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Editorial: Knowledge gaps from the IPCC special report on the ocean and cryosphere in a changing climate and recent advances (volumes I and II)

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Editorial on the Research Topic
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Introduction

The Sixth Assessment cycle of the Intergovernmental Panel on Climate Change (IPCC) is nearing its conclusion with the upcoming release of the Synthesis Report, expected in early 2023. This was an ambitious assessment cycle, with three Special Reports complementing the Assessment Reports produced by each of the three IPCC Working Groups. The Special Reports were also unique in that they combined the scope of multiple working groups. The Special Report on Oceans and Cryosphere in a Changing Climate (SROCC) assessed both the physical basis (WG I) along with the impacts of, and adaptation to, climate change (WG II) on high mountain areas, the polar regions, and the global ocean.

Stark messages emerged from the SROCC:

1. The world's ocean and cryosphere have been "taking the heat" from climate change for decades.
2. The consequences for nature and humanity are sweeping and severe, with impacts already experienced across the entire planet.
3. Timely, ambitious, coordinated, and enduring mitigation and adaptation actions are urgently required to limit these impacts and future risks.

These high-level messages were distilled from the assessment of thousands of peer-reviewed studies, organized into chapters focused on the high mountain cryosphere, polar regions, sea level rise and coastal extremes, and the ocean and marine life. As part of the assessment process, knowledge gaps were identified within each SROCC chapter. The realities of word limits and editing required these sections to be brief, but of course the identification of key uncertainties, emerging issues of concern, and priorities for further research are an important outcome of the assessment process.

To allow a more fulsome consideration of key gaps and uncertainties, we initiated this Research Topic on Knowledge Gaps from the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Here, we introduce the collection of papers within this Research Topic which acknowledge and address the knowledge gaps identified in the SROCC in more depth, and capture recent advances to address these issues. Twenty papers (including original research, perspectives, and reviews) were published from across the cryosphere and ocean science communities. While these studies span disciplines, perspectives, and methodologies, we have grouped them into five themes.

Processes, rates, and impacts of cryosphere change: Observations need to be improved to inform process understanding, and to ensure ongoing monitoring of change

The terrestrial cryosphere is undergoing rapid change. Monitoring these changes, and associated impacts, is challenged by a lack of surface observations. Pritchard argues for a transformation in the quantity and quality of basic observations of snow and ice particularly related to seasonal snow-monitoring and glacier-surveying instruments. Thornton et al. analyze the distribution of *in situ* monitoring and coverage of key climate records (air temperature, precipitation, and snow depth) across global mountainous regions. Measurement coverage is insufficient for baseline monitoring in many areas, most alarmingly in regions with great hydrological importance to hundreds of millions of people. Marshall reviews the observed changes in mountain and polar glaciers due to mass loss resulting from increased temperatures, spanning the direct melt-related triggers along with more subtle processes such as increased ice flow and the loss of meltwater retention in firn (perennial snow). Non-linear processes and feedbacks influence the sensitivity of glaciers and ice sheets to climate warming, many of which require improved process understanding and associated model development.

The assessment of projected carbon release from northern permafrost regions was poorly constrained in SROCC because of large uncertainties in processes and pathways. Treharne et al. provide perspectives on the incomplete state of knowledge regarding carbon cycle implications of disturbance-related events such as abrupt thaw and fire. Improvement in process understanding is needed to ensure these events are accounted for when estimating future carbon emissions. The importance of fire-related disturbance is also addressed by Loranty et al. Connections between ecosystem processes unique to the larch forest and ice-rich yedoma permafrost are described for northeastern Siberia. Walvoord and Striegl address the disconnect between the assessment in SROCC of *very high confidence* in projections of near surface permafrost thaw, yet only *low/medium confidence* in the associated response of hydrologic and aquatic carbon cycling. They stress the need to properly account for the critical thermal, hydrologic, and biogeochemical processes in models designed to assess and predict permafrost thaw and its impacts.

Physical oceanography: There is still much to understand about the impact of climate change on physical ocean phenomena

The Weddell Sea polynya forms intermittently, but has important implications for deep water ventilation, heat release from the deep ocean, and the uptake of anthropogenic carbon. Rheinlænder et al. use a global coupled ocean-sea ice model to explore the Weddell Sea polynya activity. The use of a repeating annual atmospheric cycle illustrates the potential for ocean process to trigger polynya development. They suggest that changing surface waters in the Weddell Sea (warmer; saltier) could result in a more frequent Weddell polynya in the future. Progress since SROCC on recent and future trends in the Atlantic Meridional Overturning Circulation (AMOC) are presented by Swingedouw et al. A new high resolution ocean model projects stronger weakening of the AMOC compared to an associated CMIP6 model, due in part to impacts of freshwater runoff from the Greenland Ice Sheet. Accounting for ice sheet melt water is therefore considered a priority for the next generation of ocean models. Levin et al. highlight the limited assessment in the SROCC of the deep ocean (depths $>$ 200 m) and associated ecosystems. Although deep ocean observations and earth system model capabilities have improved, the need to consider "what we don't know, but need to know and why" as a component of the assessment processes is a particular concern for the deep ocean.

Ocean ecosystems and resources: While they remain under threat, ocean ecosystems can also be part of the solution to climate change

Ottersen et al. examine the evolution of confidence in observed and projected climate-linked changes in polar ecosystems since the SROCC. Strong regional differences in the depth of knowledge of marine ecosystem response to climate change are identified, with highly fragmented approaches a particular concern across the Southern Ocean. Tagliabue et al provide ocean net primary production (NPP) projections, through a comparison of CMIP5 and CMIP6 models. They identify an increase in model uncertainty between CMIP5 and CMIP6 for projections of NPP, although the assessment is challenged by the relatively simple ocean biology components in the models. Limitations in the projections of NPP impact the potential for informed management of associated ecosystem services. The potential for Blue Carbon ecosystems to mitigate climate change was assessed for coastal wetlands in SROCC, but not for the open-ocean. To address this gap, Hilmi et al. provide a review of the mitigation potential of Blue Carbon resources in coastal, open-ocean and deep-sea ecosystems. They emphasize the importance of ocean solutions through the protection and restoration of marine carbon stocks and sequestration processes while acknowledging valuation and governance challenges. Cassotta provides a regulatory and climate justice perspective on climate change-driven ocean acidification. The interplay between states, corporations, and communities creates a complex landscape for executing responses to the challenges posed by ocean acidification.

The importance of multiple ways of knowing: Indigenous knowledge and local knowledge is extremely valuable and equality, diversity and inclusion is essential for fair adaptation

During the Sixth Assessment Cycle process, the IPCC made a concerted effort to recognize and include both Indigenous knowledge and local knowledge as important contributors of information to observing, understanding, and responding to climate change. A literature survey by Eerkes-Medrano and Huntington identified the predominant themes in peer-reviewed publications concerning Arctic Indigenous peoples and climate change spanning economics, culture, health and mental health, policy and governance. Indigenous voices and ideas must be a meaningful part of the discussion about Arctic change and successful adaptation. In a successful case of partnership with Indigenous knowledge, Wilson et al. present the Mittimatalik siku asijjipallianinga (sea ice climate atlas), produced for the community of Mittimatalik, Nunavut (Canada). Combining sea ice charts, remote sensing, and Inuit knowledge, this community-focused information is ideally suited for local-scale climate change adaptation.

Muelbert et al. review the gaps and opportunities for the uptake of ocean and climate science in Latin America. Accessible and inclusive information at the local level is highlighted as an essential requirement for engaging governments and societies in climate adaptation. Prakash et al. analyzed over 1,000 publications to determine the extent to which gender inequality is addressed within the coastal climate change adaptation literature. While gender inequality was recognized in the SROCC as an important dimension to climate change adaption in coastal areas, the overall lack of consideration in the literature shows that greater efforts are required to document and analyse gender and coastal climate adaptation dynamics.

Managing climate-related risks: The integration of natural science and social science alongside the input of stakeholders is required for effective risk management

The challenges to risk management and adaption related to abrupt changes, cascading effects, and compound extreme events in ocean environments are reviewed by Bouwer et al. They identify an inequality between the state of knowledge of changes to natural systems, with comparatively little emphasis on the economic impacts of these changes. Vulnerabilities are particularly acute for marine heat waves, extreme ENSO events, and shifts in cyclone tracks. Climate-driven coastal flood hazard risks in Alaska are very high. Williams and Erikson identify a pathway to resilient adaptation through the integration of observations and modeling to information local-level planning. Developing and deploying state of the art modeling and prediction at the community level poses a unique set of challenges. Constable et al. provide an overview of decision support tools for developing and managing resilient climate adaptation. By emphasizing the varied political, socio-economic, and cultural contexts (and hence the lack of universally applicable solutions), they capture a range of appropriate tools depending on culture, resources and other circumstances.

This collection of manuscripts provides a cross-section of perspectives on knowledge gaps and assessment priorities for the oceans and cryosphere, which emerged from the

SROCC. We hope this will help spur further research in these areas, in order to provide stronger and more consistent evidence to underpin high confidence statements in future assessments, and to support actions to both adapt to and mitigate climate change.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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