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Editorial: Advances in Understanding Marine Heatwaves and Their Impacts

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Editorial on the Research Topic

Advances in Understanding Marine Heatwaves and Their Impacts

In recent years, prolonged, extremely warm water events, known as marine heatwaves, have featured prominently around the globe with their disruptive consequences for marine ecosystems. Over the past decade, marine heatwaves have occurred from the open ocean to marginal seas and coastal regions, including the unprecedented 2011 Western Australia marine heatwave (Ningaloo Niño) in the eastern Indian Ocean (e.g., Pearce et al., 2011), the 2012 northwest Atlantic marine heatwave (Chen et al., 2014), the 2012 and 2015 Mediterranean Sea marine heatwaves (Darmaraki et al., 2019), the 2013/14 western South Atlantic (Rodrigues et al., 2019) and 2017 southwestern Atlantic marine heatwave (Manta et al., 2018), the persistent 2014–2016 "Blob" in the North Pacific (Bond et al., 2015; Di Lorenzo and Mantua, 2016), the 2015/16 marine heatwave spanning the southeastern tropical Indian Ocean to the Coral Sea (Benthuysen et al., 2018), and the Tasman Sea marine heatwaves in 2015/16 (Oliver et al., 2017) and 2017/18 (Salinger et al., 2019). These events have set new records for marine heatwave intensity, the temperature anomaly exceeding a climatology, and duration, the sustained period of extreme temperatures. We have witnessed the profound consequences of these thermal disturbances from acute changes to marine life to enduring impacts on species, populations, and communities (Smale et al., 2019).

These marine heatwaves have spurred a diversity of research spanning the methodology of identifying and quantifying the events (e.g., Hobday et al., 2016) and their historical trends (Oliver et al., 2018), understanding their physical mechanisms and relationships with climate modes (e.g., Holbrook et al., 2019), climate projections (Frölicher et al., 2018), and understanding the biological impacts for organisms and ecosystem function and services (e.g., Smale et al., 2019). By using sea surface temperature percentiles, temperature anomalies can be quantified based on their local variability and account for the broad range of temperature regimes in different marine environments. For temperatures exceeding a 90th-percentile threshold beyond a period of 5-days, marine heatwaves can be classified into categories based on their intensity (Hobday et al., 2018). While these recent advances have provided the framework for understanding key aspects of marine heatwaves, a challenge lies ahead for effective integration of physical and biological knowledge for prediction of marine heatwaves and their ecological impacts.

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This Research Topic is motivated by the need to understand the mechanisms for how marine heatwaves develop and the biological responses to thermal stress events. This Research Topic is a collection of 18 research articles and three review articles aimed at advancing our knowledge of marine heatwaves within four themes. These themes include methods for detecting marine heatwaves, understanding their physical mechanisms, seasonal forecasting and climate projections, and ecological impacts.

DETECTION METHODS

Defining and identifying extreme warm water events require historical temperature records for quantifying climatological means and variance. Schlegel et al. investigate the results of using sub-optimal temperature time series. They determine how time series shorter than 30 years or with missing data affect marine heatwave statistics and offer best practices for improving the accuracy of marine heatwave detection. Identifying marine heatwaves with depth has the challenge of data sparsity and with instruments that may change position over time. Elzahaby and Schaeffer present new ways of identifying and comparing sub-surface marine heatwaves, using observations in the Tasman Sea. They find that surface characteristics of marine heatwaves do not necessarily reflect characteristics with depth and meso-scale eddies influence the deeper structure.

PHYSICAL MECHANISMS

Documenting marine heatwaves, through observations and ocean models, and developing the physical understanding of why they occur are essential for building the tools for prediction and mitigating their impacts. The articles document a diversity of marine heatwaves arising from changes in the atmospheric circulation and air-sea heat fluxes, ocean heat advection, and ocean heat content preconditioning.

Off southeast Queensland, Australia, Heidemann and Ribbe show that marine heatwave days tend to correlate with El Niño years in biodiverse, ecologically important marine sub-regions. They find that the time-lagged relationship with El Niño was strongest in the Southeast Queensland Marine Coastal Zone. Hervey Bay had the longest and most intense marine heatwave events and was likely more influenced by air-sea heat flux in its shallow and sheltered environment.

In the Tasman Sea, Behrens et al. demonstrate how wind stress curl and meridional heat transport are important for setting the ocean heat content. Enhanced ocean heat content preconditions waters to marine heatwaves. Ocean heat content has a predictive skill on timescales of weeks, thus acting as an indicator for marine heatwave likelihood.

In the southeast Indian Ocean, Feng and Shinoda analyze air-sea heat flux variability during Ningaloo Niño events off Western Australia. They determine that major sources of uncertainties owe to bulk flux algorithms based on six air-sea flux products. In the development phase, large uncertainties occur primarily related to sea surface temperature anomaly differences. However, during the decay phase, anomalous latent heat flux is consistently important in all datasets.

In the North Pacific Ocean, Fewings and Brown examine the 2014–2016 marine heatwave and its dipole structure in sea surface temperature anomalies. They find that the 2015 split in spatial structure was caused a dipole-wind pattern configured by the coastline. The regional winds experienced longer than usual relaxations and were consistent with a large-scale, persistent mid-level atmospheric ridging pattern.

In the northwest Atlantic Ocean, Gawarkiewicz et al. describe an extensive, advective marine heatwave in the coastal waters off the northeastern USA in early 2017. The warm, salty water anomalies reached $+6^{\circ}$C and were associated with a warm core ring, which impinged on the shelf south of Nantucket Shoals, with warm waters transiting southward along the Middle Atlantic Bight. They suggest that increasing occurrences of warm core rings combined with trapping processes may be an important contributor to marine heatwave events along shelf waters.

SEASONAL FORECASTS AND CLIMATE PROJECTIONS

Seasonal forecast models and climate model projections provide a path toward informing strategies for proactive marine ecosystem management given marine heatwave conditions months to years into the future. Using a multi-model ensemble of seasonal forecasts, Jacox et al. assess the predictability of the 2014–2016 northeast Pacific Ocean marine heatwave. For the California Current System, skillful predictions of warming periods in 2014 coincided with offshore warm anomalies and in 2016 with an oceanic response to the strong El Niño. Reduced forecast skill occurred during late-2014 consistent with the lack of skill for wind-driven sea surface temperature anomalies during a neutral El Niño Southern Oscillation.

Over longer timescales, climate projections are used to measure the change in likelihood of marine heatwaves under greenhouse gas emission scenarios. Based on global climate simulations, Oliver et al. consider the future changes in marine heatwaves based on their category and potential ecological impact. A “permanent marine heatwave state” arises in many parts of the ocean by the late 21st Century. Based on these projections and known ecological responses from exposure time and temperature anomalies, impacts on marine ecosystems are expected to be widespread, significant, and persistent through this century.

ECOLOGICAL IMPACTS

There has been a shift toward not only understanding how gradual global and regional warming trends affect marine ecosystems but also how marine species, populations, and communities respond to acute thermal stress during marine heatwaves. Here, articles document marine heatwave impacts on foundation species, including coral, seagrass, and kelp, invertebrate species, fishes, and also micronekton and microzooplankton. For coral reef environments, the review by Fordyce et al. provides a framework describing how compounding factors, including extreme thermal anomalies and light penetration, affect the coral photo-endosymbiotic organism causing coral tissue loss and skeletal decay. Summer marine heatwave "hotspots" are proposed as a distinct class of thermal stress events with particular coral physiological responses. Marine heatwave metrics identified coral bleaching events when degree heating week estimates did not indicate a bleaching alert, and hence such metrics may improve ecological response predictability.

The review by Straub et al. provides an overview of how seaweeds have responded to past marine heatwaves with consequences varying from no detectable effects to local extinction. Marine heatwaves negatively affected canopy-forming seaweeds while promoting turf-forming seaweeds. They highlight the challenges associated with monitoring how marine heatwaves impact seaweeds based on extreme thermal stress compared with co-occurring stressors and interacting processes.

The systematic review by Kendrick et al. examines how the 2011 Ningaloo Niño and concurrent flooding affected the Shark Bay (Western Australia) seagrass ecosystem. Extensive temperate seagrass meadows perished, paving the way for small tropical seagrasses. These changes had flow-on effects to consumers, including sea snakes and dugongs, who rely on seagrass for food and habitat. They synthesize the conditions, feedbacks, and responses affecting seagrass structure and composition during the event's timeline.

Following southern New Zealand's strongest recorded marine heatwave in 2017/18, Thomsen et al. document the local extinction of bull kelp, a habitat-forming seaweed, in low intertidal zones. Losses were attributed to extremely warm ocean temperatures, given an assessment of potential stressors. These events were followed by a bloom of invasive kelp *Undaria* and colonization of other fast-growing seaweeds.

Giant kelp forests are fundamental habitats that were affected by the 2014–2016 marine heatwave in the California Current System. Using satellite imagery from southern California to Baja California, Cavanaugh et al. found that canopy biomass loss and recovery had latitudinal variations. Kelp loss was found to occur when the warmest month's mean sea surface temperatures exceeded 24°C. At sites in the Baja California Pacific Islands, Arafeh-Dalmau et al. document losses in giant kelp density and coverage, sessile invertebrates, sea stars, and cold water species and the appearance of invasive seaweed species. Both studies indicate that kelp forests at the equatorial edge are vulnerable to marine heatwaves and future increases in their likelihood.

Burdett et al. experimentally simulated sub-lethal, acute heat stress in two common, habitat forming kelp species from the northeast Atlantic. The shallow water species *Laminaria digitata*, from populations near their upper thermal limit, had higher sensitivity in terms of photosynthesis compared to *Laminaria hyperborea*, which displayed no apparent change in net photosynthesis. While the kelp species displayed some resilience to short term heat stress, further studies are important for assessing photo-physiological responses with greater duration heat stress.

Following the 2011 Ningaloo Niño, Caputi et al. synthesize the recovery status of Western Australia's invertebrate fisheries and develops a framework for managing fish stocks during and post marine heatwaves. The recovery rate was affected by factors including the species' distribution and sensitivity to increased water temperatures, level of recruitment and spawning stock impairment, life-cycle characteristics, habitat loss, and if management interventions occurred. Prior to a fishing season, fisheries pre-recruit surveys provide early detection of marine heatwave impacts on the stock and potential early management strategies. Furthermore, Chandrapavan et al. examine how the marine heatwave caused recruitment failure and subsequent stock decline of the commercially important blue swimmer crab fishery in Shark Bay. Stock partially recovered within 18 months. By 3 years, full recovery occurred largely owing to water temperatures and fishery closure to aid spawning stock recovery. The studies demonstrate how the rebuilding of impacted stocks can occur through increased monitoring of stock abundance and the environment and timely management actions combined with industry cooperation.

Off Western Australia, Smith et al. discuss a longer-term poleward shift in *Sillago schomburgkii*, a temperate fish known as yellowfin whiting that is commercially fished. They propose that self-recruitment at higher latitudes is important. After the 2011 Ningaloo Niño, whiting abundance was found shifted markedly poleward. This shift was associated with the unusually strong poleward flow and larval dispersal combined with an extended spawning period from warmer waters at higher latitudes.

In the California Current System, Brodeur et al. examine the pelagic micronekton (crustaceans, small fish, and squid) and macrozooplankton communities prior to and during the 2014–2016 marine heatwave. Using multi-year trawl catch data, they find a major structural shift in species assemblages, from a crustacean to a gelatinous dominated system, in relation to environmental conditions.

For Australia's coastal ecosystems, Babcock et al. synthesize the impacts of recent extreme climate events, including marine heatwaves, on habitat forming species such as coral reefs, kelp forests, seagrasses and mangroves. They use ecosystem models to contrast the long-term implications of simulated pulse, episodic, or step-change disturbances. From multiple model types, the longest recovery times were associated with delays in habitat recovery, with longer recovery timescales for tropical systems compared to temperate systems.

ADVANCING OUR UNDERSTANDING OF MARINE HEATWAVES

In summary, this Research Topic contributes toward progress in understanding the detection, mechanisms, and prediction of marine heatwaves and their ecological consequences. In this emerging research field on ocean temperature extremes, rapid dissemination of knowledge is crucial for meeting the challenges of the increasing frequency of marine heatwaves. This collection has brought together research aimed at closing the gap in our understanding of the physical mechanisms for marine heatwaves, the ecological impacts and risks for marine ecosystems and timescales of recovery. In doing so, this Research Topic supports a framework for disseminating new, multidisciplinary knowledge so scientists, marine resource managers, and marine industries can develop proactive responses through monitoring, prediction, and solution-oriented approaches to marine heatwaves.

AUTHOR CONTRIBUTIONS

JB led the writing with all other authors contributing in summarizing the literature and editing. All authors listed have contributed to this work and approved the manuscript for publication.

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