, which has been fully implemented since 1987, has sites throughout the Antarctic in which monitoring data on key prey, predators, and environmental indicators are collected (Agnew, 2004). However, CCAMLR has yet to include the CEMP monitoring data as parameters for their fisheries management (Hill et al., 2020; Hinke et al., 2017). Further, biodiversity information, including the status of key species, remains inadequate to fully understand Southern Ocean ecosystem dynamics (Chown and Brooks, 2019).

Notably, CCAMLR has been discussing climate change at its annual meetings since 2008 when it was added as an agenda item under its Scientific Committee (SC-CAMLR, the scientific advisory body with representatives from all Member States) (CCAMLR, 2009). In 2009, CCAMLR adopted a non-legally binding resolution which emphasized the need for increased consideration of Southern Ocean climate change impacts to better inform CCAMLR's management decisions, drawing attention to Article II (CCAMLR, 2009). In 2022, CCAMLR adopted an additional climate change resolution stressing urgent action, including managing for climate resilience, again highlighting the ecosystem management provisions under Article II (CCAMLR, 2022a).

Other important efforts have been made to incorporate climate change into CCAMLR's management approach (see Table 1). In 2015, an intersessional contact group was established to consider approaches for integrating climate change considerations into the work of CCAMLR (CCAMLR, 2015, paragraph 7.12). In 2016 CCAMLR held a joint workshop on climate change and monitoring with the Committee for Environmental Protection (CEP), the body which advises on the implementation of the Environmental Protocol to the Antarctic Treaty, (CEP/SC-CAMLR, 2016) with the goal of identifying the effects of climate change that are considered most likely to impact the conservation of the Antarctic. A recommendation from this workshop was to encourage support and cooperation between scientific programs (especially SCAR, the Southern Ocean Observing System (SOOS), and Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED)) and SC-CAMLR and CEP towards contributing work on climate change and monitoring (CEP/SC-CAMLR, 2016). Furthermore, in 2017 and 2018, Delegates from Australia and Norway, on behalf of the intersessional group, proposed a Climate Change Response Work Program (CCRWP) for CCAMLR (Delegations of Norway and Australia, 2018). The proposed CCRWP identified five specific conservation issues in the Southern Ocean and recommended actions to incorporate responses into CCAMLR's management. Evidence underpinning the proposed management responses was grounded in science and aligned with best practices in the literature for climate resilient fisheries (see Table 2).

The CCRWP built on related work of SC-CAMLR and its Working Groups, along with ongoing work of the CEP and scientific programs such as the SCAR, SOOS, and ICED. Modeled on the CCRWP of the CEP, CCAMLR's version was designed "to provide a mechanism to facilitate the production, delivery, and use of climate related information and advice for the Commission to take account of climate change impacts in achieving the objective of the CAMLR Convention." (Delegations of Norway and Australia, 2018, p. 1).

SC-CAMLR recommended that CCAMLR adopt the CCRWP (SC-CAMLR, 2017a; para 8.13), however two members opposed its adoption, ultimately rejecting the scientific advice provided by SC-CAMLR (Goldsworthy, 2022). While the draft CCRWP has not been discussed at CCAMLR since 2019, and would need to be updated, its basic premise would support management for the resilience of Southern Ocean ecosystems in the face of climate change. Moving forward,

Table 1

EBFM for climate resilience can draw on a variety of management tools. Some fall under the general umbrella of EBFM as described in Row 1. Others fall under sub-areas identified in the literature: Climate models (Row 2), Integrated stock assessments (Row 3), and MPAs (Row 4). Column 1 describes the different tools, column 2 lists the elements within each tool, column 3 lists the supporting literature and column 4 describes CCAMLR's progress with respect to each of the management tools.

Climate Resilient Management Tools	Elements within each tool	Supporting Literature	CCAMLR's progress
Implementation of **ecosystem-based fishery management tools** specific to enhance the resilience of marine ecosystems and help improve the future status of fisheries	- Adaptive management - Dynamic management - Holistic ecosystem management - Risk assessments - Integrated ocean management	Barnett and Baskett, 2015; Burden and Fujita (2019); Busch et al. (2016); Cavanagh et al. (2016); Free et al. (2020); Gaines et al. (2018); Harvey et al. (2018); Hilborn and Ovando (2014); Holbrook and Johnson (2014); Kirkfeldt, 2019; Link et al. (2020); Mellin et al. (2016); McLeod et al, 2009; Meyer et al. (2020); Ojea et al. (2020); Sekadende et al., 2020	CCAMLR manages Southern Ocean fisheries under a system encompassing the principles of an EBFM approach, and has stated provisions for adaptive management, however its current management framework lacks integrated consideration of climate change impacts. It has made progress in areas (noted below) on MPAs, risk assessment (for krill), adding statements on climate change and environmental variability to Fishery Reports, and scientific discussions (e.g., SC-CAMLR's 2017–2022 five year work plan (SC-CAMLR, 2017b, and the draft CCRWP).
Incorporation of **climate model** outputs into fisheries management applications	- Weather forecasts - Regional productivity forecasts - Mapping seasonal and spatial variability (of key ecosystem drivers and indicators) - Climate vulnerability analyses - Population forecasts - Scenario planning - Holistic ecosystem models - Mapping species distributions	Brander (2010); Burden and Fujita (2019); Cavanagh et al., (2017); Collins et al. (2019); Constable et al. (2014); Constable et al. (2017); Constable et al. (2022); Free et al. (2020); FAO, 2019; Goethel et al. (2021); Hill et al. (2020); Hobday et al. (2018); IPCC, 2012; IPCC, 2014; IPCC, 2019; IPCC, 2021; Karp et al. (2019); Lindegren and Brander (2018); Meredith et al. (2019); Meyer et al. (2020); Murphy et al. (2021); Pinkerton et al. (2021); Quentin Grafton (2010); Saba et al. (2014); Stock et al. (2017); Tommasi et al. (2017); Watters et al. (2020)	Currently climate models have not been directly applied in CCAMLR's fisheries management, however, there has been discussion of the use of, and application of climate models and climate modeling tools in the context of targeted species in recent years in CCAMLR Working Groups and SC-CAMLR meetings. The CCRWP also identifies a variety of actions that are supported by the use of climate models (e.g., develop models on the impact of climate change on food web dynamics). A variety of scientific programmes (e.g., SCAR, ICED) are doing ongoing research in this vein and provide scientific outputs to SC-CAMLR and its Working Groups. For example, the development of ecosystem models is identified as a priority for established toothfish fisheries in SC-CAMLR's five year work plan.
Innovative **stock assessments** that account for environmental change and uncertainty	- Climate models - Population models and forecasts - Models that project changes in stock abundance - Climate change catch quotas - Monitor shifts in oceanographic conditions - Tracking species historical movements	Abrams et al. (2016); Cisneros-Mata et al. (2019); Constable et al. (2000); Constable et al. (2017); Karp et al. (2019); Miller and Slicer (2014); Poloczanska et al. (2016); Quentin Grafton (2010); Thøgersen et al., 2015; Weatherdon et al. (2016)	CCAMLR has yet to incorporate climate change or ecosystem monitoring indices as variables in their stock assessments. The development of integrated assessments at population scales to address the impacts of climate change is identified in SC-CAMLR's five year work plan. Currently, for krill, CCAMLR's stock assessment only considers the adult life stage of krill and assumes that the krill population is at equilibrium, with random recruitment, and that changes in krill population are always proportional to the year before. CCAMLR scientists are in the process of developing a risk assessment, and CCAMLR also considers information from the CCAMLR Ecosystem Monitoring Program. The CCRWP suggests the development of spatially explicit stock assessments that account for changes in spatial distribution of fish due to sea ice changes.
Implementation of **marine protected areas** to conserve biodiversity and reduce the	- Create networks of MPAs that represent the full range of ecoregions and biodiversity	Brito-Morales et al. (2022); Cabral et al. (2020); Dunham et al. (2020); Free et al. (2020);	CCAMLR has committed to designate a network of representative MPAs in the Southern Ocean. Thus far two MPAs

(continued on next page)

Table 1 (*continued*)

Climate Resilient Management Tools	Elements within each tool	Supporting Literature	CCAMLR's progress
pressure of climate change on ocean ecosystems	- Promote conservation - Mitigate threats, including those posed by climate change	Grorud-Colvert et al. (2021); Lubchenco et al. (2003); Lubchenco and Grorud-Colvert, 2015; Miller and Slicer (2014); Pentz and Klenk (2017); Pentz et al. (2018); Olds et al. (2014), Roberts et al. (2017); Wendebourg (2020)	have been adopted. However, current MPAs are not representative of the full range of benthic and pelagic ecoregions of the Southern Ocean. Three more MPAs in the East Antarctic, Weddell Sea, and western Antarctic Peninsula remain under negotiation and would increase ecological representativeness of protection significantly.

CCAMLR could better integrate ecosystems and fisheries work streams by utilizing an adaptive management approach to understand the mechanism by which climate change will affect multiple trophic levels across the food web (Saba et al., 2014). CCAMLR could increase the effectiveness of its conservation strategies by applying systematic conservation planning principles such as the ongoing development of Southern Ocean MPAs (elaborated on further below), adaptive management, including risk assessments (also elaborated below), and incorporating information from climate model outputs (elaborated on below).

To date, CCAMLR has not collaborated sufficiently with climate experts, yet there is recognition that this would strengthen its capacity to incorporate relevant scientific information and inform decision-making, including developing methods for assessing current and future impacts of climate change on ecosystem structure and function (Constable et al., 2014; Cavanagh et al., 2017, 2021b; Murphy et al., 2017). Successful integration of climate information into CCAMLR's decision frameworks will depend on open dialogue and collaboration between CCAMLR decision-makers and climate scientists (Tommasi et al., 2017; Francis et al., 2018; Cavanagh et al., 2021b). Decision-makers will then need to incorporate ecosystem-based strategies to achieve their conservation objectives in relation to climate change (McCormack et al., 2021). While, as noted in Table 2, an array of scientific bodies and programs submit work outputs to CCAMLR, among them only SCAR serves as an observer to CCAMLR and SC-CAMLR, and none have access to the Working Groups (unless individuals which are part of these groups sit on a national delegation). This can be a barrier to enabling independent work being integrated in the decision-making process. However, SC-CAMLR does allow in its Rules of Procedure the invitation of independent experts (SC-CAMLR, 2021a), and would greatly benefit from further seeking climate specific expertise, including from SCAR, ICED and other Antarctic science programs.

4.2. Climate models

The application of climate model outputs within CCAMLR's management of Southern Ocean ecosystems could enhance population models and stock assessments, such as for krill and toothfish, (Constable et al., 2017). Using climate models to inform fishery management could allow CCAMLR to account for current and future climate trends (Constable et al., 2017), and ultimately respond to these changes by applying environmentally informed dynamic stock assessments (described further below) and adaptive spatial and temporal

Table 2
Description of the five conservation issues outlined in the proposed climate change response work plan (CCRWP) with suggested actions and responses for implementation by CCAMLR. We also highlight CCAMLR's progress towards the identified action, based on CCRWP (Delegations of Norway and Australia, 2018) and CCAMLR, SC-CAMLR and Working Group reports. Issues and actions in direct quotes are directly from the CCRWP (Delegations of Norway and Australia, 2018).

Issue	CCRWP Action	CCAMLR's progress
"Structural reform and dialogues to improve consideration of climate change impacts"	"Include climate change as agenda item for all working groups and incorporate climate change advice into considerations for SC-CAMLR; Working Groups to identify specific research and monitoring requirements".	Climate change was added to the permanent agenda of SC-CAMLR in 2008; also added to the Working Group on Ecosystem Monitoring and Management (WG-EMM) but has not yet been added for all Working Groups (WGs). However, this is now set to change. Following the 2022 SC-CAMLR and Commission meetings, climate change will be added to the Terms of Reference for all WG starting in 2023.
	SC-CAMLR and CCAMLR papers and Fishery Reports to include climate change implication statements.	All fishery reports include a climate change implication statement (see Table 3); A work plan is only included for *D. mawsoni* in 88.1; Climate Change Implication Statements have been considered for inclusion (since 2015) in SC-CAMLR and CCAMLR papers, but they have not yet been adopted into CCAMLR's practice.
	Coordination across CCAMLR and with the Committee for Environmental Protection (CEP).	The climate change intersessional contact group continues to operate. Updated Terms of Reference have been proposed but not yet endorsed. SC-CAMLR coordinates and facilitates relevant actions (e.g., in their 5-year work plan). CEP and CCAMLR conducted a joint workshop for climate change and monitoring in 2016 with the potential for a second one in the near future.
	"Identify and engage relevant climate experts, and ensure experts have opportunity to provide information to the Scientific Committee and its Working Groups; " SC-CAMLR engage with relevant international research programs.	CCAMLR has made efforts in recent years to build capacity (e.g., through the CCAMLR Scientific Scholarship Scheme), but has still been criticized for its need to improve transparency and provide independent experts access to WGs. CCAMLR is currently engaging with relevant research programmes in the context of climate change including SCAR, ICED, SOOS.
"Effects of climate change on Antarctic marine living resources and associated sustainable exploitation"	Encourage research and assessment on climate change impacts on key species, ecosystems, and food webs. Includes national and international (e.g.,	Continuous advice from SC-CAMLR and WG, but not yet being applied in management.

(*continued on next page*)

Table 2 (*continued*)

Issue	CCRWP Action	CCAMLR's progress
	SCAR, ICED) programs, including field-based.	
	Develop quantitative scenarios and projections of change in Antarctic marine living resource populations, food web/community structure and regions; Assess status and trends of fisheries (including fishing impacts and spatial changes); Spatially explicit stock assessments; Improve habitat and species baseline data.	Research (including through fishing vessels) is ongoing. Scientific efforts e.g., through SCAR, MEASO (Marine Ecosystem Assessment for the Southern Ocean), and ICED (including the 2018 ICED-CCAMLR Projections Workshop (Murphy et al., 2018) and the 2021 ICED krill modeling workshop (Veytia et al., 2021) have sought to fill some of these gaps. Outputs from these groups are submitted to SC-CAMLR and its WGs, but improved mechanisms for incorporation into management are needed. A SC-CAMLR workshop on integrating climate change and ecosystem interactions into CCAMLR science is scheduled for 2023.
	Develop and evaluate models of krill populations, including dependent predators and climate change effects; develop and adopt feedback management for krill fisheries, including stock assessments.	In 2019, SC-CAMLR endorsed a new work plan towards updating management for kill, which includes a risk assessment. In 2021, the krill management strategy was further updated to encompass more nuanced spatial scale, connectivity, and ecosystem impacts. Environmental drivers have yet to be incorporated into krill stock assessments.
	Enhance ecosystem resilience, including through establishing a representative system of MPAs.	Two MPAs are adopted, with three MPAs in the East Antarctic, Weddell Sea and western Antarctic Peninsula under negotiation.
"Marine habitats at risk due to climate change"	Research and assessment on ocean acidification impacts; review and revise management tools to address the risk from ocean acidification.	National programs, including the Australian Antarctic Program, have increasingly advocated for more research on the impacts of ocean acidification on Antarctic krill. SCAR has an Ocean Acidification Action Group.
	Encourage research by national programs, SCAR, ICED and others regarding habitat status, trends, vulnerability and distribution; include collaborative long-term monitoring of change. Revise existing management tools towards climate change adaptation for at risk habitats.	Conservation Measure 24–04 provides a framework for this, however, it has only been fully implemented in one location thus far. Ongoing work, including through scientific research programs such as by SOOS, ICED, and SCAR, and information sharing with CCAMLR is progressing this.
	"Identify reference areas for future research, including research specified in MPA Research and Monitoring Plans."	Represented in current Southern Ocean MPAs (South Orkney Islands Southern Shelf and Ross Sea region MPAs); current MPA proposals include reference areas; progressing in ongoing research activities, including through SCAR and ICED.
"Marine species at risk due to climate change"	"Examine spatial management across CCAMLR to account for changes in species distribution"	Management for CCAMLR fisheries does not account for changes in species distributions. However, all fishery reports now have Climate change and environmental variability statements (see Table 3).
	Synthesize existing information for important species, complete quantitative analyses of population processes, develop models of impacts of change on food webs and community structure, and identify knowledge gaps; encourage targeted field studies and research by national programs including SCAR and ICED.	Programs such as those operating through SCAR, SOOS, ICED & MEASO all have extensive efforts underway including: 2018 MEASO conference and related publication outputs (see Frontiers in Ecology and Evolution, 2022); the 2018 & 2021 ICED workshops (see above); ongoing joint ICED-CCAMLR activities; ongoing SCAR and ICED studies of key species' and systems responses to change; activities by the SCAR Krill Action Group (SKAG); ICED development of key species models; ICED-Sentinel benchmarking field program; the 2017 third International Symposium on Krill (WG-EMM-16/34, 2017). Outputs from these groups are submitted to SC-CAMLR and its WG, but better mechanisms for incorporation into management are needed.
	Review and revise management tools towards affording the best adaptation promise and conservation status for species at risk of climate change; consider if and how IUCN Red List criteria can be applied; continue to identify reference areas for future research (including in MPA research and monitoring plans).	Ongoing through information sharing with SCAR and other programs; MPA research and monitoring plans (current and proposed) have some climate change elements.
"Enhanced potential for non-native species introduction and establishment"	"Assessment of whether existing regimes for preventing marine non-native species introductions and transfer are sufficient. Analyze management tools applied in other marine ecosystems."	CEP leads on non-native species in the Antarctic, and its work plan has prioritized work on risks associated with marine non-native species in coming years.
	"Assessment of risks of introducing non-native marine species"; ongoing monitoring.	The CEP is scheduled to undertake a risk assessment in 2023/24.

management. While extensively discussed by SC-CAMLR and its Working Groups, currently climate models have not been directly applied in CCAMLR's fisheries management (see Table 1).

Fisheries across the globe have grappled with applying climate models for fishery management; and thus, CCAMLR is not alone. This is in part due to the high costs associated with adopting new technologies, lack of resources for data collection, bureaucratic barriers preventing the adoption of high tech fishery data systems, lack of trust from fishery management organizations, and ultimately lack of expertise (Bradley et al., 2019). Similarly, discrepancies between scales (spatial and temporal) of climate models versus biological processes is a substantial challenge, partially due to the mismatch between global climate forecasts and localized environmental effects (Brown et al., 2016; Cavanagh et al., 2017).

Yet, these barriers are not insurmountable. Recent improvements in global dynamic climate models are already proving to be helpful across a wide variety of industries and could be applied to the Southern Ocean. Applications of climate model outputs have allowed industry managers to reduce the vulnerability of the agricultural sector to climate variability (Meza et al., 2008) as well as enhancing the capability of seasonal forecasts of living marine resources targeted by the fishing industry (Siedlecki et al., 2016; Stock et al., 2017). When applied to the Southern Ocean, identifying models that consider seasonal variability and the potential effects of climate change and fisheries on recruitment, such as for krill, will be crucial for setting sustainable catch limits (Meyer et al., 2020). Currently, CCAMLR's krill biomass estimate in the Antarctic Peninsula region (~62 million tonnes) was conducted by a single acoustic survey, and therefore only represents a snapshot in time that does not consider seasonal variability and the potential effects of climate and fisheries on krill recruitment (Hill et al., 2020; Meyer et al., 2020).

4.3. Environmentally informed dynamic stock assessments

While CCAMLR has a precautionary catch limit for krill and toothfish (and icefish) (Miller and Slicer, 2014), the parameters used for the stock assessments do not consider environmental change nor the effects of climate on recruitment, mortality, and growth (Hill et al., 2020). This is especially problematic because krill recruitment is extremely variable (recruitment cycles can take 5–8 years) and distinctly specific to each region (Loeb, 2007; Ross et al., 2014; Watters et al., 2020). A long term goal of CCAMLR has been to manage krill fisheries based on ecosystem monitoring indices (Wang et al., 2021), as stated in the CEMP. Implementing this would require an integrated and environmentally informed stock assessment, one that considers the environmental factors affecting the life stages of krill populations. (Fabra and Gascón, 2008; Wang et al., 2021). Similarly, toothfish fishery stock assessments are single-species and do not incorporate ecosystem monitoring indices or environmental variability (Abrams et al., 2016). In CCAMLR's second performance review conducted in 2017, the panel observed that harvest strategies for both krill and toothfish use parameters that imply no change to the ecosystem other than due to natural variability. The panel argued that strategies need to be developed that will achieve the Convention objectives and be robust to ecosystem changes, including climate change, fishing, and tourism (Performance Review Panel, 2017).

While climate informed quotas (based on climate data) and climate quotas (implemented to reduce catch to factor stress/declines from climate change) have not been widely implemented in fisheries, other industries have implemented similar strategies. For example, many water managers now account for climate change and predicted reductions in rainfall by setting "reduced irrigation allowances from river flow" to protect the future ecological integrity of the system (Johnson and Welch p. 119, 2010). Considering climate informed quotas and incorporating ecosystem monitoring indices in CCAMLR's stock assessments might allow for accounting for climate variability and its long term effects on the ecological system, thereby helping to meet the objectives under Article II.

Notably, in 2018, SC-CAMLR's Working Group on Fish Stock Assessment updated all of CCAMLR's Fishery Reports to include a section on climate change and environmental variability (SC-CAMLR, 2018; CCAMLR, 2022b). This section includes information on potential changes in model parameters and productivity assumptions as well as considering the impact of observed changes in biological parameters on management advice. Thus far, while all of CCAMLR's fishery reports for krill, toothfish and icefish have this section, almost all of them have the same statement which points to the risk and CCAMLR's approach to climate resilience being focused on a EBFM approach, MPAs, and monitoring programs (see Table 3). Only Antarctic toothfish fisheries in the Ross Sea (Subarea 88.1 and 88.2) had a stock specific statement and there is only a Work Plan for Antarctic toothfish in Subarea 88.1. While having these statements is a useful first step, formal evaluation and work plans are needed to move towards actually assessing the stocks and managing for climate change and environmental variability. A Climate Change workshop is planned for 2023 to focus on integrating climate change and ecosystem interactions into CCAMLR science (SC-CAMLR, 2022; Hughes et al., 2022).

CCAMLR has made other modest strides towards managing for climate change. For example, they have an ongoing Memorandum of Understanding with some adjacent RFMOs (e.g., the South Pacific Regional Fisheries Management Organization) (SPRFMO, 2022) which would allow for cross institutional collaborative management if harvested species shift distributions. Further, in 2019 CCAMLR agreed on a new framework for managing Antarctic krill (SC-CAMLR, 2019), which includes the use of a risk management approach that ideally provides actionable information to inform decision-making (Bryndum-Buchholz et al., 2021). The risk assessment entails looking at areas where predators and fisheries access krill, and ultimately minimizing the risk of overlap (SC-CAMLR, 2021b; Warwick-Evans et al., 2022). Evidence shows that even low scale fishing for krill in the wrong place at the wrong time can have significant effects on predators (Trathan et al., 2022; Watters et al., 2020). While the risk assessment is not included as a parameter in the stock assessment, it can be considered when setting catch limits.

4.4. Marine protected areas

CCAMLR has committed to create a network of Southern Ocean MPAs for the conservation of marine biodiversity, including being a tool for climate resilience (CCAMLR, 2011). While CCAMLR's efforts to establish a network of MPAs has been commendable, CCAMLR has come under criticism for the rate at which it is able to complete work on MPA designations (Performance Review Panel, 2017). Only two MPAs have been adopted, with three more MPAs under negotiation (see Fig. 1). These additional proposed MPAs would increase ecological representativeness of protection significantly (Brooks et al., 2020). Most of these MPA proposals also include climate change reference areas and explicit intention to enhance resilience to climate change. CCAMLR Members have been discussing these proposals for years (e.g., the East Antarctic Proposal has been discussed since 2011), and while the majority of members agree on the establishment of MPAs as an essential part of their obligations to conserve Antarctic marine life, two members of CCAMLR have continued to object (Goldsworthy, 2022; Teschke et al., 2021; Sylvester and Brooks, 2020; Tang et al., 2020). MPA implementation will improve adaptation capacities and ultimately contribute to enhancing the Southern Ocean ecosystem's resilience to the effects of climate change (Constable et al., 2022; Pentz et al., 2018; Roberts et al., 2017; Chown and Brooks, 2019).

Adjacent to CCAMLR's MPA discussions, in 2016 CCAMLR adopted an innovative climate responsive spatial management measure. Conservation 24–04 *Establishing time-limited Special Areas for Scientific Study in newly exposed marine areas following ice-shelf retreat or collapse in Statistical Subareas 48.1, 48.5 and 88.3* (CCAMLR, 2017), focused on the rapidly warming Antarctic Peninsula, provides a means to protect areas

Table 3
Climate change and environmental variability statements and work plans for CCAMLR managed fisheries (extracted from CCAMLR's Fishery Reports (CCAMLR, 2022b, Section 7).

Fishery & Area	Statement	Workplan
Euphausia superba, Area 48 *Dissostichus eleginoides*, Subareas 48.2, 48.3, 48.4, 51, 58.6, 58.7; Divisions 58.4.3a, 58.4.3b, 58.4.4a, 58.4.4b, 58.5.1, 58.5.2 *Dissostichus mawsoni*, Subareas 48.2, 48.4, 48.6, 88.1; Divisions 58.4.1, 58.4.2, 58.4.3b *Champsocephalus gunnari*, Subarea 48.3 (statement and work plan listed to the right applies to all fisheries and areas listed above)	“A recent summary of the potential impacts of climate change on Southern Ocean fisheries (FAO, 2018) highlights the following key points: *The Antarctic region is characterized by a complex interaction of natural climate variability and anthropogenic climate change that produce high levels of variability in both physical and biological systems, including impacts on key fishery taxa such as Antarctic krill.* *The impact of anthropogenic climate change in the short-term could be expected to be related to changes in sea ice and physical access to fishing grounds, whereas longer-term implications are likely to include changes in ecosystem productivity affecting target stocks.* *There are no resident human populations or fishery-dependent livelihoods in the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Area, therefore climate change will have limited direct implications for regional food security. However, as an “under-exploited” fishery, there is potential for krill to play a role in global food security in the longer term.* *The institutional and management approach taken by CCAMLR, including the ecosystem-based approach, the establishment of large marine protected areas, and scientific monitoring programmes, provides measures of resilience to climate change.*”	There is no formal evaluation of the impacts of climate change and environmental variability available for any of these fisheries.
Dissostichus mawsoni, Subarea 88.1, 88.2	“The impact of Anthropogenic climate change in the short-term could be expected to be related to changes in sea ice and physical access to fishing grounds, whereas longer-term implications are likely to include changes in ecosystem productivity affecting target stocks (FAO, 2018). In anticipation of potential impacts of climate change on targeted fish stocks, the Scientific Committee indicated that changes in productivity parameters may impact assessments and management advice, and these changes may be related to long-term environmental change, shorter-term variability, or potential effects of fishing (SC-CAMLR XXXVII paragraph 3.51, Annex 9 paragraph 2.28). The parameters that could be evaluated for the effects of environmental variability and change would include mean recruitment, recruitment variability, mean length at age, mean weight at length, natural mortality, and maturation ogives. Other factors that may impact assumptions underlying the assessments that could also be considered, including stock distribution (for example, for its impact on tagged fish distribution or research survey interpretation), sex ratio (indicating maturation or other sex specific changes), and the ages or lengths observed in the fishery (indicating changes in vulnerability patterns or mortality).”	The work plan associated with the impacts of climate change on Subarea 88.1 *D. mawsoni* is to: i. Use historical data to investigate trends in key parameters affecting estimates of toothfish yield (and hence management advice). ii. If trends are identified, adjust parameters in stock assessment and yield estimate to allow for trends continuing in future. iii. Investigate evidence for trends being related to physical, oceanographic or ecological drivers, but note that establishing causality of trends may not be possible and is not essential. – There is no formal evaluation of the impacts of climate change and environmental variability available for Subarea 88.2 *D. mawsoni.*

recently exposed due to ice-shelf retreat or collapse so that they can be studied. This measure provides a powerful tool to facilitate studying the most rapidly changing regions of the Antarctic and was first implemented in 2017 with a section of the Larson C Ice Shelf designated as a Special Area for Scientific Study (protected for a ten year period, through 2028). A major calving of the Pine Island Glacier received initial designation in 2019. However, consensus could not be reached to extend its designation (CCAMLR, 2021), due to political barriers and challenges with consensus-based decision-making (see below).

5. Challenges in managing fisheries under climate change

While much attention has been given to the effects of climate change on ocean ecosystems across the globe, fisheries management bodies have grappled with implementing strategies to manage for climate change (McBride et al., 2021; Bryndum-Buchholz et al., 2021), and CCAMLR is no exception. Beyond barriers noted above (e.g., related to data availability, scale, capacity), this is in part due to the lack of political incentives to acknowledge and prepare for the effects of climate change (Termeer et al., 2017). Hughes et al. (2021) suggests some of the major challenges facing Southern Ocean management are: (i) helping CCAMLR policymakers understand the current and future impacts of climate change on Southern Ocean ecosystems, and (ii) successfully implementing conservation management tools to address climate change impacts at a regional level. CCAMLR is aware of the urgent need to develop climate responsive options within its ecosystem approach to management, however, factors such as limited capacity and political differences have slowed progress (Cavanagh et al., 2021b). The situation

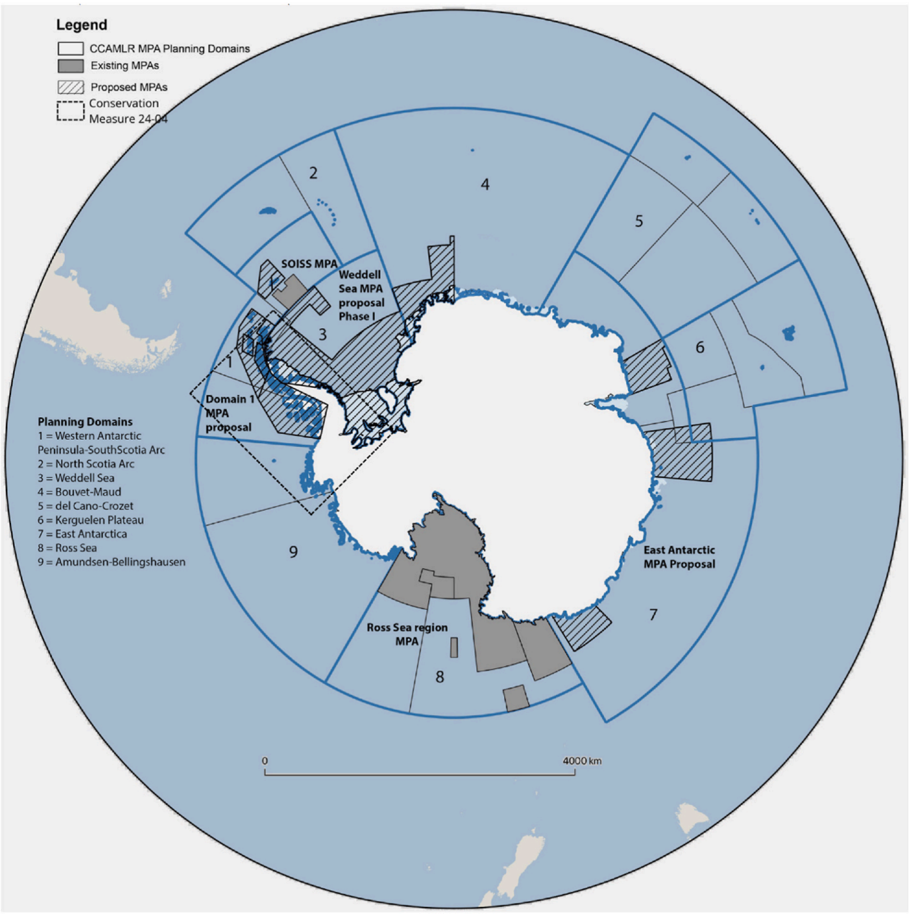

Fig. 1. CCAMLR area boundaries, showing the nine MPA planning domains, along with adopted and proposed MPAs. The region applicable to Conservation Measure 24–04 (time-limited Special Areas for Scientific Study in newly exposed marine areas following ice-shelf retreat or collapse) shown by dashed line box (CCAMLR boundaries, MPA planning domains, adopted MPAs, Conservation Measure 24–04 all based on CCAMLR data (CCAMLR GIS, 2022); MPA boundaries based off of previous published coordinates in Apelgren and Brooks (2021) (CCAMLR, 2017).

is further complicated by CCAMLR's consensus requirement. For example, while there is emphasis on the use of "best available science" to determine appropriate harvest levels (Performance Review Panel, 2017; Constable et al., 2000), there is often disagreement between CCAMLR Members about what "best available" constitutes, and a tendency to delay policy adoption in the face of scientific uncertainty (Constable, 2011). In the context of climate change, while better climate models and forecast evaluations for Antarctic ecosystems are needed (Murphy et al., 2017; Constable et al., 2014; Brooks et al., 2018; Busch et al., 2016; Cavanagh et al., 2017; Heenan et al., 2015; Karp et al., 2019; Quentin Grafton, 2010), policymakers should not wait for the perfect scientific information – to do so would foreclose options for future decision-making and restrict the ability to manage for environmental change effectively (Press, 2021).

Furthermore, managing for climate resilience in the Southern Ocean could be improved by increasing scientists' awareness of the opportunities to inform environmental policy making within the Antarctic Treaty System (Hughes et al., 2018, 2022). This would allow for better communication across the Antarctic Treaty System and the possibility to address knowledge gaps in research and management (Hughes et al., 2018). Achieving climate resilient fisheries in the Southern Ocean will heavily rely on the co-production of knowledge to build governance and management strategies that consider the effects of climate change (Mills et al., 2022). There is an argument that CCAMLR's consensus-based decision-making approach will ultimately progress only to the level deemed acceptable by the parties least interested in reform (Pentz and Klenk, 2017). Consensus-based rules, especially when employed in multilateral conventions having members with diverse interests, such as CCAMLR, heavily favor the status quo rather than embracing adaptive approaches (Pentz and Klenk, 2017; Goldsworthy, 2022).

Some fisheries across the globe are making significant strides to manage for climate resiliency and can provide lessons learned to CCAMLR. The Australian government for example, passed a climate adaptive management strategy to enhance the resilience of fishing industries to climate change, and between 2010 and 2016, 9 million AUD were invested in preparatory research for a climate adaptation program (Bryndum-Buchholz et al., 2021). In Belize, in 2020, after decades of fisheries being managed through an open-access system, Belize adopted the New Fisheries Resource Act which incorporates an MPA program and a Managed Access Program to transition Belize fisheries management towards long term sustainability and climate resiliency (Rader et al., 2021). However, as Bryndum-Buchholz et al. (2021) points out, none of the active fishery policies and legislations reviewed in the extensive study, including Australia and Belize, explicitly address climate change impacts or incorporate mandates to account for climate change in stock assessments.

A similar study by Sumby et al. (2021) examined RFMOs (including CCAMLR in the RFMO category) operating in "climate change hotspots" and showed that while 94% of the fisheries managers surveyed demonstrated awareness of climate change, only 41% showed some sort of action; most of which were mainly procedural and administrative, such as requesting more research, forming committees, proposing education programs etc. (Sumby et al., 2021). Of the 17 RFMOs or fisheries bodies surveyed, only two made explicit statements about incorporating climate change in their future management (Sumby et al., 2021) and CCAMLR was one of them. Other more substantive actions by RFMOs included making climate change considerations part of stock assessments, pushing for management reforms that are resilient to climate change, and reaching out to the international community for greater transparency and action against climate change (Sumby et al., 2021).

However, there is very little indication that climate change management is accounted for in RFMOs fishery policy, annual decision-making, or operational regulation (Sumby et al., 2021).

The future of global fisheries has the potential to be sustainable for the long-term, but depends in part on the implications of climate change being accounted for in their management (Free et al., 2020; Gaines et al., 2018). There is a global need to develop and utilize new technologies focused on ecosystem-based principles that ultimately improve knowledge of linkages between the physical environment and biological productivity at all scales (Tin et al., 2014). CCAMLR has taken some strong strides towards managing for climate change by adopting a climate change Resolution, committing to a network of representative MPAs, adopting Conservation Measure 24–04 to protect areas recently exposed by ice shelf collapse, progressing on a krill risk assessment, improving coordination across CCAMLR, developing a draft CCRWP, and holding an upcoming 2023 Climate Change Workshop. Continuing this work and further integrating climate resilient tools that are specific to the climate change impacts faced in the Southern Ocean will allow CCAMLR to better address the vulnerability of this system. CCAMLR has the opportunity to pave the way for other fisheries management bodies by incorporating climate change into its management (Cavanagh et al., 2021b). However, CCAMLR must move faster and with a sense of urgency to incorporate climate change considerations into its management actions, and ultimately find efficient ways to achieve consensus on climate-related measures.

6. Conclusion

While scientists have proposed numerous methods for climate resilient fisheries management - such as EBFM and tools such as MPAs, climate model outputs, and environmentally informed dynamic stock assessments - fishery management bodies across the globe are grappling with implementing these, and the extent of fisheries explicitly addressing climate change remains low (Bryndum-Buchholz et al., 2021; Sumby et al., 2021; Skern-Mauritzen et al., 2016). While CCAMLR has precautionary catch limits based on stock assessments and has implemented MPAs within its ecosystem approach to management, it does not yet use climate model outputs to inform its decision-making, and incorporation of climate change considerations into its management is lacking. Further, despite substantial efforts by many CCAMLR Members to propose and support progress with this, together with extensive ongoing scientific research in this area, lack of consensus and ultimately lack of political will continue to delay progress. Resilience of Southern Ocean ecosystems to global warming will require the establishment of science-based, climate-informed, ecosystem-based management (Constable, 2022). Given the threats to the Southern Ocean posed by climate change, and that the CAMLR Convention encompasses the principles of an ecosystem-based precautionary approach, CCAMLR has an urgent responsibility to develop and implement climate resilience management tools. Ultimately, climate resilient management of the Southern Ocean will require diverse perspectives in planning and implementation (Constable et al., 2022), and will only be possible with the cooperation of all CCAMLR Member States.

With a mandate for managing marine living resources in the Southern Ocean, which comprises ~10% of the global oceans, CCAMLR has the chance to lead the way on climate resilient fisheries and to be a catalyst for other ocean management bodies to follow. The tools and recommendations highlighted above provide an avenue of strategies that can facilitate a transition to climate resilient fisheries. As climate change and increased human activity across the world's oceans continues to pose a threat to fish, fisheries, and biodiversity, implementing dynamic, flexible, and forward looking tools for fishery management would facilitate fisheries resilience to climate change impacts (Free et al., 2019; 2020).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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