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EDITED AND REVIEWED BY
Peter Kareiva,
Aquarium of the Pacific, United States

*CORRESPONDENCE
Alex Sen Gupta
✉ a.sengupta@unsw.edu.au

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Editorial: Advances in marine heatwave interactions

Alex Sen Gupta[1,2,3]*, Svenja Ryan[4] and Vanessa Hernaman[5]

[1]Climate Change Research Centre, University of New South Wales, Sydney, NSW, Australia, [2]Centre for Marine Science and Innovation, University of New South Wales, Sydney, NSW, Australia, [3]Australian Research Council Centre of Excellence for Climate Extremes, Sydney, NSW, Australia, [4]Woods Hole Oceanographic Institution, Woods Hole, MA, United States, [5]Climate Science Centre, Commonwealth Scientific and Industrial Research Organisation, Hobart, TAS, Australia

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Editorial on the Research Topic
Advances in marine heatwave interactions

Introduction

With growing appreciation of the predominant role of climate extremes as the most impactful manifestation of anthropogenic warming, marine heatwave (MHW) research has exploded. Changes to the physical environment driven by MHWs can have devastating effects on ecosystems and reliant industries, with losses of tens of millions of US$ associated with many individual MHW events (Smith et al., 2021). This special edition explores new directions in MHW research around forecasting events across different timescales, understanding drivers, delving below the surface, examining the interaction between different types of extremes, and understanding the ecosystem and fisheries implications and how to manage these disruptive events.

MHW drivers

Considerable effort has gone into understanding the local drivers of MHWs (e.g., Holbrook et al., 2019; Sen Gupta et al., 2020). Different drivers affect the potential predictability of MHWs and determine the size, duration, and depth structure of events. The workhorse tool for understanding these drivers is an upper ocean heat budget (Oliver et al., 2021). This quantifies the heat flow to and from a MHW region from processes including air-sea fluxes, ocean currents and mixing. However, heat budgets are difficult to construct, and various approximations are often used to simplify their implementation. Elzahaby et al. examine choices made in constructing heat budgets and provide an important message of caution: incorrect implementation of one of the parameters, the mixed layer depth (MLD), can lead to the wrong attribution of the dominant MHW drivers. In particular, an underestimated MLD will artificially inflate the importance of air-sea fluxes.

Two studies use the heat budget approach to investigate global patterns in MHW drivers but come to contrasting conclusions. Focussing on the most extreme MHWs in an ocean reanalysis, Marin et al. find that MHW growth is most frequently driven by ocean heat advection, while decay is affected more evenly between atmospheric or oceanic processes. In contrast, Vogt et al. use direct heat flux output from an Earth System Model (ESM) and find that at mid- to high-latitudes, atmospheric processes (primarily reduced evaporative cooling and increased insolation) dominate the growth of MHWs while in the tropics, suppressed vertical mixing dominates. During MHW decay, increased evaporative cooling and ocean mixing dominate.

Some of the most significant MHW impacts are close to continents where there is ample life that fuels important fisheries. Two studies examined local MHW drivers off Chile and New Zealand (NZ). Pujol et al. examined an extended MHW off Patagonia in 2016. Weak winds led to reduced ocean heat loss that warmed the already elevated temperatures associated with enhanced warm water advection from lower latitudes, causing record breaking conditions. Cook et al. used the two longest daily *in-situ* datasets in the Southern Hemisphere, from coastal sites off NZ. They found that MHWs in enclosed nearshore environments can be decoupled from events in the open ocean, questioning the usefulness of global datasets for evaluating coastal conditions.

Below the surface

The majority of MHW studies to date is based on sea surface temperatures (SSTs) due to the uniform temporal and spatial coverage of satellite products. In recent years, interest in studying the subsurface expression of MHWs has grown, which is important given pelagic and benthic ecosystems are more sensitive to subsurface than surface temperature anomalies. However, a lack of long-term and continuous subsurface observations poses additional challenges. Using an eddy-resolving ocean model, Großelindemann et al. show that subsurface MHWs along the Northeast US coast typically have significantly higher intensities, up to 7°C, while surface events reach an average intensity around 3°C. Surface-intensified MHWs are often limited to the shallower coastal shelf, associated with an increased surface heat-flux into the ocean, while subsurface events can be linked to mesoscale warm-core eddies shedding from the Gulf Stream. Regional, high-resolution models provide another valuable tool. Kerry et al. use an Adjoint Sensitivity Analysis to diagnose upper ocean heat content extremes around NZ. In this boundary current dominated region, advection is a main driver of heat content extremes, while in other regions upper ocean stratification changes, likely connected to local downwelling winds act as a driver. Both studies demonstrate the importance of understanding the regional circulation associated with extreme events, which is ultimately the key to more accurate predictability.

Forecast and projections

MHW prediction is a vital for improved marine management and decision-making. Given sufficient forecast lead times, many sectors can employ mitigation measures to reduce MHW impacts and aid recovery. With extensive historic evidence of devastating MHW impacts and projected future increases in ocean temperatures, MHW predictability has never been more important. New work in this collection investigates the potential for MHW predictability at different temporal and spatial scales using various techniques including numerical and statistical models and recent advances in machine learning. Challenges in developing such systems and, importantly, ensuring stakeholders can use and benefit from them are also discussed (Stevens et al.).

Using a coupled global ocean-atmosphere model Spillman et al. mapped regions where rates of MHW onset and decline were changing, and found highest monthly predictive skill (up to 4 months lead time) in the tropical east Pacific and lowest skill in dynamic regions (e.g., northwest Atlantic; eastern Australia). Alternative approaches for such dynamic regions at short forecast lead times was demonstrated by Zhao et al. showing that eddy distributions in the Tasman Sea could act as predictors of individual ocean advection-dominated MHW events. Using sea surface height anomaly as predictor variable, their statistical model could forecast MHWs up to 7 days in advance using mesoscale eddy-tracking methods.

Other prediction approaches include machine learning techniques. Taylor and Feng presented a new deep learning modeling framework to forecast monthly global SST. The model was trained with seven decades of monthly SST and surface air temperatures. Prediction skill was high (up to 18 months) in the equatorial and subtropical Pacific for specific events, while limited to shorter lead times in some areas (e.g., southeast Indian Ocean), demonstrating the potential of data-driven methods in SST anomaly predictions.

Global climate models remain important tools for long-term climate projections. Using the NZ ESM, Behrens et al. investigated projected future change in MHW characteristics under different emissions scenarios. Under a high-emissions scenario (SSP3 7.0) projections indicated an 80–100% increase of median MHW intensities in coastal regions by 2,100 and potentially permanent year-round MHW conditions.

Compound events

An emerging concern are compound events, where multiple extreme conditions co-occur, causing ecological and economic impacts. Previous studies describe MHWs that co-occur with, for example, low chlorophyll (Le Grix et al., 2021) or ocean acidity extremes (Burger et al., 2022), both increasing the stress on ecosystems. In this collection, Pathmeswaran et al. use observational and reanalysis data to explore potential links between terrestrial and marine heatwaves around Australia. They find that the presence of MHWs increases the likelihood of terrestrial heatwaves with an impact up to 150 km inland. Vice versa, certain synoptic conditions during coastal terrestrial heatwaves can favor the development of MHWs with the appropriate prior ocean state. Rathore et al. show that a MHW in the Bay of Bengal led to an unprecedented intensification of a tropical cyclone to a super cyclone within 24 h. Wind-induced mixing by the cyclone can in turn reduce upper ocean warming and trigger a decline in MHW intensity. Coupled models and integrated observing systems are essential tools in better understanding linkages between multiple extreme events, their drivers and impacts.

Impacts and management

Our primary motivation for understanding MHW characteristics, drivers and predictability is the large and sometimes permanent impact they have on ecosystems and reliant human systems. The interactions can be complex, with unforeseen outcomes.

A major consequence of the 2014-16 Blob was the collapse of the Bull Kelp Forests along northern California. Rogers-Bennett and Catton examined 15 years of biological survey data to understand the impact on the red abalone fishery. An initial reduction in abalone productivity and condition due to the loss of food led to a shoreward migration which gave the false impression to recreational fishers that populations were actually thriving, thwarting management efforts. However, the nearshore environment posed new threats for abalone including greater wave energy during storms, harmful algal blooms and even warmer temperature extremes. As such, fisheries management alone can only partly alleviate the threats facing this species.

Another iconic MHW, the Ningaloo Nino in 2010-11 led to record low spawning stocks for scallops in different populations off Western Australia. To allow for recovery, fisheries were closed for the subsequent 4 years. Kangas et al. found that scallop populations at different latitudes recovered at different rates, related to their spawning characteristics. At warmer equatorward sites scallops typically spawn during autumn, so spawning stock is most heavily impacted at this warmest time of year. Further south, however, spawning occurs in austral spring, so juveniles are most affected during the warmest autumn months. The study also highlights the importance of pre-season stock monitoring to allow for adaptive management.

More information is needed around how species and ecosystems are likely to respond to extremes outside of the historical envelope. Stipcich et al. examined the response of introduced seagrass samples to MHW conditions representative of the past and the future. A novel approach was used whereby seagrass were placed close to the outlet of a power plant allowing for raised temperatures in open ocean environments. As expected, negative impacts on many species traits were amplified in future MHW conditions. Seagrass originally sourced from warmer sites were better able to withstand the future MHWs, highlighting the importance of sample selection in the consideration of species restoration.

Concluding remarks

There has been an incredible advance in our understanding of MHWs in the last decade, spurred on by a number of iconic MHW events that have had severe impacts on ecosystems and economies. Interdisciplinary work to address the impacts of MHWs is essential moving forward. Limited data as well as the changing climate and associated changes in, for example, the upper ocean circulation or coupled ocean-atmosphere processes continue to pose challenges to the community. However, with the advent of new datasets and tools, novel research directions are opening up and the next decade will no doubt see many more insights into our understanding and prediction of these impactful events.

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