ICES Journal of Marine Science

ICES Journal of Marine Science (2019), 76(5), 1215–1220. doi:10.1093/icesjms/fsz084

Introduction to the Symposium: '*The Effects of Climate Change on the World's Oceans*'

Introduction

Recent advances in understanding the effects of climate change on the world's oceans

Anne B. Hollowed [1]*, Manuel Barange[2], Véronique Garçon[3], Shin-ichi Ito [4], Jason S. Link [5], Salvatore Aricò[6], Harold Batchelder[7], Robin Brown[7], Roger Griffis[8], and Wojciech Wawrzynski[9]

[1]*Alaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration (NOAA), Seattle, WA, USA*
[2]*Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome, Italy*
[3]*Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Centre National de la Recherche Scientifique, France*
[4]*Atmosphere and Ocean Research Institute, The University of Tokyo, Chiba, Japan*
[5]*National Marine Fisheries Service, NOAA, Woods Hole, MA, USA*
[6]*Ocean Science Section, Intergovernmental Oceanographic Commission of UNESCO, Paris, France*
[7]*North Pacific Marine Science Organization (PICES), Sidney, BC, Canada*
[8]*Office of Science and Technology, National Marine Fisheries Service, NOAA, Silver Spring, MD, USA*
[9]*International Council for the Exploration of the Sea, Copenhagen, Denmark*

**Corresponding author: tel: 01 206 526 4223; e-mail: Anne.Hollowed@noaa.gov.*

Hollowed, A. B., Barange, M., Garçon, V., Ito, S., Link, J. S., Aricò, S., Batchelder, H., Brown, R., Griffis, R., and Wawrzynski, W. Recent advances in understanding the effects of climate change on the world's oceans. – ICES Journal of Marine Science, 76: 1215–1220.

Received 4 March 2019; revised 11 April 2019; accepted 12 April 2019; advance access publication 4 August 2019.

In June 2018, >600 scientists from over 50 countries attended the Fourth International Symposium on the Effects of Climate Change on the World's Oceans (ECCWO-4). ECCWO-4 provided a forum for scientists to share information, build understanding, and advance responses to climate impacts on oceans and the many people, businesses and communities that depend on them. Seven Key Messages emerging from the symposium and relevant information from recently published literature are summarized. Recent scientific advances are improving our ability to understand, project, and assess the consequences of different levels of 21st century climate change for ocean ecosystems and ocean dependent communities. Outcomes of the symposium highlighted the need for on-going engagement with stakeholders, communities, and managers when considering the trade-offs associated with tactical and strategic opportunities for adaptation to climate change. Science informed adaptation frameworks that engage the public in their development are needed for effective management of marine resources in a changing climate. The summary provides a brief overview of the advances in climate-ocean science emerging from the symposium and provides context for the contributed papers within the broader socio-ecological advances of the discipline.

Keywords: adaptation, climate change, climate forecasting, climate projections

Introduction

The Fourth International Symposium on the Effects of Climate Change on the World's Oceans (ECCWO-4) was jointly convened in Washington, USA in 2018 by the International Council for the Exploration of the Sea (ICES), the North Pacific Marine Science Organization (PICES), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO); the Food and Agriculture Organization of the United Nations (FAO), and the U.S. National Oceanic and Atmospheric Administration (NOAA). Previous symposia were held in Gijón, Spain, in 2008 (Valdés *et al.*, 2009), Yeosu, South Korea, in 2012 (2nd ICES/PICES/IOC Effects of

Climate Change on the World's Oceans. 2013. ICES JMS 70:915–1054) and Santos, Brazil, in 2015 (Barange *et al.*, 2016).

ECCWO-4 occurred at a key juncture for the scientific community's understanding of the implications of climate impacts on ocean systems and societies responses to these impacts. National and international assessments confirm that the Earth's climate and oceans are rapidly changing. The impacts are already evident in some regions and more impacts are expected with continued changes in the planet's climate system (Jay *et al.*, 2018; IPCC, 2018). Several critical milestones have been achieved since the last ECCWO symposium. The publication of the IPCC Fifth Assessment Report (AR5) laid the foundation for a landmark international agreement to curb carbon emissions (the Paris Agreement, agreed at the 21st session of the Conference of the Parties of the UN Framework Convention on Climate Change or "COP 21" in December 2015). The adoption by the UN General Assembly in 2015 of the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) provided a roadmap for global efforts to incorporate climate change impacts within the global socio-ecological system. These developments underscore the worldwide recognition that changing oceans will have significant impacts on a range of issues spanning health, food security, gender equality and women's empowerment, sanitation, energy, sustainable economic growth, ensuring sustainable consumption and production, mitigating and adapting to climate change, protecting biodiversity, and maintaining peaceful dialogues among nations. The symposium organizers recognized that future efforts to inform the public of the risks associated with these changes would benefit from the products, outcomes and lessons that emerged from this symposium [website (https://meetings.pices.int/meetings/international/2018/climate-change/background)]. These factors provided the motivation to organize ECCWO-4 to review and evaluate new science relevant to the ECCWO-4. More specifically, the timing of the symposium was designed to provide scientists an opportunity to prepare peer-reviewed publications that could be considered by national and international climate change assessment teams tasked with informing policy makers of the observed and projected impacts of climate change on the world's oceans and trade-offs of different adaptation options with respect to ocean systems.

Key messages and their relevance to articles in this issue

Convening a symposium of over 600 scientists from over 50 nations to discuss the consequences of different levels of 21st century climate change for ocean ecosystems and ocean dependent communities [for details see symposium scope (https://meetings.pices.int/meetings/international/2018/climate-change/scope)] required contributions from many scientists. To minimize the chance of missing Key Messages, we used a multi-pronged approach that included input from session and workshop conveners [see list of conveners (https://meetings.pices.int/meetings/international/2018/climate-change/program)], the scientific steering committee [see Organizers (https://meetings.pices.int/meetings/international/2018/climate-change/organizers)], the Plenary Speakers (https://meetings.pices.int/meetings/international/2018/climate-change/speakers), and participating scientists, to identify and compile Key Messages that emerged from the symposium and that represent the current state of the discipline. Session conveners were asked to prepare a summary slide that identified the main "takeaways" from their session and any new scientific advances that have emerged since ECCWO-3. We synthesized input from these sources into the following seven Key Messages. We also, identify the articles in this symposium volume that highlight one or more of these Key Messages.

Climate change is already affecting the oceans and the socio-ecological systems that depend on them

Many of the sessions at the symposium provided evidence that oceans are changing in ways that impact humans. Rapid ecosystem changes were reported in high latitude systems (Overland *et al.*, 2018; Stevenson and Lauth, 2019). Previous studies found evidence of trophic level differences in responses to climate change in marine ecosystems (Perry *et al.*, 2010; Friedland *et al.*, 2012; Kortsch *et al.*, 2015; Ullah *et al.*, 2018). Friedland *et al.* (in press) also detected such differences in trophic responses in his study of the northeast shelf of the United States. These transitions have far reaching implications for weather, national security, food security, transport and commerce (Larsen *et al.*, 2014; Hoegh-Guldberg *et al.*, 2014; IPCC, 2018; Free *et al.*, 2019).

The Quo Vadimus "graphic novel" article provides a pictorial summary of key findings from the symposium based on selected cartoons by Bas Kohler (Link *et al.*, in press). This graphic novel describes the future landscape of our world under changing climate conditions. Using clever and humorous cartoons the artist conveys the message that oceans are changing and there is much at stake if these changes continue. The cartoons depict the urgent need for scientists to advance our understanding of these changes and the risks associated with them. The graphic novel concludes with a reminder that finding solutions to deal with climate induced change and their consequences will require two-way communication with managers and stakeholders to co-design effective adaptation pathways. The full set of cartoons from the Symposium are available on the ECCWO-4 website (https://www.flickr.com/photos/pices/sets/72157669719136128).

Technical advances in existing and new observation networks are improving our understanding of key ocean processes, but our ability to project future ocean conditions at seasonal to multi-decadal time scales is still incomplete

To monitor changes in ocean environments, scientists are developing new technologies to collect more and targeted measurements to better understand the oceanic carbon cycle and to minimize uncertainties for both short-term prediction and long-term projection of carbon uptake, ocean acidification, and deoxygenation. The continuation and enhancement of ocean observing using diverse technologies (satellite, moorings, ships, profiling floats, gliders, etc.) is the foundation for detecting and understanding the implications of climate change on ocean systems. Several international groups are developing initiatives to enhance global ocean observing systems. For example, in response to this need, the Chinese Academy of Sciences created a new Center for Mega Science [Fang Wang Symposium Video (https://meetings.pices.int/publications/video#2018-ECCWO)]. The UN launched the United Nations Decade of Ocean Science for Sustainable Development (https://en.unesco.org/ocean-decade) (2021–2030), which is designed to collect the information necessary to understand and project ocean responses to multiple stressors.

Several scientists reported on extreme ocean events and their ecosystem and societal impacts. Marine heat waves have been observed in several regions and they are expected to be more common and persistent in the future [Alistair Hobday Symposium Video (https://meetings.pices.int/publications/video#2018-ECCWO)]. The development of a coherent standardized framework for reporting ocean heat waves is advancing this field of research (Hobday *et al.*, 2018a). It was noted that these extreme events may allow researchers to rehearse their responses to persistent anomalous warming events [a "stress test," see Francisco Werner Symposium Video (https://meetings.pices.int/publications/video#2018-ECCWO)].

For decades scientists have been striving to identify leading indicators of anomalous climate events. Advances in the collection and availability of ocean observations and new analytical methods for rapid synthesis of large data sets using models have improved our ability to predict anomalous ocean conditions on seasonal scales. However, predictions of future ocean states at decadal time scales may not yet be possible in all regions. The symposium provided an opportunity for scientists to assess short- and medium-term ocean forecasting skill (Tommasi *et al.*, 2017; Payne *et al.*, 2017; Frölicher and Laufkötter, 2018; Frölicher *et al.*, 2018). In several ocean regions there is strong evidence that short-term (3–9 months) forecasting of oceanographic processes is now feasible. This finding opens new opportunities for the advancement of ecosystem-linked stock assessments. New methods and frameworks are being developed to detect regime shifts and utilize early detection systems of changing climate conditions to inform management (Hobday *et al.*, 2016; Payne *et al.*, 2017; Hobday *et al.*, 2018b; Oliver *et al.*, 2018).

Hobday *et al.* (in press) tackle the ethical responsibilities of scientists who are developing forecasting systems for use in management and industry planning. Their article includes reviews of seven examples of forecast systems serving a range of stakeholders. They identify a variety of issues that should be considered during the scoping, development, delivery and evaluation phases of climate forecasting systems. The authors provide ten principles, which serve as a useful guide for forecasting teams.

The paper by Bisagni *et al.* (in press) explores inter-annual variability in Gulf Stream warm-core rings (WCRs) in a Western Boundary Current ecosystem. This paper is another example of the importance of collecting and maintaining time series of ocean observations. This study utilizes a rich set of observations to evaluate time trends in the interannual variability in the frequency and location of strong WCRs over a 44-year time frame. The authors then used this long time series to identify a statistically significant relationship between time trends in the abundance of longfin squid (*Doryteuthis pealeii*) over the U.S. Northeast Shelf Large Marine Ecosystem and the spatially averaged annual mean WCR encounter area.

Mochizuki and Watanabe (in press) found a distinct subdecadal variation in the 2000s over the tropical Pacific that was rarely observed in other decades. The authors compared observed patterns of ocean-heat-content to decadal hindcasts and found that subdecadal variations were difficult to predict. This demonstrates one of the comparative studies needed to fully interpret and understand patterns in the predictive skill of models that was called for in Hobday *et al.* (in press).

Hermann *et al.* (in press) provide a good demonstration of the technical advancements in our ability to project multi-decadal ocean trajectories. Multiple publications (Sundby *et al.*, 2016; Cheung, 2018; Overland *et al.*, 2018; Stevenson and Lauth, 2019) provide evidence that high latitude ecosystems are changing rapidly and that widespread change is projected in the future under different emission scenarios (e.g. RCP 4.5 and RCP 8.5). Hermann *et al.* (in press) present results from the Alaska Climate Integrated Modeling project. In their study, outputs from the Fifth Coupled Model Inter-comparison Project are downscaled for use in projecting future ocean conditions in the eastern Bering Sea to 2100. The paper considers both scenario (representative concentration pathways) and structural (between model differences) uncertainty in projections. The authors use multivariate statistical methods to explore the modes of variability and covariability across variables to characterize the dominant relationships among bio-physical features. They demonstrate that these dominant modes can be used to rapidly estimate the regional ecosystem responses to large ensembles of forcing scenarios. These approaches reveal the spatial extent and magnitude of ecosystem change expected to occur in the region by the end of the century, and locations where high levels of variability are expected.

Despite significant gaps, our understanding of socio-ecological systems has improved sufficiently to enable us to contrast the ecological and societal impacts of different future scenarios

An exciting advance since ECCWO-3 has been the development of fully coupled socio-ecological models capable of projecting future scenarios based on global responses to the challenges of climate change and regional responses to natural resource management. New modelling tools and insights into climate-impacts allow us to contrast futures under alternative societal responses to climate change (Lotze *et al.*, 2019; Skogen *et al.*, 2018; Hermann *et al.*, in press). The uncertainty associated with ecological projections of climate change impacts on marine ecosystems is being incorporated by contrasting outcomes from a range of ecosystem models with varying levels of complexity. Kaplan *et al.* (2019) explored the relative importance of incorporation of mechanistic linkages in stock projection models. Understanding and predicting how ecological changes will impact human societies, institutions and economies will be critical for effective adaptation (Karp *et al.*, in press).

Some marine organisms exhibit a capacity to adapt to climate change, but there are energetic and physiological costs, as well as limits

Research continues to reveal complex energetic and physiological trade-offs associated with individual or species adaptation to changing environmental conditions [see Widdicombe Symposium Video (https://meetings.pices.int/publications/video#2018-ECCWO)]. There are several publications in this issue focused on the ecological effects of climate change. The research findings from the current efforts build on previous ECCWO symposia and they reveal complex and sometimes unexpected biological and ecological responses at different life stages, with lagged effects. Important lessons can be learned by examining the variations in adaptive responses and consideration of the full suite of environmental stressors within the socio-ecological system (Hobday *et al.*, in press).

Friedland *et al.* (in press) conducted a retrospective examination of the role of ocean temperature on phytoplankton, zooplankton, fish and macroinvertebrate distributions along the northeast US

continental shelf large marine ecosystem. They found that species and marine communities responded differently to thermal change. The authors conclude that the different responses may be linked to the organism's capacity to adapt to novel thermal regimes. They hypothesized that spatial distributions of lower trophic level organisms were less responsive to thermal change because of their ability to integrate seasonal thermal changes, whereas, the responses of higher trophic level species depended on both the availability of lower trophic level organisms and environmental conditions.

Two papers in this volume reveal the costs and tradeoffs of species adaptation to environmental stress. Long *et al.* (in press) explore the implications of ocean acidification on the respiration and feeding of juvenile red and blue crabs in the Bering Sea. The results show that crabs can adapt to ocean acidification exposure if feeding ration is increased, but there are energetic and physiological costs to this adaptation. Crawford *et al.* (in press) utilize a 38-year time series of the abundance and diets of three South African sea bird species to assess the effects of climate on forage availability. The results of these papers illustrate the need for multi-dimensional considerations when evaluating the adaptive capacity of sea birds to changing environmental conditions.

Options available for societal adaptation are more limited if current trends of greenhouse gas emissions continue

Coupled socio-ecological models and vulnerability assessments have been used to evaluate the trade-offs associated with different societal responses. Results from these models and assessments show that adaptation options are more limited when the higher greenhouse gas emission scenarios are considered. Recent studies show that as CO_2 increases, there are fewer and less effective adaptation and repair options for ocean systems (Gattuso *et al.*, 2015, IPCC, 2018). Understanding these trade-offs within an integrated socio-ecological framework helps to inform options for human responses to climate driven changes to marine ecosystems (Holsman *et al.*, in press).

Tactical and strategic opportunities for societal adaptation to climate change have also been revealed through engagement with institutions and dependent communities eager to plan their own future

Several case studies where researchers engaged coastal communities in efforts to develop effective climate adaptation strategies were presented at the symposium. Some of these case studies have been extensively documented in a recent FAO report (Barange *et al.*, 2018). The symposium highlighted that there is an urgent and on-going need for scientists to interact with dependent communities to assist in the development and evaluation of realistic adaptation pathways that are based on the best available scientific information. Commitments to an on-going process of science product delivery to resource managers and users will enable more intelligent decision-making by stakeholders, which is necessary to keep up with the changing ocean ecosystems (Wise *et al.*, 2014; Hobday *et al.*, in press).

Coastal communities are seeking adaptation options and a guide to good governance to plan for the future. Many coastal communities are turning to aquaculture, marine ranching, and fish attraction technologies to fill critical needs for food security and dietary demands. While technological advancements in fish capture and fish production are emerging, holistic studies that assess the long-term implications of these adaptation responses will be needed to guide future developments to sustain food resources and preserve human and planetary health (Willett *et al.*, 2019). Whether operating at the global or local level, it is important to engage respectfully in adaptation by involving all stakeholders, supporting their progress and recognizing the importance of local knowledge [see Merle Sowman Symposium Video (https://meetings.pices.int/publications/video#2018-ECCWO) and Colenbrander and Sowman, 2015]. It is important that stakeholder involvement in adaptation planning be ongoing and iterative to address obstacles that arise along the way. Communicating and documenting these challenges could provide valuable lessons for similar initiatives.

In this volume, Karp *et al.* (in press) reviewed the conservation and management challenges encountered when U.S. fisheries target species that are shifting their distributions and/or productivity. The authors identify six tactical steps that scientists and managers can take to address shifting spatial distributions and abundance of managed species. Among these, the authors encourage continued close collaboration and communication among scientists, managers, and stakeholders as a key step in the development of adaptation options to support sustainable fisheries management in a changing world.

Adaptive management frameworks are urgently needed to address climate-driven policy issues

Recent studies suggest that coordinated adaptation frameworks that are capable of incorporating flexibility and insights from past experiences, will lead to wiser decision making and more effective long-term management of impacts (Poulain *et al.*, 2018). Cooperative fishery management frameworks will be needed for effective management of fisheries targeting species with shifting spatial distributions (Pinsky *et al.*, 2018). Two contributed papers in this volume considered adaptive frameworks at different levels of community, manager, stakeholder, and government engagement.

Pinnegar *et al.* (in press) applies a vulnerability and an adaptive capacity analysis of the fisheries sector of Dominica. They consider the implications of long-term climate change and the occurrence of extreme weather events. The paper identifies which parishes in Dominica are most vulnerable to climate change impacts on fish and fisheries. The authors conclude that the vulnerability framework provides useful information for government and development agencies that can be used to enhance resilience and build adaptive capacity.

Holsman *et al.* (in press) also consider pathways to build climate-informed management portfolios. They define climate-resilient management as a mix of dynamic, adaptive and fixed management approaches. The authors address the trade-offs of these different approaches and their relative utility for managers considering current, near future and distant future management of fisheries resources. Holsman *et al.* (in press) propose a nested adaptation framework that applies different tools for short, medium, and long-term climate impact planning horizons may be needed to address the climate change issues on marine ecosystems. They identify suites of key research activities that could be adopted to improve the adaptation of management frameworks to develop climate-informed policies that foster science-management-stakeholder dialogs.

Summary and next steps

This brief introduction provides a brief glimpse of the exciting new developments happening in the ocean and climate science arena. ECCWO-4 made it clear that integrated multidisciplinary research programs are appearing across the globe in response to the societal need for information on the impacts of climate change on the world's oceans. ECCWO-4 included numerous opportunities for the discussion of socio-ecological systems with two way feedbacks between human responses and the ecosystem change [see additional ECCWO-4 session summaries in PICES newsletter (https://meetings.pices.int/publications/pices-press/volume26/PPJul2018.pdf)]. As we look forward to the ECCWO-5 symposium, we anticipate that the scientific community will strive ever harder to provide sound scientific information to inform climate actions that preserve life under water while providing food, jobs, and other services contributing to human well-being into the future. This symposium series informs the public of recent advances in climate science and engages the community in thoughtful consideration of the societal choices we all face with respect to climate change implications on, and consequences for, the world's oceans. We trust that the papers presented in this symposium issue, not only represent a useful snapshot of the state of climate science research with respect to the ocean, but will also help direct the community toward future advances in assessing the impacts and effects of changing climate on the world's oceans.

Acknowledgements

We appreciate the organizing committee, session conveners, presenters, and participants of the Fourth International Symposium on the ECCWO-4. We express our gratitude to the Royal Norwegian Embassy in Washington D.C. and the fourteen co-sponsoring organizations for their active interest and support. We acknowledge that numerous national and international scientific organizations provided critical support that helped to sustain the pace of scientific advancement noted in this symposium. We also thank the student volunteers who helped to make the symposium a success. Anne Hollowed's participation was supported by the Fisheries and the Environment (FATE), Stock Assessment Analytical Methods (SAAM) and the North Pacific Regimes and Ecosystem Productivity (NPCREP) programs with the National Marine Fisheries Service, and NOAA's Research Transition Acceleration Program. Shin-ichi Ito's participation was supported by the Japan Society for the Promotion of Science KAKENHI project, grants JP15H05823 and JP18H03956. The scientific ideas, views, and opinions presented in this paper are solely those of the authors and do not represent the views of ICES, PICES, IOC-UNESCO, FAO, or NOAA.

References

Barange, M., Bahri, T., Beveridge, M., Cochrane, K., Funge-Smith, S., and Poulain, F. 2018. Impacts of climate change on fisheries and aquaculture – synthesis of current knowledge, adaptation and mitigation options. *In* Fisheries and Aquaculture Technical Paper. FAO, Rome.

Barange, M., King, J., Valdés, L., and Turra, A. 2016. The evolving and increasing need for climate change research on the oceans. ICES Journal of Marine Science, 73: 1267–1271.

Bisagni, J., Nicols, O., Pettipas, R. in press. Inter-annual variability of Gulf Stream warm core ring interactions without continental shelf and effects on longfin squid abundance, 1981–2004. ICES Journal of Marine Science.

Cheung, W. W. L. 2018. The future of fishes and fisheries in the changing oceans. Journal of Fish Biology, 92: 790–803.

Colenbrander, D. R., and Sowman, M. R. 2015. Merging socioeconomic imperatives with geospatial data: a non-negotiable for coastal risk management in South Africa. Coastal Management, 43: 270–300.

Crawford, R., Sydeman, W. J., Thompson, S. A., Sherley, R., and Makhado, A. in press. Food habits of an endangered seabird indicate recent poor availability of abundant forage resources. ICES Journal of Marine Science, 76: 1344–1352.

Free, C. M., Thorson, J. T., Pinsky, M. L., Oken, K. L., Wiedenmann, J., and Jensen, O. P. 2019. Impacts of historical warming on marine fisheries production. Science, 363: 979–983.

Friedland, K. D., Stock, C., Drinkwater, K. F., Link, J. S., Leaf, R. T., Shank, B. V., Rose, J. M. *et al.* 2012. Pathways between primary production and fisheries yields of large marine ecosystems. PLoS ONE, 7: e28945.

Friedland, K. D., McManus, M. C., Morse, R. E., and Link, J. S. in press. Event scale and persistent drivers of fish and macroinvertebrate distributions on the Northeast US Shelf. ICES Journal of Marine Science, 76: 1316–1334.

Frölicher, T. L., Fischer, E. M., and Gruber, N. 2018. Marine heatwaves under global warming. Nature, 560: 360–364.

Frölicher, T. L., and Laufkötter, C. 2018. Emerging risks from marine heat waves. Nature Communications, 9: 650.

Gattuso, J. P., Magnan, A., Billé, R., Cheung, W. W. L., Howes, E. L., Joos, F., Allemand, D. *et al.* 2015. Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. Science, 349: aac4722.

Hermann, A. J., Gibson, G. A., Cheng, W., Ortiz, I., Aydin, K., Wang, M., Hollowed, A. B. *et al.* in press. Projected biophysical conditions of the Bering Sea to 2100 under multiple emission scenarios. ICES Journal of Marine Science, 76: 1280–1304.

Hobday, A. J., Hartog, J. R., Manderson, J. P., Mills, K. E., Oliver, M. J., Pershing, A. J., and Siedlecki, S. in press. Ethical considerations and unanticipated consequences associated with ecological forecasting for marine resources. ICES Journal of Marine Science, 76: 1244–1256.

Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C. J., Benthuysen, J. A. *et al.* 2016. A hierarchical approach to defining marine heatwaves. Progress in Oceanography, 141: 227–238.

Hobday, A. J., Oliver, E. C. J., Gupta, A. S., Benthuysen, J. A., Burrows, M. T., Donat, M. G., Holbrook, N. J. *et al.* 2018a. Categorizing and naming MARINE HEATWAVES. Oceanography, 31: 162–173.

Hobday, A. J., Spillman, C. M., Eveson, J. P., Hartog, J. R., Zhang, X., and Brodie, S. 2018b. A framework for combining seasonal forecasts and climate projections to aid risk management for fisheries and aquaculture. Frontiers in Marine Science, 5, Article 137. doi:10.3389/fmars.2018.00137

Hoegh-Guldberg, O., Cai, R., Poloczanska, E. S., Brewer, P. G., Sundby, S., Hilmi, K., Fabry, V. J. *et al.* 2014. The ocean. 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, pp. 1655–1731. Ed. by 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 University Press, Cambridge, United Kingdom and New York, NY, USA.

Holsman, K., Hazen, E., Haynie, A., Gourguet, S., Hollowed, A., Borgrad, S., Samhouri, J. *et al.* in press. Toward climate-resiliency in fisheries management. ICES Journal of Marine Science, 76: 1368–1370.

IPCC. 2018. Summary for policymakers. *In* 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, p. 32. Ed. by Masson-Delmotte V., Zhai P., Pörtner H-O., Roberts D., Skea J., Shukla P. R., Pirani A., Moufouma-Okia W., Péan C., Pidcock R., Connors S., Matthews J. B. R., Chen Y., Zhou X., Gomis M. I., Lonnoy E., Maycock T., Tignor M., and Waterfield T. World Meteorological Organization, Geneva, Switzerland.

Jay, A., Reidmiller, D. R., Avery, C. W., Barrie, D., DeAngelo, B. J., Dave, A., Dzaugis, M. *et al.* 2018. Overview. In impacts, risks, and adaptation in the United States. In Fourth National Climate Assessment, pp. 33–71. Ed. by D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart. U.S. Global Change Research Program, Washington, DC, USA.

Kaplan, I. C., Francis, T. B., Punt, A. E., Koehn, L. E., Curchitser, E., Hurtado-Ferro, F., Johnson, K. F. *et al.* 2019. A multi-model approach to understanding the role of Pacific sardine in the California Current food web. Marine Ecology Progress Series, 617–618: 307–321.

Karp, M. A., Peterson, J. O., Lynch, P. D., Griffis, R. B., Adams, C. F., Arnold, W. S., Barnett, L. A. K. *et al.* in press. Accounting for shifting distributions and changing productivity in the development of scientific advice for fishery management. ICES Journal of Marine Science, 76: 1305–1315.

Kortsch, S., Primicerio, R., Fossheim, M., Dolgov, A. V., and Aschan, M. 2015. Climate change alters the structure of arctic marine food webs due to poleward shifts of boreal generalists. Proceedings of the Royal Society B, 282: 20151546.

Larsen, J. N., Anisimov, O. A., Constable, A. J., Hollowed, A. B., Maynard, N., Pestrud, P., Prowse, T. D. *et al.* 2014. Polar regions. *In* Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1567–1612. Ed. by 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. Levey, S. MacCracken, P. R. Manstrandrea, and L. L. White. Cambridge University Press, New York.

Link, J. S., Kohler, B., Brady, M. M. P., Griffis, R., Ito, S-I., Garçon, V., Hollowed, A. *et al.* in press. A graphic novel from the 4th International Symposium on the Effects of Climate Change on the World's Oceans. ICES Journal of Marine Science, 76: 1221–1243.

Long, W., Pruisner, P., Swiney, K. M., Foy, R. in press. Effects of ocean acidification on the respiration and feeding of juvenile red and blue king crabs (Paralithodes camtschaticus and P. platypus). ICES Journal of Marine Science, 76: 1335–1343.

Lotze, H. K., Tittensor, D. P., Bryndum-Buchholz, A., Eddy, T. D., Cheung, W. W., Galbraith, E. D., Barange, M *et al.* 2019. Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. Proceedings of the National Academy of Sciences Jun 2019, 201900194, doi: 10.1073/pnas.1900194116.

Mochizuki, T., and Watanabe, M. in press. Observed and hindcasted subdecadal variability of the tropical Pacific climate. ICES Journal of Marine Science, 76: 1271–1279.

Oliver, E. C. J., Donat, M. G., Burrows, M. T., Moore, P. J., Smale, D. A., Alexander, L. V., Benthuysen, J. A. *et al.* 2018. Longer and more frequent marine heatwaves over the past century. Nature Communications, 9: 1324.

Overland, J., Dunlea, E., Box, J. E., Corell, R., Forsius, M., Kattsov, V., Olsen, M. S. *et al.* 2018. The urgency of Arctic change. Polar Science, doi:10.1016/j.polar.2018.11.008.

Payne, M. R., Hobday, A. J., MacKenzie, B. R., Tommasi, D., Dempsey, D. P., Fässler, S. M. M., Haynie, A. C. *et al.* 2017. Lessons from the first generation of marine ecological forecast products. Frontiers in Marine Science, 4: 1–15.

Perry, R. I., Cury, P., Brander, K., Jennings, S., Möllmann, C., and Planque, B. 2010. Sensitivity of marine systems to climate and fishing: concepts, issues and management responses. Journal Marine Systems, 79: 427–435.

Pinnegar, J. K., Engelhard, G. H., Norris, N. J., Theophille, D., and Sebastien, R. D. in press. Assessing vulnerability and adaptive capacity of the fisheries sector in Dominica: long-term climate change and catastrophic hurricanes. ICES Journal of Marine Science, 76: 1353–1367.

Pinsky, M. L., Reygondeau, G., Caddell, R., Palacios-Abrantes, J., Spijkers, J., and Cheung, W. W. L. 2018. Preparing ocean governance for species on the move. Science, 360: 1189–1191.

Poulain, F., Himes-Cornell, A., and Shelton, C. 2018. Methods and tools for climate change adaptation in fisheries and aquaculture. *In* Impacts of Climate Change on Fisheries and Aquaculture. Synthesis of Current Knowledge, Adaptation and Mitigation Options, pp. 535–566. Ed. by M. Barange, T. Bahri, M. C. M. Beveridge, K. L. Cochrane, and F. Poulain. FAO Fisheries and Aquaculture Technical Paper, Rome, Italy.

Skogen, M. D., Hjollo, S. S., Sando, A. B., and Tjiputra, J. 2018. Future ecosystem changes in the Northeast Atlantic: a comparison between a global and a regional model system. ICES Journal of Marine Science, 75: 2355–2369.

Stevenson, D. E., and Lauth, R. R. 2019. Bottom trawl surveys in the northern Bering Sea indicate recent shifts in the distribution of marine species. Polar Biology, 42: 407–421.

Sundby, S., Drinkwater, K. F., and Kjesbu, O. S. 2016. The North Atlantic spring-bloom system – where the changing climate meets the winter dark. Frontiers in Marine Science, 3: 1–12.

Tommasi, D., Stock, C. A., Hobday, A. J., Methot, R., Kaplan, I. C., Eveson, J. P., Holsman, K. *et al.* 2017. Managing living marine resources in a dynamic environment: the role of seasonal to decadal climate forecasts. Progress in Oceanography, 152: 15–49.

Ullah, H., Nagelkerken, I., Goldenberg, S. U., and Fordham, D. A. 2018. Climate change could drive marine food web collapse through altered trophic flows and cyanobacterial proliferation. PLoS Biology, 16: e2003446.

Valdés, L., Peterson, W., Church, J., Brander, K., and Marcos, M. 2009. Our changing oceans: conclusions of the first International Symposium on the Effects of Climate Change on the World's Oceans. ICES Journal of Marine Science, 66: 1435–1438.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T. *et al.* 2019. Food in the anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. The Lancet Commissions, 393: 447–492.

Wise, R. M., Fazey, I., Stafford Smith, M., Park, S. E., Eakin, H. C., Archer Van Garderen, E. R. M., and Campbell, B. 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. Global Environmental Change, 28: 325–336.