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# Building a coordinated framework for research and monitoring in large-scale international marine protected areas: The Ross Sea region as a model system

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## Abstract

To fulfill their conservation potential and provide safeguards for biodiversity, marine protected areas (MPAs) need coordinated research and monitoring for informed management through effective evaluation of ecosystem dynamics. However, coordination is challenging, often due to knowledge gaps caused by inadequate access to data and resources, compounded by insufficient communication between scientists and managers. We propose to use the world's largest MPA in the Ross Sea, Antarctica as a model system to create a comprehensive framework for an interdisciplinary network supporting research and monitoring that could be implemented in other remote large-scale international MPAs. Our proposed framework has three key components: (i) policy engagement, including delineation of policy needs and ecosystem metrics to assess MPA effectiveness; (ii) community partner engagement to elevate diverse voices,

Cassandra Brooks and Sharon Stammerjohn contributed equally to this work.

build trust, and share resources; and (iii) integrated science comprising three themes. These themes are: advancement of data science and cyberinfrastructure to facilitate data synthesis and sharing; biophysical modeling towards understanding ecosystem changes and uncertainties; and execution of observational and process studies to address uncertainties and evaluate ecosystem metrics. This proposed framework can improve MPA implementation by generating policy-relevant science through this coordinated network, which can in turn improve MPA effectiveness in the Ross Sea and beyond.

**KEYWORDS**
Antarctic, CCAMLR, high seas, international collaboration, marine conservation, marine protected area, research and monitoring, Ross Sea, science–policy, Southern Ocean

## 1 | INTRODUCTION

Healthy oceans are critical to the functioning of the Earth system, yet are threatened by human activities. Overfishing, pollution, invasive species, and climate change are primary threats to ocean health, which in turn impact important ecosystem services (United Nations, 2021). The cumulative impacts of these threats complicate management and mitigation (Halpern et al., 2015). Marine protected areas (MPAs), where fishing and other activities are restricted, are the primary area-based management tool designed to conserve biodiversity, including mitigating impacts imposed by multiple threats (Grorud-Colvert et al., 2021; Jacquemont et al., 2022; Roberts et al., 2017). Large-scale MPAs (>150,000 km$^2$) can be especially effective at achieving conservation outcomes because the greater spatial coverage encompasses marine ecosystems and ecological processes, as well as key migratory routes and critical habitats (Ballard et al., 2012; Lewis et al., 2017; Wilhelm et al., 2014).

Large-scale MPAs are increasingly seen as a tool for enhancing ecosystem resilience to climate change because they often include representation of all trophic levels within an ecosystem, thereby promoting genetic, species, and ecosystem diversity (Jacquemont et al., 2022; Roberts et al., 2017) and preserving critical ecosystem functions, such as carbon sequestration (Ballard et al., 2012; Roberts et al., 2017). However, numerous studies have shown that MPA effectiveness depends upon adaptive management, including research and monitoring (Gill et al., 2017) to evaluate changes in ecosystem structure and function over space and time, which is essential for active response to dynamic environmental conditions and anthropogenic pressures (Nickols et al., 2019). Without such ongoing efforts, MPAs may fail to meet conservation objectives, as lack of data and static management can lead to unaddressed threats and deteriorating ecosystem health (Dayton et al., 2000). Further, effective evaluation demands understanding of the mechanisms of ecosystem change and the drivers of change, including those that can be managed.

Effective MPA research and monitoring is challenging at any scale (Gill et al., 2017; Grorud-Colvert et al., 2021). These challenges are compounded in large-scale international remote regions, where barriers, including inadequate access to data and resources, hamper effective evaluation of MPA performance. Insufficient communication and engagement between scientists and policymakers can lead to research unaligned with policy needs. Moreover, in remote environments like the high seas (i.e., areas beyond national jurisdiction), research and monitoring encounter inherent logistical and technological challenges, and sustainable financing is often lacking, especially for long-term projects. In international spaces, uncoordinated research efforts can lead to gaps in topical and geographic coverage. Thus, effective large-scale MPA management demands engagement by different nations, management bodies, industries, and community groups (e.g., Giakoumi et al., 2018; Grorud-Colvert et al., 2021).

While relatively few MPAs are currently designated at the large scale (of >18,000 global MPAs, only 36 are >150,000 km$^2$; MCI, 2024), these comprise 81.2% by area of the globally protected ocean. Thus, large-scale MPAs are a high-profile strategy for meeting global conservation targets (Lewis et al., 2017; Wilhelm et al., 2014). Currently, ~8% of the global ocean is protected (only 2.9% in fully or highly protected zones and <1% implemented in the high seas) (MCI, 2024), and global targets call for protection of at least 30% of the ocean by 2030 (e.g., the new Global Biodiversity Framework). Further, the new High Seas Treaty provides a legal pathway for MPAs in areas beyond national jurisdiction (~64% of the global ocean). Excellent best practices exist for implementing and evaluating MPAs (e.g., Blue Park Awards; The MPA Guide), including for some high seas' areas (see, e.g., Nocito et al., 2022). Here, we build on these best practices, with

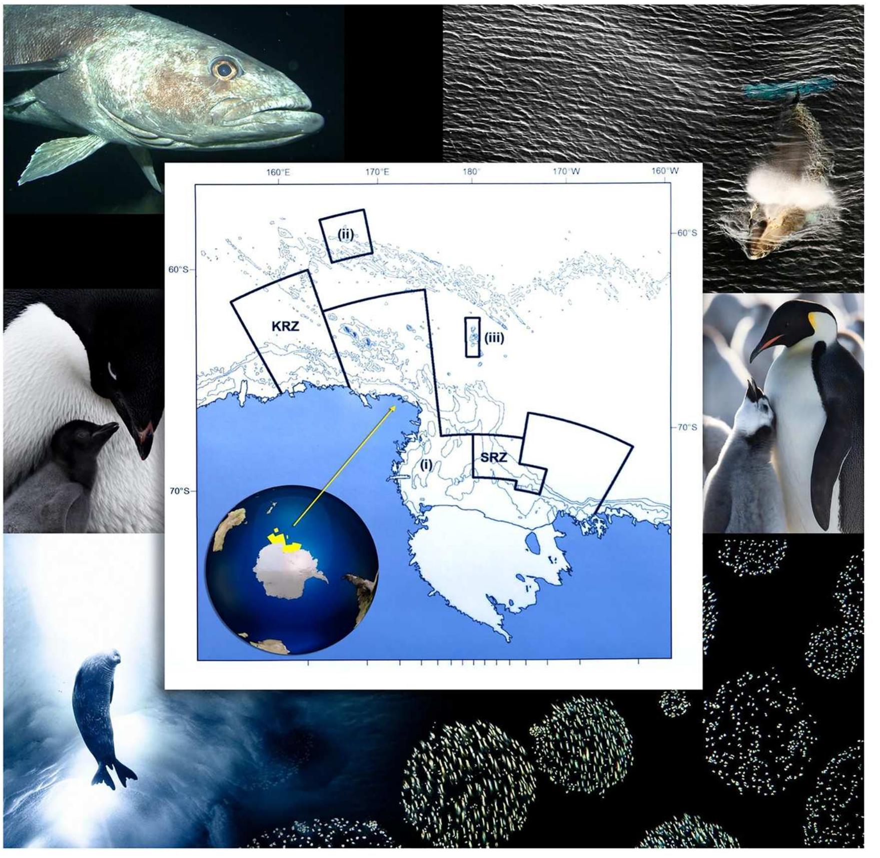


**FIGURE 1** The Ross Sea region MPA, Antarctica—the world's largest MPA. This MPA has three zones: a General Protection Zone (indicated by i, ii, iii), which is closed to commercial fishing, and a Special Research Zone (SRZ) and a Krill Research Zone (KRZ), which both allow limited commercial fishing. The Ross Sea supports a vast array of marine life, including a quarter of the world's Emperor Penguins and a third of the Adélie Penguins. Pictures show clockwise from upper left: Antarctic toothfish (*Dissostichus mawsoni*); Minke whale (*Balaenoptera bonaerensis*); Emperor Penguins (*Aptenodytes forsteri*); Phytoplankton, here showing *Phaeocystis antarctica*; Weddell Seal (*Leptonychotes weddellii*); and Adélie Penguins (*Pygoscelis adeliae*). All photos copyright John B. Weller, except for toothfish photo by Paul Cziko.

a proposed framework for building interdisciplinary networks supporting research, monitoring, and science-policy integration in large-scale remote international MPAs using the Ross Sea region MPA (RSRMPA) (Figure 1) as a model system (Box 1; Figure 2). This framework has three key components: policy engagement, community partner engagement, and integrated science. The integrated science component comprises three themes: data science and cyberinfrastructure, biophysical modeling, and observations that include monitoring and process studies (Figure 2). Three core objectives accompany each of these components (Box 1).

## 2 | RSRMPA AS A MODEL SYSTEM

In 2016, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) adopted the RSRMPA, spanning over 2 million km$^2$ and taking effect in 2017 (Figure 1). CCAMLR is responsible for managing marine living resources in waters around Antarctica and currently has 27 Members (26 Nations plus the European Union). CCAMLR is part of a larger governance regime, the Antarctic Treaty System, a suite of agreements that collectively afford protection of the region (Nocito et al., 2022). The objective of CCAMLR is conservation, and commercial fishing is allowed under a precautionary, ecosystem-based approach, which demands consensus-based decision-making based on the best available science (Constable et al., 2000). In line with this precautionary approach, CCAMLR has designated two MPAs to date: the South Orkney Islands Southern Shelf MPA (~94,000 km$^2$, established in 2009) and the RSRMPA. CCAMLR is the only management body that has implemented actively managed, highly protected, large-scale, international MPAs, setting precedent and leadership in the high seas (MCI, 2024; Nocito et al., 2022).

The RSRMPA was the first large-scale MPA in the high seas, and it is the largest in the world, comprising 7.4% of all global marine protection (18% of highly/fully protected areas) (MCI, 2024). The Ross Sea is one of the most productive regions in the Southern Ocean, supporting a disproportionate abundance of flora and fauna for its size (Ainley et al., 2010), and is considered one of the least impacted large marine ecosystems in the world (Halpern et al., 2015). It is well studied, including some time series going back >180 years (Ainley et al., 2010), and an established community of scientists collaborate via international science organizations (e.g., the Southern Ocean Observing System [SOOS] and Scientific Committee on Antarctic Research [SCAR]).

The Ross Sea ecosystem faces multiple threats, including climate change and fishing (Brooks & Ainley, 2022), mirroring oceans globally (United Nations, 2021). The

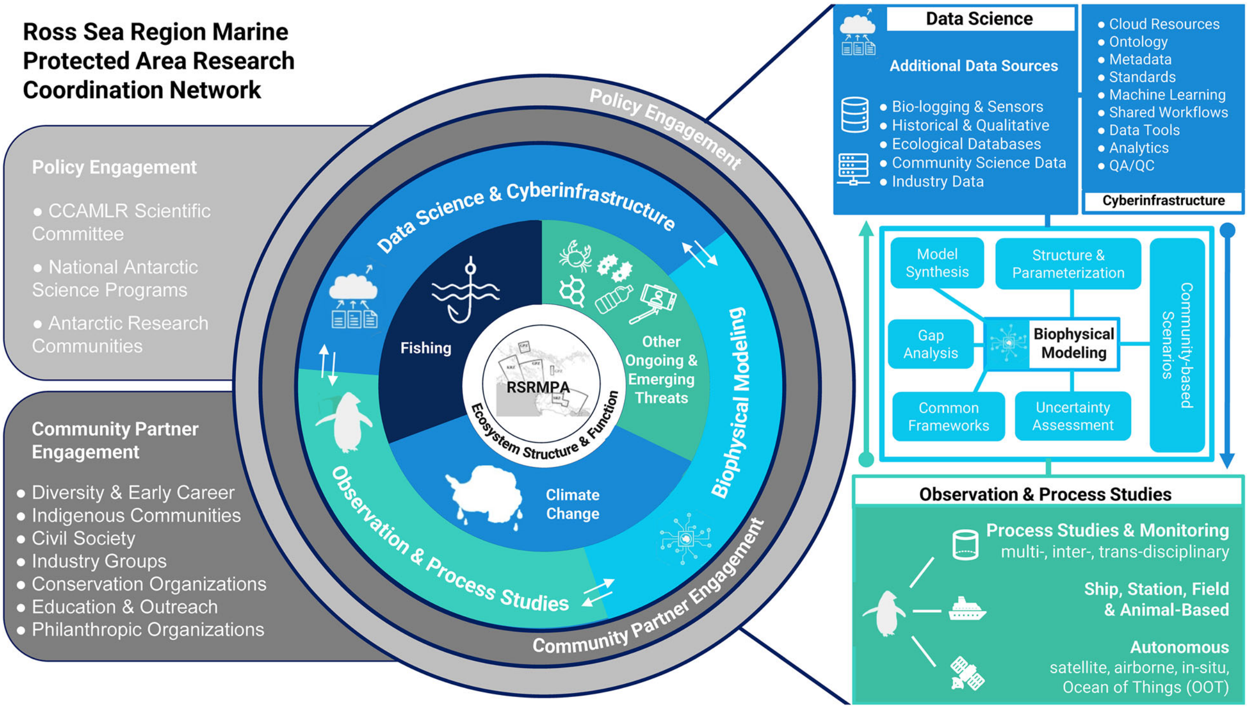


**FIGURE 2** A proposed framework for an internationally coordinated network for the Ross Sea region MPA (RSRMPA) that comprises three key components: policy engagement, community partner engagement (left), and integrated science which consists of data science and cyberinfrastructure, biophysical modeling, and observations, including monitoring and process studies (right). The placement of the RSRMPA at the center of the framework emphasizes the importance of understanding the structure and function of this ecosystem and its threats. The proposed framework for achieving policy-engaged science uses a policy (outer ring) and community partner informed coordination space (second outer ring), within which policy-relevant science (third ring inward) is conducted.

Southern Ocean and its seasonal sea ice are highly variable and rapidly changing. Sea ice has undergone a recent shift, with record low sea ice extents starting in late 2016 and plummeting further in 2022 and 2023, with especially heavy losses in the Ross Sea (Siegert et al., 2023). Disentangling impacts is difficult, but climate change is known to affect both physical and biological systems, with increasing impacts predicted (Chown et al., 2022). These changes will likely have devastating impacts on Southern Ocean marine life, including increased potential breeding failure for Emperor Penguins (Chown et al., 2022; Siegert et al., 2023) and declines in critical Adélie Penguin molting habitat (Schmidt et al., 2023).

For more than 20 years, the Ross Sea has supported a commercial fishery targeting Antarctic toothfish, the region's top fish predator, leading to concerns about ecosystem impacts (e.g., Abrams et al., 2016). Ongoing studies have not yet disentangled fishery impacts from environmental change in the Ross Sea, but this remains a core objective of the RSRMPA. Antarctic krill (*Euphausia superba*), a key Southern Ocean prey species, is not currently fished in the Ross Sea and in general, little is known about krill (e.g., abundance, distribution, life history) in the region, representing a major knowledge gap (Brooks & Ainley, 2022). Any new krill fishing in the Ross Sea would require CCAMLR approval. Beyond climate change and potential overfishing, other ongoing threats include tourism, invasive species, pathogens, and pollutants (e.g., plastics).

The RSRMPA has 11 specific objectives focused on conserving ecosystem structure and function, as well as promoting research (Brooks & Ainley, 2022). Most of the RSRMPA (~80%) prohibits commercial fishing, while the other 20% establishes research fishing zones to study environmental change and fishing (Figure 1). The MPA will be in effect through 2052, at which point consensus agreement would be required to keep it in place. Every 10 years, CCAMLR must review the RSRMPA to evaluate whether its objectives are being achieved (or are still relevant) and whether changes to the MPA are appropriate. Every 5 years, CCAMLR Members submit reports of research and monitoring activities in support of the MPA. In 2017, a research and monitoring plan for the RSRMPA, identifying key indicators for evaluating ecosystem change and MPA efficacy, was developed and endorsed by CCAMLR's Scientific Committee (Dunn et al., 2017). To date, however, CCAMLR has not endorsed the plan. While the plan provides a framework, implementation and resources are left to CCAMLR Members, highlighting the need for international coordination.

## 3 | THE OPPORTUNITY FOR INTERNATIONAL COORDINATION IN A MODEL SYSTEM

The first 5-year reporting for research and monitoring occurred in 2022. Reports revealed that despite extensive scientific activities (460 projects in total) conducted by many CCAMLR Members (primarily the United States, New Zealand, Italy, and South Korea), gaps in both topical and geographic coverage remain (CCAMLR, 2022). Additionally, much of the research was not designed to specifically assess RSRMPA effectiveness (Brooks & Ainley, 2022; Stammerjohn et al., 2022). This indicates nationally funded research programs are currently inadequate for comprehensive MPA monitoring and assessment. Furthermore, research by scientists who are not CCAMLR representatives lacks a clear pathway into the policymaking process. Improved MPA assessment could be achieved by facilitating better international coordination of scientific and logistic capacity.

These challenges are not unique to CCAMLR and will affect any future high seas' MPAs coordinated under the new High Seas Treaty. Policy mechanisms for MPAs under this treaty must be developed and will necessarily involve collaboration with established regional fisheries management organizations (RFMOs) and other bodies. Therefore, establishing a framework for building coordinated networks supporting research and monitoring in large-scale international MPAs is paramount.

In October 2022, an international Ross Sea planning meeting endeavored to develop strategies to support these efforts in the RSRMPA. Participants emphasized the critical importance of science-policy integration and community partner engagement, which comprise the overarching objectives of the framework presented here (Box 1; Figure 2). Within this framework, three science streams were identified: data science and cyberinfrastructure, biophysical modeling, and observations including monitoring and process studies (Figure 2) (Stammerjohn et al., 2022).

Since the 2022 workshop, an international community of Ross Sea scientists has worked towards building a coordinated community for RSRMPA research and monitoring. In 2027, the first 10-year MPA review will present a critical opportunity to coordinate across the science, policy, and other partner communities to ensure the 2027 review (and subsequent reviews) are well grounded in robust scientific data and analyses, with streamlined inputs to policy. Ultimately, a coordinated research network is urgently needed to provide CCAMLR with the information to make informed decisions about MPA re-adoption in 2052. Further, lessons learned through full implementation of this coordination framework in the Ross Sea could offer guidance on how other large-scale international MPAs are monitored and assessed.

**Objectives for a scalable framework, as applied to the Ross Sea region MPA**

I. Identify the **policy needs** and the relevant **ecosystem metrics** to evaluate the RSRMPA, including consideration of generalized ecosystem metrics applicable to other large-scale international MPAs. This demands working with all the relevant partners, including directly with the policy community.

II. Identify and create targeted, audience-specific collaboration strategies to **engage and diversify** partner communities, elevate voices, enhance coordination, bridge disciplines, and engage across career levels. This critically important objective demands engagement with a diversity of audiences while creating new opportunities for inclusion and collaboration.

IIIa. Identify and expand existing **data sources and management systems, tools, and cyberinfrastructure** to support data sharing, management, and standard methodologies with a focus on user- and policy-friendly data that enhance equitable access to data products and decision-support tools.

IIIb. Identify and develop **modeling approaches** that can address policy needs to assess and predict changes in ecosystem metrics. Toward this end, knowledge and methodologies must be synthesized across the hydro-, cryo-, and biospheres and across all trophic levels, while reducing uncertainty in model projections.

IIIc. Identify **observations, including monitoring and process studies** to fill policy-identified data gaps, while informing and evaluating ecosystem metrics and model simulations, with a focus on long-term datasets and technological innovations. This demands an internationally coordinated approach to leverage field resources, acquire observations, and undertake process studies needed to address key questions.

## 4 | BUILDING A NETWORK FOR COORDINATION

By effectively engaging policy, science, and community partners, the proposed framework will directly address policy needs, improving implementation and evaluation of

MPAs through integrated science. Details of each component are elaborated on below, including on the three themes of the integrated science component. Some components and objectives of the framework (Figure 2; Box 1) could be applied across scales. However, in using the RSRMPA as a model system, we emphasize applicability for other future large-scale international MPAs.

## 4.1 | Policy engagement

A major weakness in MPA research and monitoring is the disconnect between policymaking and science, even in competent management bodies like CCAMLR. The proposed framework will streamline a process for translation of research into policy-relevant scientific advice and, conversely, incentivize scientific research based on policy priorities. Developed in consultation with the CCAMLR community to identify policy needs and policy-relevant ecosystem metrics, the framework will also establish a roadmap for scientists external to CCAMLR, identifying pathways to bring their science into the policy process. These pathways include working with CCAMLR representatives to provide scientific input (e.g., data for CCAMLR's MPA Information Repository) for consideration during annual meetings. Optimally, this also means working with CCAMLR to secure access for independent scientists to engage with and attend meetings, including CCAMLR's scientific Working Groups. Scientists must also be informed of CCAMLR's science-policy process and research priorities. Thus, communication pathways must flow between CCAMLR and external scientists. A cloud-based data-sharing platform, designed to include policy-relevant metrics, would further facilitate engagement and collaboration (see cyberinfrastructure section).

While policy engagement is critical for successful MPA research and monitoring at any scale, it is inherently more challenging in large-scale international regimes that govern remote spaces. With a conservation mandate that extends beyond most RFMOs and ongoing active MPA management, CCAMLR can be exemplary for the high seas (Nocito et al., 2022). One limitation of CCAMLR is the lack of MPA-specific sustainable financing, a core enabling condition for effective MPAs (Grorud-Colvert et al., 2021). While the CCAMLR office provides administrative and some technical support, they do not have dedicated funding for MPA research and monitoring; thus, it must be funded by CCAMLR Members. This emphasizes the need for coordination between all programs engaged in Ross Sea research, to build even better bridges to and between well-established science communities for the Southern Ocean (including SCAR and SOOS), and to provide pathways for coordination on science–policy engagement, modeling, cyberinfrastructure, and observation research as identified below. Lessons learned from coordinating across national and international institutions will be critical for other large-scale international MPAs.

## 4.2 | Community partner engagement

The Ross Sea region's status and management has profound implications for all communites on Earth due to Antarctica's crucial role in regulating global circulation, carbon sequetration, and sea-level rise (Chown et al., 2022). Collaboration and engagement must recognize this interconnectedness, elevate under-represented and early career voices, and include diverse community partners including Māori rūnanga (tribal councils), conservation groups, civil society, and industry among many others. Engaging effectively across community partners is critical to creating a network for coordination and facilitating engaged and active research and monitoring. Conservation organizations, civil society, and industry groups already engage with CCAMLR through annual meetings, creating opportunities for continued education, outreach, and engagement. Because the Ross Sea is so close to Aotearoa New Zealand, the inclusion of Te Ao Māori (Māori world view) in the Ross Sea is timely, as recent research has revealed complex histories of voyaging into the Southern Ocean (Anderson et al., 2021). Partnering with Māori from the ground floor in all activities, decisions, and future work on MPA assessment will not only build community and trust but also set precedent of culturally appropriate methods in international waters.

Building trust and engaging effectively among community partners will be critical towards building an international collaborative community for research and monitoring of the RSRMPA. Effective coordination demands creating strategies to engage, educate, and diversify across nations, career stages, and disciplines. Further, to fulfill the overarching objectives of the framework, in-kind resources and sustainable financing should be pursued. This includes enhanced coordination with fishing and tourism industries and new projects and relationships with philanthropic and conservation organizations which can lead to opportunities for financing long-term research. We emphasize the role of science communication for effective partner engagement and thus the importance of engaging with outreach and media organizations and training scientists in public/policy communication techniques. This can be particularly important for regions like Antarctica and other international remote regions. We also emphasize creating research and professional opportunities for early career scientists, including students.

## 4.3 | Integrated Science

### 4.3.1 | Data science and cyberinfrastructure

Data science and cyberinfrastructure provide critical structures for coordinated research. Despite gaps, extensive datasets exist for the Ross Sea. However, many are not easily accessible, emphasizing the need to ensure accessibility to historic and ongoing datasets for both the research community and policymakers. Data management must establish a two-way data exchange, which accommodates and integrates external data, while also ensuring transparency and alignment with data sovereignty principles for government programs and Indigenous communities, as well as Findable, Accessible, Interoperable, and Reusable (FAIR) principles (Wilkinson et al., 2016). The overarching aim is to reduce barriers between scientists, community partners, and policymakers, while increasing usability and interpretability of data for cross-disciplinary research within and beyond the Ross Sea.

Development focuses on identifying and integrating existing databases and datasets; creating infrastructure to store, process, analyze, and disseminate large amounts of diverse data; enhancing data accessibility and interoperability; establishing data governance protocols that ensure integrity and ethical use; and leveraging commercial technologies (e.g., Sarma & Van Der Hoek, 2002; Wright et al., 2009), including cutting-edge data science stacks and off-the-shelf tools. This theme utilizes predictive modeling, advanced machine learning, data visualizations, and other innovative tools on collaborative cloud-based platforms and will support a proactive, open, and data-driven approach to marine conservation that can be applied across scales to create policy-relevant products.

### 4.3.2 | Biophysical modeling

Biophysical modeling is critical for evaluating ecosystem metrics identified by policy needs. Given the logistical difficulty and high costs of conducting in situ research in large-scale remote spaces, modeling can provide a cost-effective means of making projections across space (filling data gaps) and time (projecting into the future) and can also incorporate existing observational data. The biophysical modeling theme of the proposed framework aims to identify, develop, and evaluate modeling approaches that integrate the climate system (ocean, sea ice, atmosphere), biogeochemical cycling, food-web interactions, and fishing activity. This work can then be used to: (1) assess policy-relevant ecosystem metrics and evaluate ecosystem response; and (2) synthesize knowledge and methodologies for representing interactions within the biophysical system. This theme involves: combining biological, physical, and biogeochemical data; identifying key limitations of existing models and developing approaches for addressing limitations; identifying and developing modeling frameworks to separate climate change and fisheries impacts on ecosystem structure and function; identifying critical knowledge or data gaps that limit model skill at projecting future states and impacts; assessing uncertainty in model projections; developing approaches for reducing uncertainty; and developing community-based scenarios that can be used to assess and evaluate MPA effectiveness. Ultimately, the biophysical modeling efforts help inform evaluations of the RSRMPA's effectiveness, as well as provide tools for assessing other future large-scale international remote MPAs.

### 4.3.3 | Observations, including monitoring and process studies

The RSRMPA research and monitoring plan provides a detailed description of the observations needed to address identified research gaps, providing clear priorities for this component of the framework (see Dunn et al., 2017). Implementing these priorities entails clarifying hypotheses relevant to the RSRMPA; identifying datasets and knowledge gaps relevant to evaluating these hypotheses and assessing MPA effectiveness; identifying new technologies to address data gaps; advancing long-term datasets; coordinating field campaigns across national programs to expand observations in space and time; and working with cyberinfrastructure to improve sharing of data, code, and analytical approaches.

By coordinating observations across the international landscape, this aspect of the framework can address knowledge gaps more efficiently and effectively, thereby informing management and conservation prioritization (cf. Ballard et al., 2012). Advances in technology, such as sensors, biologgers, and autonomous vehicles, have enabled data collection across various geographic locations and seasons, addressing a broader range of physical, biological, and ecological questions (e.g., Hindell et al., 2020; Yoda, 2019). Furthermore, field observations can be expanded not only through international collaboration with other national programs but also with industry (e.g., tourism, fishing) to increase opportunities for fieldwork. Effective coordination of observation, monitoring, and process studies is critical for research and monitoring in large-scale international spaces and will both contribute to the continuous improvement of MPA conservation efforts in the Ross Sea and serve as a model for how fieldwork in other large-scale international MPAs can be coordinated and leveraged.

## 5 | CONCLUSIONS

In summary, a comprehensive framework is presented here (Figure 2) as a guide for building a policy- and community partner-engaged network that can facilitate internationally coordinated research and monitoring of remote large-scale MPAs. This framework builds on other well-established MPA frameworks aimed at achieving global goals for the ocean (Grorud-Colvert et al., 2021) and further seeks to address the specific requirements for conducting research and monitoring of large-scale MPAs in remote international waters, acknowledging the need to innovate in modeling and synthesis, observations, and cyberinfrastructure and data science. Further, science–policy contributions from this framework, aimed at remote large-scale MPAs, can also facilitate significant advances in our ability to understand these remote marine ecosystems and how these systems respond to cumulative stressors like climate change and fishing, along with other threats. In short, the overarching goal of the large-scale MPA framework presented here is to support effective conservation and management of those ocean areas that are internationally governed, remote, and vast—and thereby ensure protection and long-term sustainability of global ocean biodiversity.


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## DATA AVAILABILITY STATEMENT

No primary data were collected for this article.


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