THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY
Oceanography

CITATION

Durack, P.J., A. Sen Gupta, and L.H. Smedsrud. 2018. Introduction to the special issue on ocean warming. *Oceanography* 31(2):28–31, https://doi.org/10.5670/oceanog.2018.226.

DOI

https://doi.org/10.5670/oceanog.2018.226

Introduction to the Special Issue on

Ocean Warming

By Paul J. Durack, Alex Sen Gupta, and Lars H. Smedsrud

With atmospheric CO_2 levels rising unabated, the climate system is warming at the fastest rate in human history. It has long been known that the vast bulk of extra heat associated with anthropogenic carbon dioxide emissions is entering the ocean (e.g., Hansen et al., 1988; Levitus et al., 2000; Barnett et al., 2005), causing warming at the surface and through much of the ocean's depth. This warming drives thermal expansion of the ocean that, together with added mass from rapidly melting glaciers and ice sheets, is accelerating the rise in sea levels (Church et al., 2013). As the mean state of the ocean changes, so do its extremes. Marine heatwaves are becoming more frequent and more intense (e.g., Oliver et al., 2018; **Hobday et al.**), and increasing sea levels are resulting in more damage from storms in coastal regions (e.g., Hauer, 2017). In addition, marine species are being significantly affected, with populations moving poleward to escape the heat (e.g., Sorte et al., 2010), loss of key habitat-forming species (e.g., Wernberg, 2013, 2016), and mass bleaching and mortality of coral reefs (e.g., Hughes, 2017). Simultaneously, more intense hurricanes, destructive wildfires, and severe droughts have been occurring across the global terrestrial landscape.

With these ocean and land changes as a backdrop, this special issue of *Oceanography* examines some of the new science around ocean warming that involves the use of ocean observations and modeling, and that range from changes in the physical environment to impacts on marine ecosystems.

The ocean is the dominant flywheel of the climate system, and the overview paper by **Schmitt** elucidates this role well. **Schmitt** highlights the ocean as a central player in climate evolution due to its enormous heat capacity (more than 1,000 times that of the atmosphere) and its role, through ocean-atmosphere interactions, in absorbing, storing, and transporting heat from incoming solar radiation as well as the excess heat associated with greenhouse gas emissions. He also notes that the ocean is the primary water source for the atmosphere. Through latent heat exchange, atmospheric water vapor is responsible for a substantial fraction of global energy transport that is counterbalanced by transfer of heat energy in the ocean between Earth's hemispheres. **Schmitt** also describes the ocean's role as the dominant carbon reservoir in the global climate system. He concludes that progress in understanding the climate system requires collection of continuous, high-frequency ocean observations indefinitely into the future.

The next two articles focus on various aspects of observed warming in the ocean. **Durack et al.** focus on global ocean warming, assessing changes through the depths from observations and models. They revisit and extend previous analyses that showed consistent observed global ocean warming back to at least the 1950s. Using models, they infer that the observed warming may have begun in the early 1900s, with the simulated warming impacting all ocean depths since the 1950s. Using the comprehensive modern measurement network provided by the Argo Program, they investigate the hemispheric partitioning of heat over the period 2005 to the present and show a marked asymmetry, with strong warming in the Southern Hemisphere, and much weaker warming in the Northern Hemisphere. Lastly, **Durack et al.** compare and contrast deep ocean warming (>2,000 m) across observations and models, and show both similarities in the spatial distribution of warming and considerable differences, particularly in the deep Northern Hemisphere basins. **Sallée** focuses on the Southern Ocean, the only ocean without continental barriers, circling the globe and extending from 40°S to Antarctica. He shows how the complex vertical structure of the Southern Ocean makes it a primary location for excess heat from the surface to be transferred into the ocean depths, although the pattern of warming is highly heterogeneous. Accurately simulating this region in models is difficult. **Sallée** highlights numerous issues with the current generation of

global climate models that are routinely used to generate future projections of climate responses to continuing greenhouse gas emissions.

A number of articles consider the importance of modes of climate variability on ocean evolution. **Penduff et al.** investigate interannual-to-multidecadal chaotic variability using a suite of large ensemble 1/4° ocean simulations. They use this model suite to tease out atmospherically forced versus intrinsic ocean variability modes and show that ocean variability can be considered broadband "noise." Temporal scales extend into decades, far longer than comparative atmospheric modes, and can also extend spatially to ocean basin scales. **Liu and Xie** investigate the role of the ocean in the recent global surface warming hiatus period and highlight the important role of the modes of ocean-atmosphere coupled variability. They show heat relocation throughout the three-dimensional ocean, vertically and between ocean basins, which plays a considerable role in accounting for the change in the rate of surface warming during the hiatus period of 1998 to 2012 when it is contrasted with the longer timeframe of warming history. The role of ocean dynamical responses and coupled ocean-atmosphere interactions are also key aspects of understanding the rate of realized surface warming. **Gruenberg and Gordon** focus on the Indonesian Throughflow (ITF), a choke point of global ocean circulation that transports warm, fresher water from the Pacific to the Indian Ocean as part of the upper branch of the global thermohaline circulation. They investigate the period 2004 to 2017 when comprehensive field campaigns provided moored velocity measurements from the surface to the sill depth around 700 m. These measurements, along with Argo analyses, show a strong relationship between heat transport through the ITF and heat content anomalies in the eastern tropical Indian Ocean. These results tie into the variability modes described by **Liu and Xie** that lead to heat transport between ocean basins. **Timmermans et al.** consider one of the primary physical responses to ocean surface warming: enhanced hurricane activity and the extreme waves that interact with coastlines in response to these events. As the surface ocean continues to warm, the energy that drives tropical cyclones and hurricanes will intensify, resulting in significant changes to the extreme wave climate. While they note some limitations in their approach, their simulations show large increases in extreme wave heights particularly for the tropical North Pacific and Atlantic basins. Such large changes in response to a 1.5° or 2.0°C warming would be bad news for communities that have already suffered during recent hurricane seasons.

The focus of the special issue then shifts to interactions between the ocean and the cryosphere. **Willis et al.** describe NASA's Oceans Melting Greenland (OMG) mission and the field campaign that mapped changes to two of Greenland's marine-terminating glaciers, Tracy and Heilprin. While these two glacier systems are located side by side in Inglefield Gulf in northwestern Greenland, the changes that each has experienced could not be more different. Since 1892, Tracy Glacier has dramatically accelerated, thinned, and retreated, while Heilprin Glacier has retreated only slightly during the last century and has remained almost stationary in the last decade. These detailed assessments highlight the importance of knowledge of ocean-ice interactions to accurate simulation of glacier responses to a warming ocean. **Nowicki and Seroussi** describe the next steps toward more comprehensive Earth system modeling, with efforts to incorporate dynamical ice sheet simulations in order to more accurately quantify sea level rise. The recent expansion of observations of ice sheet surface velocities, surface elevation, and mass change has provided important new insights that strongly motivate researchers to improve simulations of these complex cryospheric systems. The responses of ice sheets to ongoing ocean and atmosphere warming is one of the largest unknowns

when considering future sea level projections from climate models, and the Ice Sheet Model Intercomparison for CMIP6 (ISMIP6) aims to address this issue.

The Arctic Ocean is the most strongly warming region across the globe, a feature termed "Arctic amplification." The ongoing loss of sea ice, snow, and ice on land is also one of the most visible aspects of ongoing global warming. **Bintanja et al.** show not only that Earth system models are able to simulate Arctic amplification but also that the climate system may incorporate a negative feedback mechanism that could help to limit future surface Arctic Ocean warming. As Arctic precipitation increases (a well-documented consequence of anthropogenic-driven warming), the additional freshwater may create a more stable Arctic Ocean by decoupling the mixed layer from the deeper warm Atlantic layer, which would lead to smaller ocean heat flux from the deeper ocean upward into the sea ice.

The special issue then moves along from the physical world to consider ocean ecosystems and biological responses to ocean change. Existing species and animal populations have evolved to operate within optimal temperature ranges where their biological processes function efficiently. Factors such as growth, reproduction, and survival are adversely affected as temperatures stray too far from this range. If thermal thresholds are exceeded too often or for extended periods, the population is no longer viable. Thus, the impact of rising temperatures on marine ecosystems is largely felt through changes in hot and cold extremes, where biological thermal tolerances are most likely to be surpassed.

Research into marine temperature extremes, or marine heatwaves (MHW) and cold spells, is growing rapidly as the frequency of these events increases and their biological impacts are better observed. One challenge to improving our understanding is the lack of a common framework to quantify the severity of each unique event. In response, **Hobday et al.** propose a framework for categorizing the severity of marine heatwaves that extends a recently developed MHW definition that is widely used by the scientific community. The framework provides a basis for understanding how the biological impacts are related to the physical aspects of MHW severity.

The impacts of extreme temperatures on three distinct marine ecosystems are examined in the contributions from **Pershing et al.** for the US Atlantic coast, **Colin** for the reef systems of Palau, and **Grebmeier et al.** for the Arctic. **Colin** examines coral bleaching events in Palau using extended station data to show that bleaching is not just constrained to near-surface systems but extends to the limits of coral depth range, around 90 m. He also demonstrates that the upwelling of cooler waters that would normally protect deep corals from temperature extremes can break down during La Niña events, allowing deep bleaching to occur. **Pershing et al.** evaluate the impacts of two successive MHWs in the Gulf of Maine on the valuable lobster industry. Elevated temperatures in 2012 increased early lobster landings, but had the detrimental effect of flooding the market and reducing industry profits. By applying lessons from 2012 when a similar MHW occurred in 2016, better stock management mitigated these economic impacts. The authors recommend implementing operational forecasting systems to allow marine industries to better prepare for future unexpected events. **Grebmeier et al.** examine Arctic feedback processes that are resulting in rates of warming roughly double that of the global average. Observational analyses in the Bering Sea indicate changes in seasonality, with later freeze-up and earlier breakup of sea ice. The reduced sea ice cover has resulted in a northward shift in benthic species ranges and changes in ecosystem composition, with implications for higher trophic levels.

Lynch et al. describe a final interesting consequence of ocean warming—changes to the propagation of sound energy in the ocean. They study changes in shallow-water propagation and also

pathways between the deep ocean and coastal regions. Propagation of sound energy can be altered by a variety of factors, including changes in sound speed, in the location of coastal fronts, and in the ocean soundscape associated with shipping and redistribution of fauna. Such changes have important consequences for seabed mapping and marine mammals, as well as for military applications.

In these uncertain times, it is more important than ever to focus on the fascinating and compelling aspects of science that drew us to the discipline. The global ocean is one of the last great unknowns on Earth, with the vast proportion of this underwater realm unmapped, unobserved, and unexplored. Better understanding of our ocean is one of the last opportunities for scientific discovery, adventure, and exploration, and provides a grand scientific challenge for current and future generations. The global ocean directly impacts the lives of billions of people around the world through its roles in driving and modulating aspects of the physical climate and in providing essential ecosystem services.

We hope this ocean warming special issue of *Oceanography* reminds us all of the need to better care for and understand our planet. Now more than ever, we need to advocate strongly for well-informed and timely actions to reduce future impacts of ongoing climate change.

REFERENCES

Barnett, T.P., D.W. Pierce, K.M. AchutaRao, P.J. Gleckler, B.D. Santer, J.M. Gregory, and W.M. Washington. 2005. Penetration of human-induced warming in the world's oceans. *Science* 309:(5732):284–287, https://doi.org/10.1126/science.1112418.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, and others. 2013. Sea level change. Pp. 1,137–1,216 in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, eds, Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, https://doi.org/10.1017/CBO9781107415324.026.

Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, G. Russell, and P. Stone. 1988. Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. *Journal of Geophysical Research* 93(D8):9,341–9,364, https://doi.org/10.1029/JD093iD08p09341.

Hauer, M.E. 2017. Migration induced by sea-level rise could reshape the US population landscape. *Nature Climate Change* 7(5):321–325, https://doi.org/10.1038/nclimate3271.

Hughes, T.P., J.T. Kerry, M. Álvarez-Noriega, J.G. Álvarez-Romero, K.D. Anderson, A.H. Baird, R.C. Babcock, M. Beger, D.R. Bellwood, R. Berkelmans, and others. 2017. Global warming and recurrent mass bleaching of corals. *Nature* 543:373–377, https://doi.org/10.1038/nature21707.

Levitus, S., J.I. Antonov, T.P. Boyer, and C. Stephens. 2000. Warming of the world ocean. *Science* 287(5461):2,225–2,229. https://doi.org/10.1126/science.287.5461.2225.

Oliver, E.C.J., M.G. Donat, M.T. Burrows, P.J. Moore, D.A. Smale, L.V. Alexander, J.A. Benthuysen, M. Feng, A. Sen Gupta, A.J. Hobday, and others. 2018. Longer and more frequent marine heatwaves over the past century. *Nature Communications* 9(1):1324, https://doi.org/10.1038/s41467-018-03732-9.

Sorte, C.J.B., S.L. Williams, and J.T. Carlton. 2010. Marine range shifts and species introductions: Comparative spread rates and community impacts. *Global Ecology and Biogeography* 19(3):303–316, https://doi.org/10.1111/j.1466-8238.2009.00519.x.

Wernberg, T., D.A. Smale, F. Tuya, M.S. Thomsen, T.J. Langlois, T. de Bettignies, S. Bennett, and C.S. Rousseaux. 2013. An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Climate Change* 3(1):78–82, https://doi.org/10.1038/nclimate1627.

Wernberg, T., S. Bennett, R.C. Babcock, T. de Bettignies, K. Cure, M. Depczynski, F. Dufois, J. Fromont, C.J. Fulton, R.K. Hovey, and others. 2016. Climate-driven regime shift of a temperate marine ecosystem. *Science* 353(6295):169–172, https://doi.org/10.1126/science.aad8745.

ACKNOWLEDGMENTS

Prepared by Lawrence Livermore National Laboratory (LLNL) under Contract DE-AC52-07NA27344. The work of PJD is a contribution by Lawrence Livermore National Laboratory to the science portfolio of the US Department of Energy, Office of Science, Climate and Environmental Sciences Division, Regional and Global Model Analysis Program. LLNL Release Number: LLNL-JRNL-763611.

COMPETING INTERESTS

The authors declare that they have no competing financial interests.

AUTHORS' CONTRIBUTIONS

PJD, ASG, and LHS shared responsibility for writing this special issue introduction.

AUTHORS

Paul J. Durack (pauldurack@llnl.gov) is Research Scientist, Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, Livermore, CA, USA. **Alex Sen Gupta** is Associate Professor, Climate Change Research Centre and ARC Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, Australia. **Lars H. Smedsrud** is Professor, Geophysical Institute, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway.

ARTICLE CITATION

Durack, P.J., A. Sen Gupta, and L.H. Smedsrud. 2018. Introduction to the special issue on ocean warming. *Oceanography* 31(2):28–31, https://doi.org/10.5670/oceanog.2018.226.