frontiers in Climate

PERSPECTIVE
published: 10 January 2022
doi: 10.3389/fclim.2021.733755

Climate Change Impacts on Polar Marine Ecosystems: Toward Robust Approaches for Managing Risks and Uncertainties

Geir Ottersen[1], Andrew J. Constable[2], Anne B. Hollowed[3], Kirstin K. Holsman[3], Jess Melbourne-Thomas[2,4], Mônica M. C. Muelbert[5] and Mette Skern-Mauritzen[1]*

[1] Research Group of Oceanography and Climate, Institute of Marine Research, Bergen, Norway, [2] Centre for Marine Socioecology, University of Tasmania, Hobart, TAS, Australia, [3] Alaska Fisheries Science Center, National Marine Fisheries Service NOAA, Seattle, WA, United States, [4] Oceans and Atmosphere, Commonwealth Scientific and Industrial Research Organisation, Hobart, TAS, Australia, [5] Instituto do Mar, Universidade Federal de São Paulo, Santos, Brazil

OPEN ACCESS

Edited by:
Chris Derksen,
Environment and Climate Change, Canada

Reviewed by:
Michelle Tigchelaar,
Stanford University, United States
Claudia Priscila Wanzeler Da Costa,
Vale Technological Institute (ITV), Brazil

***Correspondence:**
Geir Ottersen
geir.ottersen@ibv.uio.no

Specialty section:
This article was submitted to Predictions and Projections, a section of the journal Frontiers in Climate

Received: 30 June 2021
Accepted: 06 December 2021
Published: 10 January 2022

Citation:
Ottersen G, Constable AJ, Hollowed AB, Holsman KK, Melbourne-Thomas J, Muelbert MMC and Skern-Mauritzen M (2022) Climate Change Impacts on Polar Marine Ecosystems: Toward Robust Approaches for Managing Risks and Uncertainties. Front. Clim. 3:733755. doi: 10.3389/fclim.2021.733755

The Polar Regions chapter of the Intergovernmental Panel on Climate Change's Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) provides a comprehensive assessment of climate change impacts on polar marine ecosystems and associated consequences for humans. It also includes identification of confidence for major findings based on agreement across studies and weight of evidence. Sources of uncertainty, from the extent of available datasets, to resolution of projection models, to the complexity and understanding of underlying social-ecological linkages and dynamics, can influence confidence. Here we, marine ecosystem scientists all having experience as lead authors of IPCC reports, examine the evolution of confidence in observed and projected climate-linked changes in polar ecosystems since SROCC. Further synthesis of literature on polar marine ecosystems has been undertaken, especially within IPCC's Sixth Assessment Report (AR6) Working Group II; for the Southern Ocean also the Marine Ecosystem Assessment for the Southern Ocean (MEASO). These publications incorporate new scientific findings that address some of the knowledge gaps identified in SROCC. While knowledge gaps have been narrowed, we still find that polar region assessments reflect pronounced geographical skewness in knowledge regarding the responses of marine life to changing climate and associated literature. There is also an imbalance in scientific focus; especially research in Antarctica is dominated by physical oceanography and cryosphere science with highly fragmented approaches and only short-term funding to ecology. There are clear indications that the scientific community has made substantial progress in its ability to project ecosystem responses to future climate change through the development of coupled biophysical models of the region facilitated by increased computer power allowing for improved resolution in space and time. Lastly, we point forward—providing recommendations for future advances for IPCC assessments.

Keywords: Arctic, Antarctic, Southern Ocean, polar, marine, ecosystem, SROCC, IPCC

INTRODUCTION

The Polar Regions chapter of the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) by the Intergovernmental Panel on Climate Change (IPCC) provides a broad overview and assessment of climate change impacts on polar marine ecosystems and associated consequences for humans (Meredith et al., 2019). The report provides a comprehensive assessment of the current state of scientific findings regarding climate change related to key concepts of risk, adaptation, resilience and transformation (Garschagen et al., 2019). The report uses calibrated language modified from previous approaches (Mastrandrea et al., 2010; Mach et al., 2017) to depict the uncertainty around conclusions in a clearly defined and consistent manner. This calibrated language approach allows for qualitative and quantitative assessments of the confidence of the scientific community in a key finding. Projections of future ocean conditions are based on scenarios of future climate conditions based on a common suite of pathways (representative concentration pathways and shared socioeconomic pathways, Abram et al., 2019). Following IPCC procedure, the report underwent a large and rigorous peer review prior to publication, conducted by the global science community and national science reviews; author teams must provide responses to all reviews. As such, the report represents the global scientific community's best attempt to report the state of the science on climate change with respect to key findings and the confidence there-in at the time the report was written. These special reports form part of a regular cycle by the IPCC, updating its assessments every 7 years, thereby tracking changes in knowledge and understanding over time.

The IPCC is currently preparing its Sixth Assessment Report (AR6) and literature on polar marine ecosystems published since SROCC is being assessed in Working Group II (impacts, adaptation and vulnerabilities). This comprehensive work – in addition to published papers that contribute advances in scientific understanding (e.g., the Marine Ecosystem Assessment for the Southern Ocean, MEASO, 2020)–provides increased evidence for widespread impacts of climate change on polar regions, and new insights on approaches for adapting to imminent climate impacts. A remaining primary focus is to evaluate the feasibility and effectiveness of approaches to reduce negative consequences and retain resilience, termed "adaptations." Conclusions by Working Group 1 for AR6 (The physical science basis; IPCC, 2021) are consistent with earlier assessment reports that climate change is altering polar environments at unprecedented rates. Further, these regions cannot be fully shielded from the effects of climate change through adaptation alone; adaption effectiveness is substantially enhanced by global carbon mitigation.

Despite advancements in understanding, knowledge gaps remain that influence assessment confidence around the magnitude, timing, and scale of impacts and adaptation effectiveness. To identify these knowledge gaps, and measures to address them, we have assembled a team of all four lead authors of the marine ecosystem part of the Polar Regions chapter in SROCC and three AR6 WGII lead authors on polar marine ecosystems. Two of our team were also lead authors in the Polar Regions Chapter of AR5 (Larsen et al., 2014; Meredith et al., 2019). Our paper considers how scientific uncertainty has evolved since AR5 and SROCC and what the implications are for decision-making. Further, we consider the implications of current expectations and orientations of the IPCC for ongoing capacity to assess future climate change impacts for social-ecological systems in the polar regions and options for responding to these impacts. Finally, we put forth recommendations for future advances for IPCC assessments.

EVALUATION OF ADVANCES IN POLAR MARINE ECOSYSTEM KNOWLEDGE SINCE SROCC

Data Gaps and Skewness in Data Coverage

SROCC and AR6 are assessments based upon recent scientific advancements derived from monitoring, process studies, retrospective studies, laboratory investigations, new technologies and modeling studies. In polar regions, improved observational coverage, particularly in regions with low coverage today, will greatly improve the foundation for future assessments. For instance, earth observation systems generally are well-coordinated in large programs (like USA's NASA EOS and EU's Copernicus CMEMS). Therefore, most of the literature on production in the Arctic as a whole region is based on satellite data (Arrigo and van Dijken, 2011, 2015; Kahru et al., 2016) or bioclimatic modeling (Cheung et al., 2009; Fernandes et al., 2020). Scenarios for lower trophic levels from the Regional Ocean Modeling System Nutrient-Phytoplankton-Zooplankton Model (Bering10K ROMSNPZ; Hermann et al., 2016, 2019; Pilcher et al., 2019; Kearney et al., 2020) now also provide alternative perspectives that were still nascent during the SROCC process.

For *in situ* measurements, which are essential for understanding ecosystems at levels above primary production, the situation is quite different (**Figure 1**). Formation of a comprehensive, calibrated, multinational ecosystem monitoring program is, for both the Antarctic and Arctic, challenging given the high cost of sampling in distant regions of the planet. In the interim, nations are striving to improve coordination of existing measurement programs and access to data, such as through the Southern Ocean Observing System (Newman et al., 2019). However, classic *in situ* observations, like research cruises, are to a large degree still organized at a national or smaller regional level (but see, e.g., Eriksen et al., 2018 for joint Norwegian-Russian long term monitoring of the Barents Sea).

Still, considerable progress is being made in some fields, mostly related to ocean physics and biogeochemistry. This includes technological developments and an increasing deployment of autonomous observation platforms that utilize the most developed of these technologies, like Argo profiling floats, drifters, gliders, fixed moorings, vessels of opportunity, and Ice-Tethered Platforms. This is expected to gradually reduce the dependence on ship-based surveys for the collection of physical and biogeochemical variables. Marine mammal or fish species at or near the ocean surface (like tuna and mackerel) and

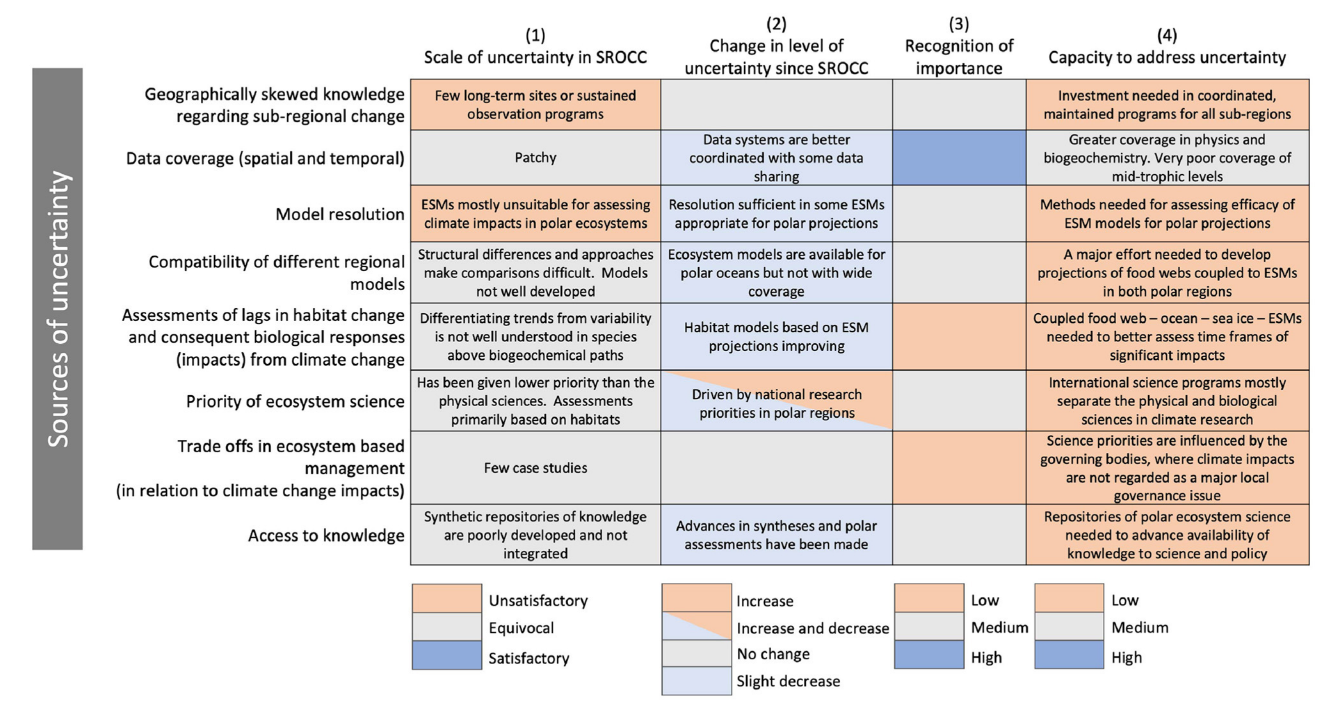

FIGURE 1 | Summary of capacity to advise on, and prognoses for, the impacts of climate change on ecosystems of the polar regions. For different sources of uncertainty, qualitative judgement is provided on (1) the scale of uncertainty in SROCC (blue, satisfactory; gray, equivocal; red, unsatisfactory); (2) change in the level of uncertainty since SROCC (blue, decrease; gray, no change; red, increase); (3) level of recognition of the importance of each source of uncertainty by research and policy communities, i.e., recognition that each source needs to be addressed (blue, high; gray, medium; red, low); and (4) existing capacity to address each source of uncertainty in assessment and decision making (blue, high; gray, medium; red, low). Cells indicate important scientific issues causing uncertainty.

anadromous fish species that return to spawn in rivers and lakes can to some degree be monitored by means of earth observation sensors on satellites or aerial surveillance technologies like Light Detection and Ranging (LIDAR). There are also some examples of *in situ* unmanned measurement of biological variables, for instance autonomous samplers that show promise for remote measurement of the abundance and spatial distribution of pelagic fish (Verfuss et al., 2019). Also, increased activity in high latitude regions, with e.g., polewards displacement of fisheries, and increased tourism, increase options for sampling from ships of opportunity (e.g., Escobar-Flores et al., 2020). However, in the forseable future most biological measurements will still depend on research vessel surveys.

In the Arctic, groups like SAON (Sustaining Arctic Observing Networks) and shorter-term projects like INTAROS (Integrated Arctic Observation System) are making progress toward long-term Arctic-wide observing activities that provide free, open, and timely access to high-quality data, also on ecological variables [see for instance Datasets–INTAROS Data Catalog (nersc.no) and https://doi.org/10.5194/essd-13-1361-2021]. For Antarctica, the Southern Ocean Observing System (SOOS) was implemented after the OceanObs'09 conference and has been instrumental for ocean and cryosphere observations in the Southern Ocean region from a climate driven perspective (Newman et al., 2019).

The science supporting SROCC on climate impacts on marine polar ecosystems reflects regional investment in monitoring and research and is strikingly skewed within and between regions (**Figure 1**). SROCC shows that more scientific results are available for the Arctic than the Antarctic. In the Arctic, there is far more published material on marine life in the eastern Bering and Barents Seas than for the remaining Arctic shelf seas. For instance, marine life in the Kara Sea is mentioned once, the Laptev Sea not at all. For the Southern Ocean, the South Atlantic and west Antarctic Peninsula region are by far the most reported on (see Meredith et al., 2019). International partnerships such as Marine Ecosystem Assessment for the Southern Ocean (MEASO) and the Arctic Monitoring and Assessment Programme (AMAP) are designed to coordinate the collection and analysis of marine life in polar regions. Such coordinated research is providing much needed observations that provide insights into the structure and function of polar ecosystems, thus informing IPCC assessments and providing help to address this regional imbalance in research.

In IPCC's 5th assessment report (AR5; Hollowed and Sundby, 2014; Larsen et al., 2014) and SROCC (Meredith et al., 2019) authors pointed to spatial heterogeneity in ecosystem responses to projected climate change. These occur in response to different physical and biogeochemical changes in the shelf seas and the Arctic Ocean or sea ice habitats in the Southern Ocean, and only strengthens the need for more knowledge on the less understood seas. However, for both the Antarctic and Arctic, closer examination of literature in languages other than English (e.g., Chinese, Japanese, Korean, Polish, Russian, Spanish and Portuguese) is likely to provide important information. Although IPCC authors are also charged with examining this literature, its accessibility is lower and with limited time available such sources of knowledge may be overlooked. In addition to language barriers, results and dissemination from some long-term monitoring programs may not find their way into primary literature due to outdated methodology or the particular focus/question considered to be of regional/local scope only. Yet, in under-sampled regions, such data and corresponding (non-English) regional reports may narrow knowledge gaps.

There is no quick fix to developing time series in under-sampled regions, retrieval of data from non-archived programs, or for making literature generally available from across the diversity of languages. These issues transcend individual experts that become lead authors in the IPCC. The responsibility for resolving them rests, institutionally, with the international scientific community and would be an important topic for consideration and resolution within the partner institutions of the IPCC and by the International Science Council.

Indigenous, Traditional, and Local Knowledge

A source of knowledge increasingly recognized as important to the work of the IPCC Working Group II, is Indigenous and Traditional Knowledge (ITK). This is because of what ITK offers for understanding climate change impacts on ecology as well as on social and human systems.

Indigenous Knowledge of Arctic marine social and ecological systems is spatially and temporally broad, especially with respect to climate impacts on Arctic social-ecological systems and effectiveness of adaptation responses. For the Arctic, ITK can provide important insights needed for understanding current climate change impacts, efficacy of adaptation measures, and future conditions and risks (Petzold et al., 2020; Van Bavel et al., 2020; Eerkes-Medrano and Huntington, 2021; Hauser et al., 2021). While the IPCC's 5th assessment report identified the need to consider information from multiple knowledge sources – and SROCC made progress in this regard for polar regions– inclusion of ITK has been hindered by inconsistent methods for participation and inclusion, and where included is often general in scope and lacks a robust and nuanced treatment of the inter-complexities of climate change impacts and colonialism (Ford et al., 2016, 2020; Petzold et al., 2020). ITK includes methodologies and peer-review processes that are different in ontology and axiology from mainstream science. Therefore, a more inclusive approach to authorship (i.e., including researchers with ITK as lead authors on IPCC reports), promotion and support of participatory and collaborative input from multiple ITK holders (e.g., as contributing authors in addition to ITK expert Lead Authorships) and broader methodology for knowledge review is needed to support greater understanding and more thorough assessment of climate impacts, risks, and responses in Arctic systems.

Language Barriers

Further, knowledge relevant to local systems and management are often published outside of (mainstream) journals and in languages other than English. Such knowledge thus receives less attention by peers and becomes hard to access in global assessments like SROCC (Muelbert et al., 2021). Smaller locally or regionally run assessments, feeding in to global reporting processes like those by IPCC, would help make suck knowledge more available.

Projections of Ecosystem Responses

Climate change will cause polar marine environments to warm further with cascading effects on sea ice extent and thickness, changing the productivity of species and the relative importance of different energy pathways through food webs (Meredith et al., 2019; Trebilco et al., 2020; IPCC, 2021; Thorson et al., 2021). Knowledge of the direction and magnitude of these changes in marine life has incrementally evolved since AR5. Conclusions from AR5 (Larsen et al., 2014) and SROCC (Meredith et al., 2019) highlight compelling evidence that the cascading effects of shifts in the timing and magnitude of seasonal biomass production could disrupt matched phenologies. The authors of the 2014 AR5 Polar chapter identified that a key knowledge gap was that ecosystem models of ecological and social systems at that time were either lacking or insufficiently validated to project the cascading effects of climate change into the future (Larsen et al., 2014). By the time SROCC was completed, projections from global models of marine life based on dynamic bioclimate envelope models were published, and this was cited in SROCC (Bindoff et al., 2019).

Since SROCC a number of studies have projected the future state of polar ecosystems, using both species distribution, multispecies, and Ecosystem-based models (EBMs, Hansen et al., 2019a; Huckstadt et al., 2020; Reum et al., 2020; Veytia et al., 2020; Rooper et al., 2021; Whitehouse et al., 2021). As ecology has no agreed-upon set of mathematics to dictate system dynamics, there is substantial heterogeneity in the theoretical underpinning of these models, processes considered, parameterizations, spatial extent and taxonomic, spatial and temporal resolution, which have implications for model dynamics and outcomes (Payne et al., 2016; Tittensor et al., 2018). Also, as for the Earth System models of the climate systems, these models are subject to uncertainties that may be structural (relating to model parameterization) or parametric (i.e., imperfect measurements, natural variability and abstractions within the model) (Payne et al., 2016; Tittensor et al., 2018). These uncertainties, and additional scenario-based uncertainties (e.g., uncertainties related to future changes in emission rates, land and sea use practices), point to the benefits of ecosystem model intercomparisons, such as the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP, Tittensor et al., 2018) or the Alaska Climate Integrated Modeling project (ACLIM; Hollowed et al., 2020). Intercomparisons of different models help identify outcomes that are similar despite variability in model construction, giving confidence in those conclusions (Peck et al., 2018; Tittensor et al., 2018; Bauer et al., 2019; Hollowed et al., 2020). Where models differ in results will highlight where uncertainties in future scenarios may lie. If the results deviate greatly then those uncertainties may be considered to have a high priority to be resolved.

A method is available for overcoming model uncertainty to assist policy makers in determining suitable adaptation strategies for responding to future climate challenges while achieving ecosystem resilience. This method, often termed "management strategy evaluation" (MSE), is to evaluate the performance of those strategies under various climate scenarios within the social-ecological-climate models of the model ensemble that are considered to suitable reflect possible futures (A'Mar et al., 2009; Hollowed et al., 2020). Strategies that perform well across all plausible models, uncertainty and climate scenarios will be more likely to be successful in future real-world applications. Choosing suitable strategies will be dependent on trade-offs amongst social and ecological performance measures (objectives) and the degree to which risk of failure to meet those objectives can be countenanced, given the uncertainties. The success of this approach has been demonstrated in many fisheries applications. As yet, it has had only limited application across polar regions (but see Hollowed et al., 2020; Kaplan et al., 2021). Nevertheless, results from validated high-resolution ecological and social system models for the Bering Sea and Barents Sea provided much greater insight into the expected trajectories of climate change in the region (Hansen et al., 2019b; Holsman et al., 2020).

Despite these advancements in understanding, the future outcome of some key policy-relevant processes remain uncertain. These knowledge gaps tempered SROCC's confidence levels on impacts of climate change on polar marine social and ecological systems, and on the effectiveness of responses to climate driven change. Since the completion of SROCC, the availability of improved regionally downscaled physical biogeochemical models (e.g., Kearney et al., 2020) and observed responses of marine life to hazards attributed to climate change (e.g., North Pacific marine heatwaves) has further impacted key conclusions in AR6.

Ecosystem Process Error and Structural Uncertainty

Climate change affects multiple physical and biogeochemical processes that impact species throughout different life stages and at different spatial scales with sometimes attenuating (or amplifying) effects. These complexities are discussed in AR5 and SROCC. There are well-known tradeoffs associated with adding ecological realism into ecosystem models associated with adding parameter uncertainty and opportunities for model misspecification. For this reason, exploring outcomes using also regional multi-model ensembles that address different levels of mechanistic complexity is needed to reveal how these play out with respect to future conditions for fish and shellfish (e.g., Hollowed et al., 2020).

EBMs provide approaches for exploring ecological responses; however, such models should build upon well-developed theory and understanding of the ecosystem in question, which again is linked to availability of data for developing and evaluating the model. An analysis of different sources of uncertainty in long-term projections of fishing and climate change by EBMs (for the eastern Bering Sea) revealed that for some species structural model uncertainty dominated (Reum et al., 2020). Moreover, synergies across multiple EBMs with different underlying structural assumptions helped reveal potential short-term benefits of increased flexibility in catch allocation scenarios (Reum et al., 2020; Whitehouse et al., 2021). This also enhanced the ability of EBMs to provide guidance toward how to stabilize catches and forestall climate-driven declines (Holsman et al., 2020; Reum et al., 2020; Whitehouse et al., 2021).

Structural Error in Climate Models and Scenario Uncertainty

Structural uncertainties emerge in polar regions from global scale ensemble model projections as a consequence of results from different models in an ensemble being spread over a wide spatial range. Recent global scale ensemble model projections indicate substantial increases in total animal biomass toward 2100 under RCP2.6 (48%, intermodel SD 93.75%) and RCP8.5 (82.0%, intermodel SD 201.07%) in the Arctic (Bryndum-Buchholz et al., 2019; Lotze et al., 2019; Nakamura and Oka, 2019). This increase is partly due to increase in primary production fuelling the food chains, and partly due to increased biological rates with increasing temperatures. However, this does not take into account significant regional declines projected for the largest Arctic fisheries in the Bering sea, nor recent agreements to delay fisheries in the high Arctic until foundational information for sustainable management can be collated (i.e., 16+ yr moratorium on commercial fishing; Vylegzhanin et al., 2020; U.S. Department of State, 2021). Further, increased variability in biomass is also projected for polar regions, and of the models evaluated the polar regions had some of the lowest agreement across models in projected changes in biomass (Lotze et al., 2019). For the Southern Ocean there are no trends, but greater variability in both primary production and total animal biomass are projected under RCP2.6, while a 15% increase (intermodel SD 36.61%) in animal biomass is projected under RCP8.5 (Bryndum-Buchholz et al., 2019; Lotze et al., 2019; Nakamura and Oka, 2019). Thus, high inter-model variability in projections, combined with regional models projecting significant distribution shifts and declining productivity in key ecological and commercial species, demonstrate that the future development of polar marine systems and associated commercial fisheries are associated with high uncertainties (Griffiths et al., 2017; Klein et al., 2018; Hansen et al., 2019a; Tai et al., 2019). Despite these uncertainties, more evidence has emerged since SROCC's finalization demonstrating that sustainable fisheries practices within an ecosystem approach to fisheries management can stabilize fisheries and forestall negative impacts of climate change on some fish populations in the near term (Gaines et al., 2018; Free et al., 2020; Holsman et al., 2020; Reum et al., 2020).

Comparison of outputs from coarse spatial (and often coarse temporal) resolution global models with regionally downscaled simulations revealed systematic differences in the projections of future climate change impacts on high latitude systems in some high latitude regions. For example, scenarios from global models (often with annual time-steps) projected increased primary production and increasing biomass across functional groups in the Barents and Bering Seas, whereas downscaled models revealed seasonal differences in the timing of primary production and declining biomass trajectories for some functional groups (Hansen et al., 2019a; Holsman et al., 2020; Reum et al., 2020; Whitehouse et al., 2021). Emerging efforts to embed high resolution ocean model capabilities along the coastal shelf within global models with two-way coupling holds great promise for future IPCC assessments (Buil et al., 2021). Sustained support for high resolution modeling platforms and model intercomparisons of integrated oceanographic-ecological-social-economic models is needed to resolve the dynamic responses of coupled-social ecological systems to climate change (Holsman et al., 2019; Hollowed et al., 2020).

Ecosystem Resilience

A fundamental question on future polar marine ecosystems relates to their resilience; the capacity of the social ecological system to maintain the current state or return to some historical state following climate-driven change, whether the benchmark be pre-industrial or some time since. Could polar ecosystems cross a tipping point or threshold making it difficult to return and after which point productivity and stability are highly uncertain? A key source of uncertainty regarding the capacity of an ecosystem to recover is how and when future physical and biogeochemical changes in the ocean will trigger tipping points in ecosystem structure and organization that will limit recovery of the system to its former state (Frölicher et al., 2016; Frölicher and Laufkötter, 2018). Having capacity to project how the system will change, and whether tipping points may arise, is central to discussing prospects for polar ecosystems. SROCC moved significantly forward on this; a chapter was dedicated to "Extremes, Abrupt Changes, and Managing Risks" (Collins et al., 2019). However, that chapter to little degree dealt with polar regions and the knowledge summarized was not integrated into the polar chapter. Since SROCC the emphasis on abrupt changes and tipping points in the ocean has been pronounced, including work by Malhi et al. (2020), Turner et al. (2020), Degroot et al. (2021), and Heinze et al. (2021).

Spatial Heterogeneity

In SROCC, the authors intended to further examine the potential for spatial heterogeneity in Arctic and Antarctic ecosystem responses to projected climate change (first raised in AR5; Larsen et al., 2014). Unfortunately, such an inter-regional comparison was restricted by the lack of sufficiently resolved large-scale model output fields. CMIP5 output was found to be too coarse to differentiate between regions by capturing oceanographic conditions that have profound impacts on species distributions and interactions and food-web dynamics (e.g., sea ice distribution and edge blooms, seasonal stratification, Bering sea cold pool formation and extent; Kearney et al., 2020; Drenkard et al., 2021). Regional climate scenarios derived from down-scaled global climate scenarios and used to drive environmentally linked fish population models were included by Meredith et al. (2019), but were then only available for the Eastern Bering Sea (Hermann et al., 2019). Efforts since SROCC to downscale CMIP6 model outputs for coupled high resolution downscaled projects further underscored the importance, for polar regions in particular, to characterize impact variability and detail as well as adaptation efficacy at a regional scale (Hansen et al., 2019a; Drenkard et al., 2021).

Social-Ecological Responses

Dynamic couplings between regional social and ecological responses to climate change also deserve increased attention, as they can both amplify and attenuate climate impacts in complex ways. Global scale evaluations and models often are unable to capture important feedbacks and connections, leading to misspecification of impacts and adaptation response. For instance, realized harvest rates reflect complexities of management, economics, and regulatory structures that by design aim for ecosystem-based-management targets rather than maximizing the yield of individual stocks (MSY); total yield from a system is often lower than the additive sums of individual MSYs (or MSY proxies; Holsman et al., 2016, 2020; Link, 2018; Reum et al., 2020). Other ecosystem-based management targets include maintaining ecosystem structure, function and productivity (e.g., Norwegian Ministry of Climate and Environment, 2020), which may be less realistic under the ongoing directional climate change driven alterations of marine ecosystems. There is thus a need to adapt current management targets to the ongoing changes, and identify and evaluate relevant management strategies to reach these targets.

Disciplinary Imbalance in Scientific Priorities

Research regarding climate impacts in polar regions – particularly that for the Southern Ocean – is dominated by physical oceanography and cryospheric science with highly fragmented approaches to ecology. In terms of projections of climate impacts, the physical system out to 2100 is uncertain but well-circumscribed. By comparison, science on the effects of climate change on ecosystems and ecosystem services lags far behind (**Figure 1**). There is an urgent need for sustained support for long-term ecosystem data collections for Antarctic systems, linked ecological and socio-economic modeling at the circumpolar scale, and synthetic evaluations of cascading impacts of climate change, risks, and adaptation feasibility and effectiveness across Antarctic ecosystems and dependent industries. There have been few positive developments in Antarctic ecosystem research funding since AR5: in the Antarctic most long-term studies recently either lost funding or were greatly reduced. To address this major source of uncertainty in climate change assessments, research funding needs to be at the scale and scope to support understanding that can fully address policy and decision-making needs, i.e., cross-disciplinary and coupling ecosystem monitoring and high-resolution oceanographic and ecosystem models with social-ecological modeling. Such integrated research approaches take multiple years to establish but once developed can easily incorporate new projections and information. Sustained support (i.e., often through coordinated government investment in climate programs) to ecosystem based adaptation and mitigation is necessary to both develop and continuously update integrated approaches but the collective and holistic information that results is invaluable for identifying key climate risks, rates and magnitude of change and the effectiveness (and limits) of responses.

The challenges with establishment and proper coordination of large-scale ecological programs can, as noted above, partly be attributed to the costs associated with the spatial and temporal coverage required for ecological investigations beyond the local scale. There has been a scarcity of collaborative research initiatives at all levels to tackle the need for ecologically based studies of the Southern Ocean. During the last International Polar Year several scientific collaborations were initiated, including Census of Antarctic Marine Life (CAML) and Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED). These have demonstrated the importance of networking and coordination in ecological research initiatives; such as Integrated Ecosystem Assessments (Levin et al., 2014) that are in development for Arctic ecosystems (Bering, Chukchi, Greenland and Barents Seas) as well as the Southern Ocean (MEASO, 2020). These IEAs are increasingly addressing the state and development of the polar seas as socio-ecological systems, assessing impacts and risks of climate change for species (Holsman et al., 2017), habitats and natural communities (MEASO, 2020), as well as on ecosystem services and coastal livelihoods (Holsman et al., 2020; Cavanagh et al., 2021). Such expansions are required to support the development of ecosystem-based adaptation and mitigation options to support management of polar systems under climate change impacts.

Policy Relevant Climate Assessments

Polar regions are a special case in IPCC assessments. They play a central role in the physical Earth System and have the potential for cascading positive feedbacks to Earth's climate system. Managing greenhouse gas emissions is the primary way that these changes in the Earth System can be moderated (IPCC, 2018). Changes in polar regions impact people the world over, not just from the perspective of physics and tangible services from within the region (Meredith et al., 2019; Cavanagh et al., 2021) but also from more distant biological and human connections with the regions (Murphy et al., 2021; Roberts et al., 2021). Adaptation may attenuate impacts of climate change to socio-ecological systems in the near term (see Simpson et al., 2021) but cannot protect the fundamental nature of cold- and ice-dependent marine ecosystems, which are projected to experience rapid and irreversible loss over the next century under high (and possibly moderate) emission scenarios. There is increasing and widespread agreement and evidence for this emergent finding across multiple lines of evidence, despite the uncertainty around the timing and rate of change. Yet, persistent uncertainties due to lack of temporal and spatial coverage, and gaps in cited resources, result in low or medium assessment confidence, potentially dampening the resonance of this critical finding. This causes a major challenge for delivering actionable science-based advice and for policy makers that must act now to address long-term climate risks.

Attribution of climate change impacts requires comparisons of impact event likelihood, through comparison of modeled or measured baselines, and/or projected to historical frequency of occurrence. For physical systems these baselines exist, enabling climate attribution, but for ecological and social systems such datasets are limited in space or time. Social-ecological systems integrate climate impacts across trophic levels and species and effects are lagged and often modulated through trophic interactions. This can make attribution of climate impacts difficult to detect when impacts are gradual or incremental, but has become more apparent with large-scale climate shocks (e.g., Huntington et al., 2020). Mismatched scales of ecological time series and seasonal and spatial gaps in information for biomass or rates of production for key ecosystem guilds (e.g., benthic detritivores) further challenge attribution. Coupling sampling and monitoring with multiple ecosystem models helps evaluate attribution and sensitivity of systems to climate impacts and is a near-term approach to improving ecological and social climate attribution.

ACTIONABLE RECOMMENDATIONS

We here present our most important recommendations with short explanations.

Development of a Scientific Framework That Moves From Assessing Future States With Attendant Uncertainties to Assessing Risks to Social and Ecological Needs Identified by Policy Makers

Assessment of climate change related risks requires development of frameworks and models that link across social and ecological dimensions, to allow evaluation of prognoses and management strategies under different scenarios. Management targets and solution options for socio-ecological systems in directional change needs to be developed, and they must capture key outcomes covering diverse societal needs and perspectives across stakeholder groups. Hence, a more inclusive approach to develop management targets and solution options is needed, both regionally, nationally and internationally. We therefore recommend both regional councils, polar nations, and international polar organizations (e.g., the Arctic Council, and CCAMLR) to establish such inclusive processes, building on diverse knowledge bases and perspectives from natural to social sciences, ITK, management bodies and other stakeholder groups. Also, in IPCC assessments, inclusiveness of e.g., ITK could be reflected in authorship and equity in contribution.

Greater Investment to Directly Assess Risks and Impacts of Climate Change on Polar Marine Ecosystems

While this is a well-worn statement in scientific literature, there is no doubt that much of the research to date used by the IPCC on the effects of climate change on polar marine ecosystems above biogeochemistry is opportunistic from outputs of other science programs. The direct, compound and cascading effects on society and ecology needs to be a directed effort.

Orientation of the Scientific Community to Progressing Repositories of Studies, From All Languages, on Climate Change Impacts in Polar Regions

Due to the strong information bias toward some regions (e.g., the Bering and Barents Seas, and the Western Antarctic Peninsula), any additional information on climate change impacts, particularly from other polar regions, will support the reduction of uncertainties and help support robust decision making for ecosystem management in a changing climate. Although charged with examining also such literature, IPCC authors may more easily overlook this. To support increased access and use of non-English literature, we recommend that IPCC WG chapter teams assessing polar regions should cover the central languages of the regions. If not possible to achieve for every assessment, the goal could be to balance representation over time. IPCC could also motivate the WG chapter teams to identify contributing authors that master relevant languages not covered by the chapter team. Finally, IPCC could identify and inform on search engines and best practices to find relevant literature from different regions and in different languages, and provide technical support to literature searches when needed.

Build Upon and Strengthen Ongoing Synergies Between Physical, Chemical, Biological, and Social Sciences in Assessing Social-Ecological Impacts of Climate Change, Their Root Causes, and Prognoses for the Future

For the full Assessment Reports, the IPCC could shift toward better integration between the three working groups as was done in SROCC (there WG1 and WG2). In recognition of the emerging integration of physical biogeochemical, ecological, social and economic research, the IPCC is encouraged to build formal conduits for information flow between working groups.

The authors have experience as lead authors in main AR reports and SROCC, one in both. For ecologists the latter approach was much preferred. Having physical and social scientists working alongside biologists on the same chapter, as in SROCC, was far more efficient and much more challenging with respect to moving our ecological knowledge to seriously take on the societal implications of climate change. One possibility is to have lead authors from one working group take part in the lead author meetings of the author two, serving as "ambassadors of knowledge." This will of course involve extensive traveling for these authors. Alternatively, one could have "regional ambassadors" who would be points of contact for key questions and discussions relevant to their working group.

CONCLUDING REMARKS

Our experience has shown that assessments on the future of polar ecosystems under climate change have been improving in recent cycles but there needs to be a phase shift in orienting the assessments to whole of system dynamics and impacts, including impacts on and risks to both social and ecological outcomes. We observe that there are a number of international initiatives that already provide the means for developing suitable polar ecosystem observing activities, providing there is support and impetus from national programs. A major gap, though with some valuable experience already on the table, is the development of a risk assessment framework for polar marine ecosystems that can utilize social and ecological whole of system models coupled to Earth System models. The development of such a framework can be common to both polar systems as they have similar requirements for their development and implementation. Lastly, we have identified a specific need for engagement across the broader scientific community and with national and international policy makers to develop repositories for the diversity of scientific information that will facilitate equitable assessments of the prognoses for polar marine ecosystems. Without an ongoing broad-based repository, polar system science will remain based only on those results that are readily disseminated and easily interpreted.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

FUNDING

GO and MS-M received funding from the Research Council of Norway through the project BarentsRISK (Grant No. 288192). GO was also supported by the European Research Council through the H2020 project INTAROS (Grant No.727890).

REFERENCES

Abram, N., Cheung, W., Cheng, L., Frölicher, T., Hauser, M., He, S., et al. (2019). "Cross-chapter box 1: scenarios, pathways and reference points," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, eds H. O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N. M. Weyer (Geneva: Intergovernmental Panel on Climate Change (IPCC)), 84–86.

A'Mar, Z. T., Punt, A. E., and Dorn, M. W. (2009). The evaluation of two management strategies for the Gulf of Alaska walleye pollock fishery under climate change. *ICES J. Mar. Sci.* 66, 1614–1632. doi: 10.1093/icesjms/fsp044

Arrigo, K. R., and van Dijken, L. G. (2011). Secular trends in Arctic Ocean net primary production. *J. Geophys. Res.-Oceans* 116:C09011. doi: 10.1029/2011JC007151

Arrigo, K. R., and van Dijken, L. G. (2015). Continued increases in Arctic Ocean primary production. *Prog. Oceanogr.* 136, 60–70. doi: 10.1016/j.pocean.2015.05.002

Bauer, B., Horbowy, J., Rahikainen, M., Kulatska, N., Muller-Karulis, B., Tomczak, M. T., et al. (2019). Model uncertainty and simulated multispecies fisheries management advice in the Baltic Sea. *PLoS ONE* 14:e0211320. doi: 10.1371/journal.pone.0211320

Bindoff, N. L., Cheung, W. W. L., Kairo, J. G., Arístegui, J., Guinder, V. A., Hallberg, R., et al. (2019). "Changing ocean, marine ecosystems, dependent communities," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, eds H. O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K Mintenbeck, A. Alegría, M Nicolai, A Okem, J Petzold, B Rama, and N. M. Weyer (Geneva: Intergovernmental Panel on Climate Change (IPCC)), 448–587.

Bryndum-Buchholz, A., Tittensor, D. P., Blanchard, J. L., Cheung, W. W. L., Coll, M., Galbraith, E. D., et al. (2019). Twenty-first-century climate change impacts on marine animal biomass and ecosystem structure across ocean basins. *Glob. Chang. Biol.* 25, 459–472. doi: 10.1111/gcb.14512

Buil, M. P., Jacox, M. G., Fiechter, J., Alexander, M. A., Bograd, S. J., Curchitser, E. N., et al. (2021). A dynamically downscaled ensemble of future projections for the california current system. *Front. Mar. Sci.* 8:612874. doi: 10.3389/fmars.2021.612874

Cavanagh, R. D., Melbourne-Thomas, J., Grant, S. M., Barnes, D. K. A., Hughes, K. A., Halfter, S., et al. (2021). Future risk for southern ocean ecosystem services under climate change. *Front. Mar. Sci.* 7:615214. doi: 10.3389/fmars.2020.615214

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., and Pauly, D. (2009). Projecting global marine biodiversity impacts under climate change scenarios. *Fish Fish.* 10, 235–251. doi: 10.1111/j.1467-2979.2008.00315.x

Collins, M., Sutherland, M., Bouwer, L., Cheong, S.-M., Frölicher, T., Jacot Des Combes, H., et al. (2019). "Extremes, abrupt changes and managing risk," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, eds H. O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K Mintenbeck, A. Alegría, M Nicolai, A Okem, J Petzold, B Rama, and N. M. Weyer (Geneva: Intergovernmental Panel on Climate Change (IPCC)), 589–655.

Degroot, D., Anchukaitis, K., Bauch, M., Burnham, J., Carnegy, F., Cui, J., et al. (2021). Towards a rigorous understanding of societal responses to climate change. *Nature* 591, 539–550. doi: 10.1038/s41586-021-03190-2

Drenkard, E. J., Stock, C., Ross, A. C., Dixon, K. W., Adcroft, A., Alexander, M., et al. (2021). Next-generation regional ocean projections for living marine resource management in a changing climate. *ICES J. Mar. Sci.* 78, 1969–1987.doi: 10.1093/icesjms/fsab100

Eerkes-Medrano, L., and Huntington, H. P. (2021). Untold Stories: Indigenous Knowledge Beyond the Changing Arctic Cryosphere. *Front. Clim.* 1–16. doi: 10.3389/fclim.2021.675805

Eriksen, E., Gjøsæter, H., Prozorkevich, D., Shamray, E., Dolgov, A., Skern-Mauritzen, M., et al. (2018). From single species surveys towards monitoring of the Barents Sea ecosystem. *Prog. Oceanogr.* 166, 4–14. doi: 10.1016/j.pocean.2017.09.007

Escobar-Flores, P. C., O'Driscoll, R. L., Montgomery, J. C., Ladroit, Y., and Jendersie, S. (2020). Estimates of density of mesopelagic fish in the Southern Ocean derived from bulk acoustic data collected by ships of opportunity. *Polar Biol.* 43, 43–61. doi: 10.1007/s00300-019-02611-3

Fernandes, J. A., Rutterford, L., Simpson, S. D., Butenschon, M., Frolicher, T. L., Yool, A., et al. (2020). Can we project changes in fish abundance and distribution in response to climate? *Glob. Chang. Biol.* 26, 3891–3905. doi: 10.1111/gcb.15081

Ford, J., Cameron, L., Rubis, J., Maillet, M., Nakashima, D., Cunsolo Wilcox, A., et al. (2016). Including indigenous knowledge and experience in IPCC assessment reports. *Nat. Clim Change* 6, 349–353. doi: 10.1038/nclimate2954

Ford, J. D., King, N., Galappaththi, E. K., Pearce, T., McDowell, G., and Harper, S. L. (2020). The resilience of indigenous peoples to environmental change. One *Earth* 2, 532–543. doi: 10.1016/j.oneear.2020.05.014

Free, C. M., Mangin, T., Molinos, J. G., Ojea, E., Burden, M., Costello, C., et al. (2020). Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. *PLoS ONE* 15:e0224347. doi: 10.1371/journal.pone.0224347

Frölicher, T. L., and Laufkötter, C. (2018). Emerging risks from marine heat waves. *Nat. Commun.* 9:650. doi: 10.1038/s41467-018-03163-6

Frölicher, T. L., Rodgers, K. B., Stock, C. A., and Cheung, W. W. L. (2016). Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors. *Global Biogeochem. Cycles* 30, 1224–1243. doi: 10.1002/2015GB005338

Gaines, S. D., Costello, C., Owashi, B., Mangin, T., Bone, J., Molinos, J. G., et al. (2018). Improved fisheries management could offset many negative effects of climate change. *Sci. Adv.* 4, 1–9. doi: 10.1126/sciadv.aao1378

Garschagen, M., Adler, C., Crate, S. H., Jacot Des, C, Glavovic, B., Harper, S., et al. (2019). "Cross-chapter box 2: key concepts of risk, adaptation, resilience and transformation," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, eds H. O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N. M. Weyer (Geneva: Intergovernmental Panel on Climate Change (IPCC)), 87–90.

Griffiths, H. J., Meijers, A. J. S., and Bracegirdle, T. J. (2017). More losers than winners in a century of future Southern Ocean seafloor warming. *Nat. Clim. Change* 7, 749–755. doi: 10.1038/nclimate3377

Hansen, C., Drinkwater, K. F., Jähkel, A., Fulton, E. A., Gorton, R., M., et al. (2019a). Sensitivity of the Norwegian and Barents Sea Atlantis end-to-end ecosystem model to parameter perturbations of key species. *PLoS ONE* 14:e0210419. doi: 10.1371/journal.pone.0210419

Hansen, C., Nash, R. D. M., Drinkwater, K. F., and Hjøllo, S. S. (2019b). Management scenarios under climate change–a study of the nordic and barents seas. *Front. Mar. Sci.* 6:668. doi: 10.3389/fmars.2019.00668

Hauser, D. D. W., Whiting, A. V., Mahoney, A. R., Goodwin, J., Harris, C., Schaeffer, R. J., et al. (2021). Co-production of knowledge reveals loss of Indigenous hunting opportunities in the face of accelerating Arctic climate change. *Environ. Res. Lett.* 16. doi: 10.1088/1748-9326/ac1a36

Heinze, C., Blenckner, T., Martins, H., Rusiecka, D., Döscher, R., Gehlen, M., et al. (2021). The quiet crossing of ocean tipping points. *Proc. Natl. Acad. Sci. U.S.A.* 118, 1–9. doi: 10.1073/pnas.2008478118

Hermann, A. J., Gibson, G. A., Bond, N. A., Curchitser, E. N., Hedstrom, K., Cheng, W., et al. (2016). Projected future biophysical states of the Bering Sea. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 134, 30–47. doi: 10.1016/j.dsr2.2015.11.001

Hermann, A. J., Gibson, G. A., Cheng, W., Ortiz, I., Aydin, K., Wang, M. Y., et al. (2019). Projected biophysical conditions of the Bering Sea to 2100 under multiple emission scenarios. *ICES J. Mar. Sci.* 76, 1280–1304. doi: 10.1093/icesjms/fsz043

Hollowed, A. B., Holsman, K. K., Haynie, A. C., Hermann, A. J., Punt, A. E., Aydin, K., et al. (2020). Integrated Modeling to Evaluate Climate Change Impacts on Coupled Social-Ecological Systems in Alaska. Frontiers in Marine Science 6. doi: 10.3389/fmars.2019.00775

Hollowed, A. B., and Sundby, S. (2014). Change is coming to the northern oceans. *Science* 344, 1084–1085. doi: 10.1126/science.1251166

Holsman, K., Samhouri, J., Cook, G., Hazen, E., Olsen, E., Dillard, M., et al. (2017). An ecosystem-based approach to marine risk assessment. *Ecosyst. Health Sustain.* 3:e01256. doi: 10.1002/ehs2.1256

Holsman, K. K., Haynie, A. C., Hollowed, A. B., Reum, J. C. P., Aydin, K., Hermann, A. J., et al. (2020). Ecosystem-based fisheries management forestalls climate-driven collapse. *Nat. Commun.* 11:4579. doi: 10.1038/s41467-020-18300-3

Holsman, K. K., Hazen, E. L., Haynie, A., Gourguet, S., Hollowed, A., Bograd, S. J., et al. (2019). Towards climate resiliency in fisheries management. *ICES J. Mar. Sci.* 76, 1368–1378. doi: 10.1093/icesjms/fsz031

Holsman, K. K., Ianelli, J., Aydin, K., Punt, A. E., and Moffitt, E. A. (2016). A comparison of fisheries biological reference points estimated from temperature-specific multi-species and single-species climate-enhanced stock assessment models. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 134, 360–378. doi: 10.1016/j.dsr2.2015.08.001

Huckstadt, L. A., Pinones, A., Palacios, D. M., McDonald, B. I., Dinniman, M. S., Hofmann, E. E., et al. (2020). Projected shifts in the foraging habitat of crabeater seals along the Antarctic Peninsula. *Nat. Clim. Chang.* 10 472–477. doi: 10.1038/s41558-020-0745-9

Huntington, H. P., Danielson, S. L., Wiese, F. K., Baker, M., Boveng, P., J., et al. (2020). Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. *Nat. Clim. Chang.* 10, 342–348. doi: 10.1038/s41558-020-0695-2

IPCC (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty,* eds V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield.

IPCC (2021). "Climate change 2021: the physical science basis," in *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, eds V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N Caud, Y Chen, L Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O Yelekçi, R. Yu, and B. Zhou (Cambridge: Cambridge University Press).

Kahru, M., Lee, Z. P., Mitchell, B. G., and Nevison, C. D. (2016). Effects of sea ice cover on satellite-detected primary production in the Arctic Ocean. *Biol. Lett.* 12:20160223. doi: 10.1098/rsbl.2016.0223

Kaplan, I. C., Gaichas, S. K., Stawitz, C. C., Lynch, P. D., Marshall, K. N., Deroba, J. J., et al. (2021). Management strategy evaluation: allowing the light on the hill to illuminate more than one species. *Front. Mar. Sci.* 8:688. doi: 10.3389/fmars.2021.624355

Kearney, K., Hermann, A., Cheng, W., Ortiz, I., and Aydin, K. (2020). A coupled pelagic-benthic-sympagic biogeochemical model for the Bering Sea: documentation and validation of the BESTNPZ model (v2019.08.23) within a high-resolution regional ocean model. *Geosci. Model Dev.* 13, 597–650. doi: 10.5194/gmd-13-597-2020

Klein, E. S., Hill, S. L., Hinke, J. T., Phillips, T., and Watters, G. M. (2018). Impacts of rising sea temperature on krill increase risks for predators in the Scotia Sea. *PLoS ONE* 13:e0191011. doi: 10.1371/journal.pone.0191011

Larsen, J. N., Anisimov, O. A., Constable, A., Hollowed, A. B., Maynard, N., Prestrud, P., Prowse, T. D., Stone, J. M. R. (2014). "Polar regions," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White (Cambridge, New York, NY: Cambridge University Press), 1567–1612.

Levin, P. S., Kelble, C. R., Shuford, R. L., Ainsworth, C., deReynier, Y., Dunsmore, R., et al. (2014). Guidance for implementation of integrated ecosystem assessments: a US perspective. *ICES J. Mar. Sci.* 71, 1198–1204. doi: 10.1093/icesjms/fst112

Link, J. S. (2018). System-level optimal yield: increased value, less risk, improved stability, better fisheries. *Can. J. Fish. Aquat. Sci.* 75, 1–16. doi: 10.1139/cjfas-2017-0250

Lotze, H. K., Tittensor, D. P., Bryndum-Buchholz, A., Eddy, T. D., Cheung, W. W. L., Galbraith, E. D., et al. (2019). Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proc. Natl. Acad. Sci. U.S.A.* 116, 12907–12912. doi: 10.1073/pnas.1900194116

Mach, K. J., Mastrandrea, M. D., Freeman, P. T., and Field, C. B. (2017). Unleashing expert judgment in assessment. *Global Environ. Change* 44, 1–14. doi: 10.1016/j.gloenvcha.2017.02.005

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M. G., Field, C. B., et al. (2020). Climate change and ecosystems: threats, opportunities and solutions. *Philos. Trans. R. Soc. B Biol. Sci.* 375:20190104. doi: 10.1098/rstb.2019.0104

Mastrandrea, M. D., Field, C. B., Stocker, T. F., Edenhofer, O., Ebi, K. L., Frame, D. J., et al. (2010). *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Geneva: Intergovernmental Panel on Climate Change (IPCC). Available online at: www.ipcc.ch (accessed November 12, 2021).

MEASO (2020). *Marine Ecosystem Assessment for the Southern Ocean*. Available online at: https://www.frontiersin.org/research-topics/10606/marine-ecosystem-assessment-for-the-southern-ocean-meeting-the-challenge-for-conserving-earth-ecosys#articles (accessed 24 June, 2021).

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A. B., et al. (2019). "Polar regions," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate IPCC*, eds H. O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N. M. Weyer (Geneva: Intergovernmental Panel on Climate Change (IPCC)), 203–320.

Muelbert, M. M. C., Copertino, M., Cotrim da Cunha, L., Lewis, M. N., Polejack, A., Peña-Puch, A. C., et al. (2021). The ocean and cryosphere in a changing climate in Latin America: knowledge gaps and the urgency to translate science into action. *Front. Clim.* 3:748344. doi: 10.3389/fclim.2021.748344

Murphy, E. J., Johnston, N. M., Hofmann, E. E., Phillips, R. A., Jackson, J., Constable, A. J., et al. (2021). Global connectivity of Southern Ocean ecosystems. *Front. Ecol. Evol.* 9:624451. doi: 10.3389/fevo.2021.624451

Nakamura, Y., and Oka, A. (2019). CMIP5 model analysis of future changes in ocean net primary production focusing on differences among individual oceans and models. *J. Oceanogr.* 75, 441–462. doi: 10.1007/s10872-019-00513-w

Newman, L., Heil, P., Trebilco, R., Katsumata, K., A., Constable, van Wijk, E., et al. (2019). Delivering sustained, coordinated, and integrated observations of the Southern Ocean for global impact. *Front. Mar. Sci.* 6:433. doi: 10.3389/fmars.2019.00433

Norwegian Ministry of Climate and Environment (2020). *Norway's Integrated Ocean Management Plans. Barents Sea–Lofoten Area; the Norwegian Sea; and the North Sea and Skagerrak. Report to the Storting (White Paper). Meld. St. 20 (2019–2020)*. Oslo: Norwegian Ministry of Climate and Environment, 171.

Payne, M. R., Barange, M., Cheung, W. L., MacKenzie, B. R., Batchelder, H. P., Cormon, X., et al. (2016). Uncertainties in projecting climate-change impacts in marine ecosystems. *ICES J. Mar. Sci.* 73, 1272–1282. doi: 10.1093/icesjms/fsv231

Peck, M. A., Arvanitidis, C., Butenschon, M., Canu, D. M., Chatzinikolaou, E., Cucco, A., et al. (2018). Projecting changes in the distribution and productivity of living marine resources: a critical review of the suite of modelling approaches used in the large European project VECTORS. *Estuar. Coast. Shelf Sci.* 201, 40–55. doi: 10.1016/j.ecss.2016.05.019

Petzold, J., Andrews, N., Ford, J. D., Hedemann, C., and Postigo, J. C. (2020). Indigenous knowledge on climate change adaptation: a global evidence map of academic literature. *Environ. Res. Lett.* 15:113007. doi: 10.1088/1748-9326/abb330

Pilcher, D. J., Naiman, D. M., Cross, J. N., Hermann, A. J., Siedlecki, S. A., Gibson, G. A., et al. (2019). Modeled effect of coastal biogeochemical processes, climate variability, and ocean acidification on aragonite saturation state in the Bering Sea. *Front. Mar. Sci.* 5:508. doi: 10.3389/fmars.2018.00508

Reum, J. C. P., Blanchard, J. L., Holsman, K. K., Aydin, K., Hollowed, A. B., Hermann, A. J., et al. (2020). Ensemble projections of future climate change impacts on the eastern bering sea food web using a multispecies size spectrum model. *Front. Mar. Sci.* 7:124. doi: 10.3389/fmars.2020.00124

Roberts, L., Kutay, C., Melbourne-Thomas, J., Petrou, K., Benson, T. M., Fiore, D., et al. (2021). Enabling enduring evidence-based policy for the southern ocean through cultural arts practices. *Front. Ecol. Evol.* 9:616089. doi: 10.3389/fevo.2021.616089

Rooper, C. N., Ortiz, I., Hermann, A. J., Laman, N., Cheng, W., Kearney, K., et al. (2021). Predicted shifts of groundfish distribution in the Eastern Bering Sea under climate change, with implications for fish populations and fisheries management. *ICES J. Mar. Sci.* 78, 220–234. doi: 10.1093/icesjms/fsaa215

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., et al. (2021). A framework for complex climate change risk assessment. One *Earth* 4, 489–501. doi: 10.1016/j.oneear.2021.03.005

Tai, T. C., Steiner, N. S., Hoover, C., Cheung, W. W. L., and Sumaila, U. R. (2019). Evaluating present and future potential of arctic fisheries in Canada. *Mar. Policy* 108:103637. doi: 10.1016/j.marpol.2019.103637

Thorson, J. T., Arimitsu, M. L., Barnett, L. A. K., Cheng, W., Eisner, L. B., Haynie, A. C., et al. (2021). Forecasting community reassembly using climate-linked spatio-temporal ecosystem models. *Ecography* 44, 1–14. doi: 10.1111/ecog.05471

Tittensor, D. P., Eddy, T. D., Lotze, H. K., Galbraith, E. D., Cheung, W., Barange, M., et al. (2018). A protocol for the intercomparison of marine fishery and ecosystem models: Fish-MIP v1.0. *Geosci. Model Dev.* 11, 1421–1442. doi: 10.5194/gmd-11-1421-2018

Trebilco, R., Melbourne-Thomas, J., and Constable, A. J. (2020). The policy relevance of Southern Ocean food web structure: Implications of food web change for fisheries, conservation and carbon sequestration. *Mar. Policy* 115:103832. doi: 10.1016/j.marpol.2020.103832

Turner, M. G., Calder, W. J., Cumming, G. S., Hughes, T. P., Jentsch, A., LaDeau, S. L., et al. (2020). Climate change, ecosystems and abrupt change: Science priorities. *Philos. Trans. R. Soc. B Biol. Sci.* 375:20190105. doi: 10.1098/rstb.2019.0105

U.S. Department of State (2021). Available online at: https://www.state.gov/the-agreement-to-prevent-unregulated-high-seas-fisheries-in-the-central-arctic-ocean-enters-into-force/ (accessed June 29, 2021).

Van Bavel, B., Ford, L. B., Harper, S. L., Ford, J., Elsey, H., Lwasa, S., et al. (2020). Contributions of scale: what we stand to gain from Indigenous and local inclusion in climate and health monitoring and surveillance systems. *Environ. Res. Lett.* 15. doi: 10.1088/1748-9326/ab875e

Verfuss, U. K., Aniceto, A. S., Harris, D. V., Gillespie, D., Fielding, S., Jimenez, G., et al. (2019). A review of unmanned vehicles for the detection and monitoring of marine fauna. *Mar. Pollut. Bull.* 140, 17–29. doi: 10.1016/j.marpolbul.2019.01.009

Veytia, D., Corney, S., Meiners, K. M., Kawaguchi, S., Murphy, E. J., and Bestley, S. (2020). Circumpolar projections of Antarctic krill growth potential. *Nat. Clim. Chang.* 10, 568–575. doi: 10.1038/s41558-020-0758-4

Vylegzhanin, A. N., Young, O. R., and Berkman, P. A. (2020). The central Arctic Ocean fisheries agreement as an element in the evolving arctic ocean governance complex. *Mar. Policy* 118:104001. doi: 10.1016/j.marpol.2020.104001

Whitehouse, G. A., Aydin, K. Y., Hollowed, A. B., Holsman, K. K., Cheng, W., Faig, A., et al. (2021). Bottom-up impacts of forecasted climate change on the eastern bering sea food web. *Front. Mar. Sci.* 8:624301. doi: 10.3389/fmars.2021.624301

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.