A Global Overview of Marine Heatwaves in a Changing Climate

Antonietta Capotondi[1,2,†], Regina R. Rodrigues[3], Alex Sen Gupta[4,5], Jessica A. Benthuysen[6], Clara Deser[7], Thomas L. Frölicher[8,9], Nicole S. Lovenduski[10], Dillon J. Amaya[2], Natacha Le Grix[8,9], Tongtong Xu[1,2], Juliet Hermes[11], Neil J. Holbrook[12,13], Roxy Mathew Koll[14], Cristian Martinez-Villalobos[15,16], Simona Masina[17], Amandine Schaeffer[18,19], Robert W. Schlegel[20], Kathryn E. Smith[21], Chunzai Wang[22,23,24]

1. Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA.
2. NOAA/Physical Sciences Laboratory, Boulder, CO, USA
3. Federal University of Santa Catarina, Florianópolis, Brazil
4. Climate Change Research Centre and Centre for Marine Science and Innovation, University of New South Wales
5. Australian Research Council, Centre of Excellence for Climate Extremes
6. Australian Institute of Marine Science, Indian Ocean Marine Research Centre, Crawley, Western Australia 6009, Australia
7. Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder CO, USA
8. Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland
9. Oeschger Centre for Climate Change Research, University of Bern, Bern Switzerland
10. Department of Atmospheric and Oceanic Sciences and Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, CO, USA.
11. South African Environmental Observation Network, Cape Town, South Africa
12. Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia
13. ARC Centre of Excellence for Climate Extremes, University of Tasmania, Hobart, Tasmania, Australia
14. Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune, India
15. Faculty of Engineering and Science, Universidad Adolfo Ibáñez, Santiago, Chile
16. Data Observatory Foundation, ANID Technology Center No. DO210001, Santiago, Chile
17. CMCC Foundation - Euro-Mediterranean Center on Climate Change, Bologna, Italy
18. School of Mathematics and Statistics, UNSW Sydney, Sydney, Australia
19. Center for Marine Science and Innovation, UNSW Sydney, Sydney, Australia
20. Laboratoire d'Océanographie de Villefranche, Sorbonne University, CNRS, Villefranche-sur-mer, France
21. Marine Biological Association of the United Kingdom, Plymouth, PL1 2PB, UK
22. State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China
23. Global Ocean and Climate Research Center, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China
24. Guangdong Key Laboratory of Ocean Remote Sensing, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China

†email: antonietta.capotondi@noaa.gov

Abstract

Marine heatwaves (MHWs) have dramatically impacted marine ecosystems and ecosystem services over large areas of the world oceans. In this paper, we review the recent substantial advances in this active area of research, including the exploration of the three-dimensional structure and evolution of MHWs, their local and remote drivers, their connection with other extremes in the ocean and over land, future projections by climate model, and assessment of their predictability and current prediction skill. Ongoing discussions involve the attribution of these temperature extremes to internal versus anthropogenic factors, their definition in the context of changing baselines, their combination with other ecosystem stressors, and the reliability of future projections from state-of-the-art climate models. To make progress on predicting and projecting MHWs, a more complete mechanistic understanding of these extremes over the full ocean depth and at the relevant spatial and temporal scales is needed, together with models that can realistically capture the leading mechanisms at those scales. Sustained observing systems, as well as measuring platforms that can be rapidly deployed, are essential to achieve comprehensive event characterizations while also chronicling the evolving nature of these temperature extremes and their impacts in our changing climate.

Introduction

In recent decades, episodes of warm ocean temperature extremes have been associated with more intense and frequent impacts on organisms, ecosystems and reliant human industries around the world[1-3]. By analogy with their atmospheric counterpart, these extreme ocean temperature events have been termed "marine heatwaves" (MHWs)[4,5]. Some of the most prominent events, together with the unprecedented warming during the boreal summer of 2023 are presented in Box 1. MHWs influence regional climate phenomena and often drive substantial impacts on the marine environment. For example, MHWs in the Indian Ocean are found to modulate the monsoon winds and rains over the Indian subcontinent, impacting water and food security over the region[6]. MHWs interact with and intensify tropical cyclones, making them more destructive[7-10]. Biological MHW impacts include mass mortality events in invertebrates, fish, birds and marine mammals[1,11-13], coral bleaching[14,15], declines in foundation species[3,16,17] and entire ecosystem restructuring[18,19], with far-reaching socioeconomic impacts[20].

Recent reviews and perspectives [13,21,22] have outlined major steps forward in understanding MHW characteristics, drivers, and predictability, along with the economic impacts they cause. However, in this rapidly evolving field, more recent research has provided new insights into MHWs, while generating important new questions and research avenues. Although MHW research has primarily considered temperature extremes at the ocean surface, subsurface temperature extremes may be more intense and longer-lasting than their surface counterparts[23-27]. Given their critical importance for marine ecology, subsurface MHWs need to be closely observed, mechanistically understood, and predicted. In addition, while the physical characterization of MHWs has mainly focused on large-scale events (Box 1), MHWs are now also studied in more localized coastal areas, marginal seas, and fjords[28-31], where they are negatively impacting the local ecology and coastal communities[3,16]. MHWs are also increasingly being examined along with other extreme conditions, like high acidity or low-oxygen[32,33], sea level extremes[34], floods[35], droughts[36], severe weather events[37] or even terrestrial heat waves over the adjacent land[38]. These "compound events" act as multiple stressors for marine life and society.

The ability to predict MHWs and compound events from days to seasons in advance is key for stakeholder preparation and mitigation efforts[39]. Skillful forecasts require enhanced understanding of MHW drivers to assess their predictability, and prediction systems that realistically capture the processes underpinning that predictability[21,40,41]. While progress has been made in prediction activities[42,43], additional improvements could be achieved through a deepened understanding of the relative roles of different MHW drivers, and dynamical model improvements, which include an assessment of the sensitivity of MHW forecasts to model resolution[44-47].

As the oceans continue to warm with anthropogenic climate change[48,49], defining MHWs under non-stationary conditions becomes increasingly challenging, as commonly used definitions will lead to a permanent MHW state in areas experiencing enhanced warming[50] (Fig. 1). In addition, separating the processes internal to the climate system from those of anthropogenic origin[51,52] is key to the mechanistic understanding of the nature of MHWs and the assessment of their predictability and their future changes.

This article extends previous reviews[13,21,22] by highlighting the new emerging areas in MHW research outlined above, including: a critical re-evaluation of MHW definitions and their detection, both at the surface and in the subsurface, in the presence of climate change; observational needs and new emerging "observing" strategies; advances in the understanding of both surface and subsurface MHW drivers to aid prediction efforts; compound events and their prediction; and investigations to assess future MHW projections using empirical approaches and state-of-the-art modeling systems. This review also provides a perspective on new and promising avenues for advancing our understanding and prediction capabilities of ocean extremes in the context of our changing climate.

Defining a marine heatwave

Defining a MHW involves multiple choices, each leading to outcomes with distinct implications. These choices may be motivated by the need to understand the physical drivers or impacts of a MHW, or they can be constrained by the characteristics of the available data, like record length or temporal resolution. For simplicity, MHWs have typically been analyzed using local definitions[53]. However, since MHWs have a three-dimensional structure that evolves over time, other approaches are emerging[25,54,55] to facilitate the tracking of extended surface or subsurface events over time.

Over the past decade, the majority of studies have adopted a common framework for defining MHWs. Following the widely used Hobday et al. (2016)[53] framework, a MHW occurs at a given location when daily sea surface temperature anomalies exceed the seasonally-varying 90th percentile climatology for five days or more (with dips below this threshold for two days or less ignored). The 90th percentile climatology is typically based on a fixed reference period, or "baseline".

These threshold criteria were chosen in analogy with atmospheric heatwaves[56], and were not necessarily dictated by specific impacts in the marine environment. As such, other definitions have also been employed[22], including, for example, definitions using the 99th percentile[57], approaches using monthly data[41,42,51,52,58,59] instead of daily data (Fig. 1), annual maximum temperatures[60], or cumulative temperatures exceeding fixed thresholds, a criterion commonly used for coral bleaching monitoring and prediction[61-63]. Attempts to incorporate information on biological impacts has led to the creation of MHW hazard indices, where species-tailored metrics were co-developed with stakeholders using absolute temperatures[64]. With a fixed baseline, MHW conditions will become increasingly common as the ocean warms[57,65], potentially leading to a "permanent" MHW state in some regions experiencing enhanced warming[10] (Fig. 1). These changing characteristics may reflect the risk these events pose to some marine organisms, particularly those with slow adaptation rates[13]. However, considering a fixed baseline limits our ability to distinguish the slow climate change-related processes from the faster processes associated with internal modes of climate variability or synoptic weather conditions[40], with implications for understanding events' predictability and assessing their prediction skill[66]. Thus, there has been a recent call to remove the effects of mean warming when defining MHWs by detrending temperature time series[67] or using a shifting baseline period[68], especially for future projections. To define MHW characteristics, the decision to use a temperature threshold that remains fixed or changes over time will ultimately depend on the application being studied, the importance of maintaining consistency with past studies and the characteristics of the data record.

Given the availability of satellite-derived sea surface temperature (SST), many MHW studies have relied on daily gridded satellite data, starting in the early 1980s. However, different datasets will have varying temporal and spatial resolutions and/or may be sporadic and contain data gaps. Modified MHW definitions may be appropriate for different datasets and specific applications. For instance, monthly means can be used in regions characterized by long ocean memory (e.g., the tropical Pacific), or when the focus is on long-lasting MHWs[20,69]. In all definitions, the temporal and spatial scales of the dynamics at play need to be considered.

Spatially, MHWs can cover large horizontal distances and extend deep into the water column. MHW structure is linked to their drivers and needs to be included in their characterization. While horizontal extent has been considered in studies assessing MHW projections[57,70], a number of new techniques have been developed to track connected MHW regions at the surface[54,55,71] or in three-dimensional space[25,72], including the splitting and merging of MHW regions, referred to as "MHW systems"[72]. These techniques treat MHWs as objects that evolve in space and time providing an illustration of their areas of influence. Similar algorithms have also been applied to ocean acidification extremes in the Northeast Pacific[73], allowing an assessment of the severity of their impacts. To date, these tracking algorithms are purely statistical and do not incorporate information about event dynamics, but the use of tracking will provide new opportunities for understanding the extent of MHW systems as they evolve through time, and facilitate the identification of their underlying dynamics.

Observations for characterizing marine heatwaves

Observations are the foundation for characterizing and understanding MHWs. For more than a century, a diversity of ways to measure ocean temperature have been developed from *in situ* stationary and moving platforms (both passive and active) to remotely sensed methods (Box 2; Table 1 of Oliver et al. 2021[22]).

The challenge for observing MHWs is to measure ocean temperature at high temporal resolution and over a long period (decades) to define a threshold for extremes, while accounting for the inherent variability of temperature at different timescales. Advances in understanding MHWs globally have relied largely on satellite derived sea surface temperature products blended with near-surface *in situ* data provided from surface drifting buoys and ship underway systems (e.g. products such as the Operational SST and Sea Ice Analysis (OSTIA) system[74,75] and NOAA Daily Optimum Interpolation SST v2.1 dataset[76]). On the other hand, long-term *in situ* temperature measurements from water samples and moorings have been crucial for characterizing temperature extremes at daily timescale, although not representative of large areas. There are coastal locations distributed worldwide where ocean temperatures have been recorded since before the satellite era[65,77-79], providing insight into long-term trends of local ocean temperatures and changes in the frequency of temperature extremes. Only a few sites include sustained measurements extending through the water column, which have been crucial to understand sub-surface MHW characteristics and drivers[23,24,80]. Globally, the network of Argo floats has provided a transformative capability to study subsurface events by sampling ocean temperatures[27,81] over the upper 2000 m for more than two decades[82]. However, Argo-derived gridded datasets are primarily available at monthly time resolution and lack coverage over continental shelves and marginal seas. The combination of different observational platforms, for example Argo and coastal moorings[29], is proving extremely valuable to achieve a comprehensive view of MHWs (Box 2).

To overcome issues associated with sparse and inconsistent observations, many studies have leveraged ocean reanalyses—models constrained by observations through data assimilation— to understand MHW drivers and dynamical processes[41,83,84], and analyze MHW characteristics at both the ocean surface and in the subsurface[25,26]. Ocean reanalyses offer uniform data coverage in time and space, in some cases at high-resolution (e.g., GLORYS12v1[85]), thus also facilitating the characterization of MHWs on continental shelves[86,87]. Reanalysis products are subject to model errors and biases, and should be used with care to study extremes, especially in areas where limited observations were assimilated.

On longer time-scales, paleoclimate proxies may offer an opportunity to extend the observational record into the past, thereby increasing sample sizes and generating more robust MHW statistics. For example, ocean temperature reconstructions based on the geochemical properties of corals offer a robust measure of thermal stress in the past[88]. Planktonic foraminifera also correlate with upper-ocean temperature[89], and their fossil samples at some locations may provide insights into MHW statistics in the past, albeit with limitations due to coarse temporal resolution.

An alternative approach for increasing the sample size of extreme events is to use empirical models trained on observations, like Linear Inverse Models (LIMs[90]), to produce multi-millennia synthetic time series. These synthetic data share similar statistical properties (covariances, autocorrelation, event evolution) with observations[35,51,58] and allow to explore the full range of possible MHW realizations that are consistent with the dynamics and noise structure of the training data.

Drivers of surface and subsurface marine heatwaves

The processes driving MHWs affect their characteristics, including duration, intensity and vertical structure, and are key for predicting their evolution. MHWs are driven by local heat fluxes associated with synoptic atmospheric conditions or ocean advective and mixing processes, and are sensitive to the ocean state (e.g., mixed layer depth). These local drivers may themselves be modulated by large-scale modes of climate variability or anthropogenic warming, and vary regionally and seasonally. In the extra-tropics, intense MHWs are commonly associated with persistent atmospheric highs, resulting in increased insolation and decreased wind speeds that reduce turbulent heat losses and vertical ocean mixing[40,91-96]. Associated shallower mixed layers can further amplify the warming from surface heat fluxes[59,83,97,98]. More broadly, heat budget analyses indicate that increased insolation and reduced evaporative cooling typically dominate the build-up of MHWs while decay is generally driven by increased turbulent heat losses[99]. In boundary current regions, anomalous warm oceanic advection is often important. Key examples include the 2011 Ningaloo Niño[5,100,101] and the long-lived 2015/16 Tasman Sea MHW[102,103]. Advection-driven MHWs typically have a smaller surface area, but last longer[21] and reach deeper[104] than atmospherically-driven events[21]. In the tropical Pacific, MHWs associated with El Niño Southern Oscillation (ENSO) are dynamically driven[105], with surface heat fluxes damping temperatures during both the onset and decay phases[99,106]. In high-energy regions, like western boundary currents, oceanic mesoscale eddies and meanders, which often cross onto the shelf, can contribute to the onset, intensity, and longevity of MHWs at small temporal and spatial scales[8,47,81,107].

Large-scale modes of climate variability can affect the likelihood of MHW occurrences regionally[6,40], by modulating the local drivers and the initial upper-ocean stratification. For example, the 2013/14 MHW in the southwest Atlantic was forced by atmospheric conditions associated with a wave train triggered by the Madden-Julian Oscillation in the tropical Indian Ocean[36]. ENSO events are associated with a significant increase in the frequency, intensity and duration of MHWs across many parts of the global oceans[65,91], enhancing the forecast skill of MHWs and ocean acidity extremes[42,108], and influencing MHW projections[52]. For example, stronger equatorial Pacific easterly winds during La Niña events lead to an enhancement of the Indonesian Throughflow and Leeuwin Current, thereby transporting warm tropical waters to the Western Australian coast, creating favorable conditions for the development of MHWs[100]. ENSO also affects the Northeast Pacific Ocean through both oceanic and atmospheric pathways[109]. However, ENSO's influence on MHWs may depend on the spatial pattern of ENSO SST anomalies[84], and may be mediated by other modes of variability at interannual or decadal timescales[40,41,95,110,111]. For example, a pre-existing positive Indian Ocean Dipole can increase the likelihood and predictability of MHWs off Western Australia up to 20 months in advance[111], while in the Northeast Pacific, MHW onset is influenced by low-frequency variability related to the Pacific Decadal Oscillation (PDO)[41,110]. Interactions between tropical basins[112,113] can also contribute to MHW development, as exemplified by the 2020 MHWs in the Northwest Pacific and South China Sea[114,115] and the unprecedented Northwest Pacific event of 2022[116]. Finally, MHWs in the far-eastern tropical Pacific ("coastal El Niño events"), result primarily from the constructive interference of the North and South Pacific Meridional Modes[117,118], and are not necessarily related to basin-wide ENSO conditions[35]. Assessing the relative contributions and links between large-scale drivers is critical to fully understand and exploit the inherent system predictability and improve predictions[119].

MHWs extend into the subsurface ocean, with depth structures that may vary considerably depending on the region[27], the leading driving mechanisms and the local bathymetry, whether in open ocean or on the shelf. MHWs can be confined to the mixed layer ("shallow MHWs"), driven by enhanced air-sea heat fluxes, ocean advection or reduced wind-induced turbulent mixing (Fig. 2a, e), or they can penetrate well below the mixed layer[27]. In shallow coastal regions, they can even extend to the ocean bottom ("Extended" events; Fig. 2c, d)[24,86] due to the intrusion of warm eddies and western boundary current meanders onto the shelf (Fig. 2c) or through warm advection by alongshore currents (Fig. 2d), as shown by data from a near-shore mooring site in eastern Australia[24]. Near the shelf, deep warm anomalies can result from downwelling processes and coexist with surface cooling[24] (Fig. 2b). More generally, subsurface intensification through the dynamical movement of the thermocline results from local Ekman pumping or from the passage of large-scale planetary waves, processes that occur ubiquitously throughout the ocean[26] (Fig. 2f). These subsurface anomalies are often larger than surface anomalies, due to the movement of the strong vertical temperature gradients around the thermocline[23,24,26,27,81,86,120]. As they evolve over time[120] (Fig. 2e-h), subsurface MHWs can extend below the mixed layer during its seasonal shoaling and persist at depth even though the surface layer cools (Fig. 2g). They may sometimes be entrained back into a deepening mixed layer, and produce a delayed surface warming, a process known as "re-emergence"[121] (Fig. 2h). Such evolutions were found in a model of the eastern tropical and North Pacific[120] and in Argo observations of Northeast Pacific MHWs during 2004-2020[122], and are likely to occur in other regions[123].

Compound and cascading events

Compound events are generally defined as a combination of extreme conditions and/or hazards that contribute to societal or environmental risk[124]. As such, they stress both natural and human systems, causing socioeconomic impacts such as loss of essential ecosystem services and income[124]. Understanding their underlying physical processes is thus critical for predictability assessments. During a compound event, extreme conditions can occur simultaneously (e.g., high ocean temperatures and low oxygen concentrations in the ocean) or in close sequence, where one event can increase the system vulnerability to a successive event. For instance, droughts and heatwaves can lead to a higher risk of flash floods over land. Events can also occur concurrently over different regions with large-scale consequences, as exemplified by the widespread impacts on fisheries caused by MHWs and low upper ocean nutrient levels during El Niño events.

Marine heatwaves and terrestrial extremes

Our understanding is more advanced for extremes and compound events over land[125]. However, work into ocean-land compound events is growing. For instance, atmospheric blocking over eastern South America and the western South Atlantic is associated with persistent high-pressure centers that can reduce cloud cover and latent heat loss, leading to simultaneous drought conditions over land and heatwaves in the adjacent ocean[36]. Similarly, synoptic conditions driving terrestrial heatwaves in some locations around Australia are also conducive to the warming of the ocean, increasing the likelihood of a concurrent MHW[38]. As many extreme extra-tropical MHWs are associated with persistent high-pressure centers[91], such systems, straddling the land and ocean, might plausibly lead to compound marine-terrestrial temperature extremes in coastal regions. MHWs can also be related to enhanced evaporation and transport of humidity, inducing heavy rainfall along coastal regions, such as during the Tasman Sea MHW in 2015-16[102] or the coastal MHW off Peru in 2017[126].

Marine heatwaves and ocean biogeochemical extremes

Given their potential impacts on marine organisms, there is growing interest in ocean biogeochemical extremes that can co-occur with temperature extremes (Fig. 3), including high acidity (OAX)[73,127-130], low oxygen (LOX)[131] and low chlorophyll extremes (LChl)[132,133]. These stressors may act additively or synergistically[134]. For example, compound MHW-LOX events can have detrimental effects on aerobic metabolic rates, especially in ectotherms, i.e., cold-blooded organisms[135-137]. Additionally, compound MHW-OAX events can adversely affect molluscs[138] or warm-water corals[139], while MHW-LChl events are often associated with extremely low fish biomass conditions[140]. Moreover, it is plausible that the concurrent extreme ocean acidification conditions amplified the devastating effects of the Northeast Pacific Marine Heatwave of 2014–2015[141] (Box 1, top panel), also known as the “Blob”[83].

Compound MHW-OAX events are more likely to occur in the subtropics than in the equatorial Pacific and mid-to-high latitudes, as high temperatures in the subtropics strongly increase the hydrogen ion [H^+] concentration (i.e., acidity)[142]. At higher-latitudes, lower background temperatures limit this effect, while in the equatorial Pacific, reduced Dissolved Inorganic Carbon due to weaker upwelling leads to a decreased [H^+] concentration, counteracting the effect of temperature. Conversely, hotspots of compound MHW-LChl events are found in the equatorial Pacific, along the boundaries of the subtropical gyres and in the northern Indian Ocean, often associated with El Niño events[132] and enhanced nutrient limitation on phytoplankton growth[133,143]. Notably, the North Pacific MHW in 2014-2016 was identified as a quadruple compound event during some phases of its development, involving high temperature, low oxygen, high acidity and low chlorophyll levels[32,132,144]. For example, in January 2014, the extreme warming of the Blob (Box 1, top panel) co-occurred with low chlorophyll over part of the MHW area (Fig. 3c).

Climate model projections indicate that long-term trends in acidification, deoxygenation, and nutrient decline in the low-latitude upper ocean will persist for decades[145,146], amplifying the frequency, intensity and scale of compound MHWs and biogeochemical extremes[32,142]. Notably, even when using a shifting baseline, whereby the effect of long-term warming and OAX are removed, OAX events and, therefore, compound MHW-OAX events are expected to increase due to projected increases in the seasonal and diurnal variations in [H^+][129,147,148].

Despite initial studies, understanding ocean compound extreme events is still in its infancy[32]. A global perspective on the temporal and spatial characteristics of these events, especially at depth, and a mechanistic understanding of relevant processes and their cascading impacts on ecosystems, are currently missing, mainly due to the lack of available subsurface data.

Climate models representations of MHWs

Given the sparsity of long-term observational records, especially at depth, numerical models can help us to better understand MHW characteristics and their drivers. Global Earth system models (ESMs), which include both physical and biogeochemical components, are essential to provide future projections of both MHWs and biogeochemical extremes. But how well do climate models represent MHWs? Global coupled climate models vary in their degree of fidelity in representing climatological characteristics of basic MHW metrics (frequency, intensity and duration) at both daily[44,60], and monthly[51,52] timescales. CMIP-type ESMs tend to overestimate the duration of MHWs[47,52] (Fig. 4). In addition, regions of strong ocean currents are especially problematic in models without eddy-permitting resolution[44,45,47], due to the models' inability to capture the influence of mesoscale eddies on MHW development in those regions[107]. Observed changes in MHW characteristics over the historical period are also challenging for models to simulate, although those stemming from mean state changes are better represented than those due to changes in internal variability[51]. However, the observational record of surface MHWs is relatively short, consisting of approximately 40 years for daily SSTs derived from satellite remote sensing, and approximately 100 years for monthly SSTs measured by ships of opportunity, with subsurface MHW records being even shorter. Such observational records only provide a limited sample of all the possible realizations that are consistent with the dynamics and noise of the climate system.

Unlike observations, coupled climate models offer the potential for multiple realizations of the past and future, thereby enhancing sample sizes of extreme events. In particular, so-called "Single Model Initial-condition Large Ensembles" (SMILEs) have become a powerful tool in climate research for studying the simulated characteristics of internal variability and forced responses on local and regional scales[149]. SMILEs consist of many historical and future scenario simulations (generally 30-100) for a particular model, each starting from slightly different initial conditions, and allow a clean separation between the forced signal (the ensemble mean) and internal variability/extremes (departures from the ensemble mean). The power of SMILEs is only beginning to be exploited for the study of MHWs and their projected changes[52,57,142,150].

Figure 4 illustrates the effect of sampling uncertainty on MHW characteristics during the historical period 1950-2020, obtained from the 100-member CESM2 SMILE[52], after the forced signal is removed. The simulated composite MHW intensity (Fig. 4a) and duration (Fig. 4g) metrics based on all ensemble members mask the considerable range found across individual realizations (Fig. 4 d-f and j-l), underscoring the need for SMILEs to guard against sampling uncertainty. Since the single observational record (Fig. 4b, h) provides a limited sample size of extreme events, it may be challenging to separate true model biases from apparent biases stemming from inadequate sampling. One approach is to assess whether the characteristics of the single observed composite MHW lie outside the plausible (5th-95th percentile) range across SMILE members, in which case the model shows a likely bias (Fig. 4c, i). ESMs are also used for seasonal predictions of MHWs and other biogeochemical extremes. Thus, the fidelity of models in accurately simulating such extremes is critical for assessing the reliability of their predictions.

Prediction of MHWs and associated biogeochemical extremes

Understanding MHW predictability and building effective prediction systems can greatly benefit marine management[21]. For example, accurate seasonal predictions of MHWs have the capacity to transform resource management practices that affect ecosystem services such as fisheries, aquaculture, and tourism[21,43]. Motivated by many potential benefits, recent research has quantified subseasonal-to-seasonal MHW predictability and forecast skill using dynamical and statistical approaches[41,42,151-153].

Forecast systems based on global climate models have been used to estimate MHW probabilistic forecast skill and errors by comparing initialized hindcasts (i.e. retrospective forecasts) with the actual evolution of historical temperature anomalies. Results indicate that, for many open-ocean regions, these dynamical forecast systems are capable of skillfully predicting MHW onset, intensity, and duration several months in advance in both the surface and subsurface ocean[42,151,152]. Forecast skill, quantified by the correlation of ensemble-mean SST with that of the observations, is generally higher in the tropical and northeast extratropical Pacific, beating the skill associated with statistical (damped persistence) forecasts[42,108,152]. MHW forecast skill is also higher in the subsurface (0-40 m) than the surface when compared to a reanalysis product, though subsurface skill outside the tropics is primarily due to persistence[151].

While in some cases dynamical forecast systems can produce skillful predictions of MHWs multiple months in advance, this is not always true. For example, 9-month lead forecasts initialized in July 1997 predicted an elevated likelihood of surface ocean MHW occurrence in the eastern Tropical Pacific, Gulf of Alaska, California Current, subtropical Atlantic and Indian Oceans, and the Pacific sector of the Southern Ocean during March 1998 (Figure 5a). However, dynamical 8-month lead forecasts initialized in March 2013 predicted low probability of surface ocean MHWs nearly everywhere in the global ocean for November 2013 (Figure 5b). The observed SST anomalies in March 1998 (Figure 5c) and November 2013 (Figure 5d) indicate that the forecasts generated in July 1997 were more accurate than the March 2013 forecasts. The accuracy of the July 1997 initialized forecast is primarily due to the development of the 1997/1998 El Niño event, as ENSO predictability imparts prediction skill to initialized forecasts of MHWs[21,42]. The March 2013 initialized forecast provides little indication of the development of the Blob in late-2013[83,154]. This comparison highlights the difficulties in forecasting MHWs that are driven by stochastic atmospheric processes, like the Blob[153], or energized by modes of variability not accurately captured by the models. On the other end, surface and subsurface MHWs that are associated with ENSO variability and/or oceanic teleconnections may be predictable several months in advance[21,42,108,151].

Statistical MHW forecasts may have similar skill as forecasts from dynamical models, while requiring substantially less computational resources. McAdam et al. (2023)[151] showed that a simple statistical persistence forecast can skillfully predict the number of subsurface MHW days one season in advance in approximately half of the ocean, but it underestimates the number of events compared to the reanalysis product used as validation. More complex statistical models, including empirical-dynamical models such as Linear Inverse Models (LIMs), can be used to probe sources of predictive skill for particular regions or events. For example, LIM-based studies showed that a decadal mode of variability was a precursor for MHW growth in the Northeast

Pacific Blob region[41], and that predictability of MHWs off Western Australia was enhanced up to 20 months in advance by the presence of a positive Indian Ocean Dipole[155].

ESM dynamical forecast systems display promising levels of forecast skill for surface and subsurface biogeochemical properties affected by MHWs, such as oxygen, acidity, or productivity[156-158]. Recent studies have explored dynamical forecast skill of ocean biogeochemical extremes. For example, Mogen et al. (2024)[108] showed that a coupled model produces skillful forecasts of OAX events associated with aragonite saturation state anomalies, at lead times of up to twelve months in some regions, and further identify ENSO events as playing a key role in predicting this type of extremes. Such findings inspire efforts to include biogeochemical predictions in operational forecasting systems for MHWs.

Marine heatwaves in a changing climate

The ocean has stored more than 91% of the excess heat[159] that has accumulated in the Earth System due to human-induced increases in greenhouse gases, resulting in widespread ocean warming (Fig. 6a). Such slow background warming exacerbates naturally-occurring temperature excursions, resulting in increased frequency, intensity and duration of extreme SST events. Indeed, attribution studies have shown that the majority of the most impactful MHWs worldwide over recent decades could not have occurred without the influence of global warming[50,57,70]. In the presence of the global warming trend, climate models project large increases in the frequency, intensity, duration and spatial extent of warm temperature extremes, with the magnitude of the increase becoming progressively larger at higher warming levels[57].

In addition to the long-term ocean warming trend, climate change can also affect ocean extremes through changes in variability. An increase in mean SSTs, relative to, for example, to pre-industrial levels or early historical periods, will result in a shift of the probability density function (PDF) toward larger values, enhancing the likelihood of more severe events (Fig. 6c-e). Changes in variability, however, alter the PDF's width, which can also affect the probability of SST extremes (Fig. 6c-e). Moreover, changes in internal SST variability may be asymmetric, and lead to increased probabilities for either warm or cold extremes (Fig. 6d). The relative role of the warming trend vs. anthropogenically-induced changes in internal variability in MHW statistics varies geographically[51,52], with the long-term warming trend often accounting for more than 90% of the total changes[46,50-52,57,142,160], as illustrated for CESM2 in Fig. 6b. Exceptions are the Arctic, where internal variability can account for 30-40% of MHW intensity changes, and the Northeast Atlantic, with values up to 80% (Fig. 6b). While separating the effects of the temperature trend and internal variability on MHW characteristics is critical for the mechanistic understanding of MHWs, and for assessing events' predictability, this separation is challenging. The climate change trend may be nonlinear[51,79], and failure to accurately account for such nonlinearity may result in an apparent change in internal variability[51]. Approaches used to estimate the forced trend in observations for MHW studies include the use of univariate[50] or multivariate[51,161,162] statistical approaches, while SMILEs can be used in the modeling context.

There are several ways by which anthropogenic forcing can alter internal climate variability. Mixed layer shoaling may occur with global warming[98,150], resulting in increased mixed-layer temperatures for the same level of atmosphere-to-ocean heat exchange. The projected increase in upper-ocean stratification[163] and ocean heat content[160] can alter the characteristics of key large-scale drivers of MHWs. For example, increased stratification in the equatorial Pacific has been related to future enhancements of ENSO amplitude in several climate models[164], while in the extra-tropics, stronger stratification will result in faster oceanic Rossby waves and shorter adjustment processes, potentially leading to reduced growth and predictability of decadal modes of variability like the PDO[165]. In addition, changes in extra-tropical atmospheric circulation variability driven by internal atmospheric dynamics and by teleconnections from changing ENSO behavior, could alter MHW characteristics through impacts on air-sea heat and momentum exchange[166]. Dramatic changes in Arctic sea-ice coverage and amplified Arctic warming may have been responsible for the changes in atmospheric circulation and Northeast Pacific surface heat fluxes that led to the unprecedented MHWs in that region in recent decades[167]. The reduction in sea-ice will also result in an increase in MHW activity near the marginal ice zone[52,123].

Changes in ENSO characteristics are particularly critical for future MHWs. Consistent with the observed association between El Niño events and the enhanced likelihood of MHW occurrence[40,65], multi-model large ensembles project a significant reduction in MHW areal coverage, intensity and duration during ENSO-neutral periods relative to all periods, when the mean warming component is removed[52]. Thus, changes in ENSO variability can be expected to significantly influence the statistics of MHWs in the future, highlighting the critical need of constraining the spread in expected ENSO changes[168], and achieving more reliable future projections.

Summary and Future Perspectives

MHWs are an active and fast evolving area of research, and significant progress has been made in the last few years. Definitions of MHWs have been critically re-evaluated to best characterize these events and their drivers in the presence of the climate change trend, and approaches have been developed that incorporate spatial dimensions and time evolution[25,54,55]. On the observational side, novel ideas for integrated observing systems capable of providing the three-dimensional structure of MHWs in near real-time are now emerging (Box 2). Additional advances include a deepened understanding of local and remote drivers of MHWs[41,111,119,169,170], explorations of subsurface MHWs and their possible structures, investigations of land-ocean and physical-biogeochemical compound events, future projections of MHWs and related uncertainty[52], and evolving efforts in MHW prediction[42,108,151,152]. Yet, to achieve a more robust assessment of MHW predictability, additional investigations are needed to better understand large-scale drivers of MHWs in different regions and during different seasons, and their interplay in altering local processes responsible for MHW growth, evolution and persistence. MHW definitions should also be extended to reflect MHW mechanisms, and allow event characterization based on their primary drivers.

A key question for MHW prediction and projection, is whether climate models currently used for seasonal predictions and for future projections can realistically simulate MHW mechanisms beyond basic, local surface statistics (like frequency, intensity and duration). For example, can models simulate events similar to the most prominent and impactful MHWs in the historical record? Are these events driven by the same local and remote influences as in nature? Do they have similar subsurface characteristics? Assessing models' fidelity in simulating modes of variability that can influence MHW development is also critical. Given the strong association between ENSO events and MHW occurrences[40,65,91], the reliability of simulated MHWs in both present and future scenarios strongly depend on the models' ability to realistically simulate ENSO. However, ENSO representations in climate models still show significant biases, and its future projections vary significantly across models[168], calling for an in-depth understanding of model differences and biases, and concerted efforts toward model improvement.

In order to provide forecasts that are useful for stakeholders, greater focus is needed on higher resolution global and regional models, that are able to resolve processes occurring on the shelf or at scales relevant for coastal topography (e.g., embayments, fjords, coral atolls, etc.). Regional models, which are currently under development for some regions[171], should include biogeochemistry, and be used for prediction and projections applications. The availability of observations at these scales is also critical for model development and validation.

While many studies have discussed MHW impacts, this area of research is still evolving. For example, some long-lasting MHW impacts are just emerging, like the decline of the humpback whales in the North Pacific since 2014, attributed to loss of prey after the 2014-16 MHW[172]. Conversely, other research suggests that MHWs are not a dominant driver of change in demersal fishes over the recent decades[87]. Aspects in need of further research include: 1) influence of MHWs on local atmospheric extremes, like atmospheric rivers and heatwaves; 2) connections between temperature extremes and oceanic biogeochemical extremes[32,132]; and 3) long-term and cumulative consequences of MHWs on marine life across trophic levels, as well as assessment of recovery times in different regions. Also, given the reported impact of MHWs on air-sea CO_2 fluxes[69] and their association with cloud feedback in some regions[173], a deeper exploration of possible MHW influences on the Earth's carbon and radiation budgets may be important.

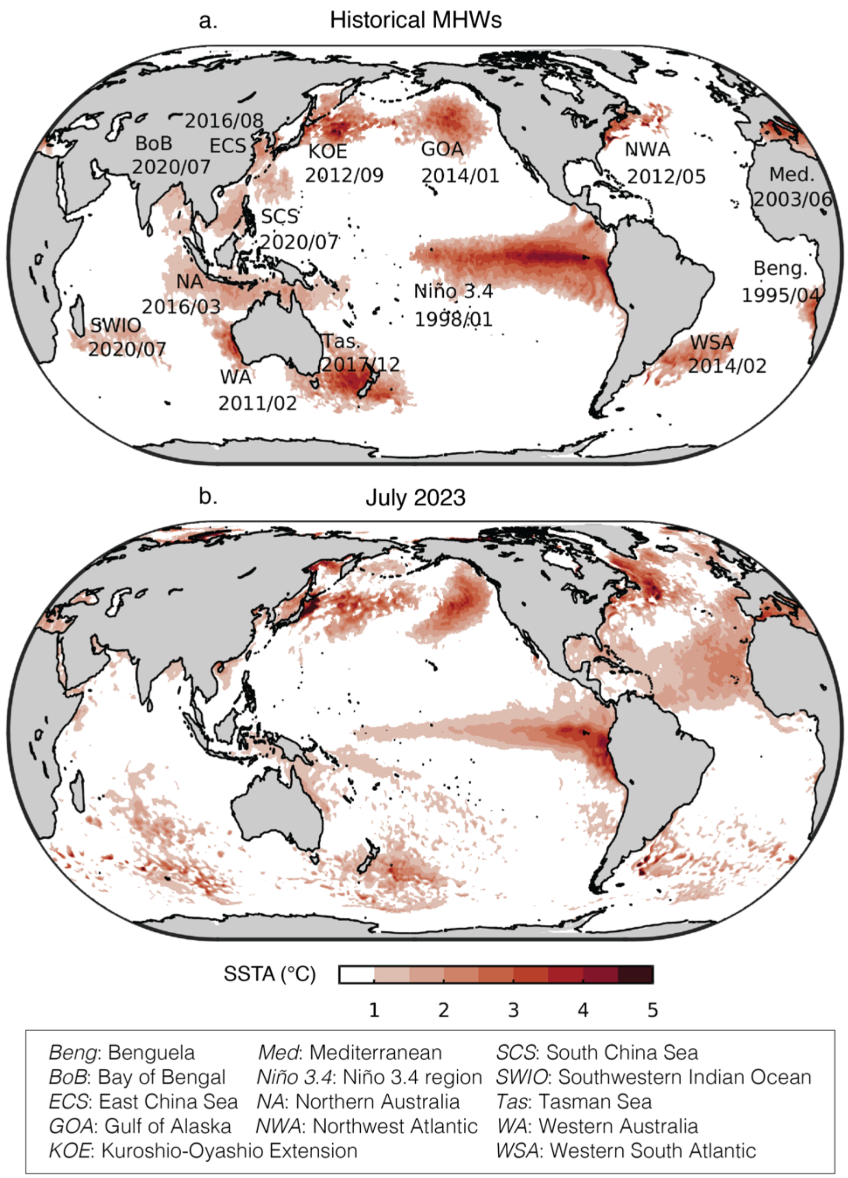
Observations of physical, biogeochemical and ecological quantities, at the surface and especially in the ocean subsurface, are key to all of the above aspects of MHW research. In particular, they are needed to constrain ocean reanalyses and assess model performance. Sustained observations, both globally (e.g., satellite) or regionally (e.g., moorings), in conjunction with ocean reanalyses and long time series from paleo reconstructions or empirical models, are necessary to monitor long-term changes in ocean properties and robustly assess the statistics of extreme warm events around those long-term changes. On the other hand, systems that can be rapidly deployed for real-time monitoring (Box 2), provide not only a comprehensive characterization of individual events, but also immediate guidance to decision-makers. Ideally, such systems should be developed in other regions where prominent MHW events tend to occur.

Enhanced understanding of MHWs and their impacts is essential to guide and support adaptation and mitigation strategies. The tremendous level of ecological, economical and societal losses resulting from these ocean extremes calls for urgent actions to drastically reduce greenhouse gas emissions in order to limit the devastating consequences of climate change.

Box 1. Historical marine heatwaves and the unprecedented summer of 2023

Recent decades have witnessed the occurrence of MHWs that were particularly intense, long-lasting and impactful (top panel of Box figure, showing SST anomalies above 1°C at the peak month of each MHW). These most prominent MHWs generally occurred in different regions at different times. However, the boreal summer of 2023 recorded global monthly-mean SSTs at record high since the beginning of the instrumental record[174], with a large fraction of the ocean experiencing extreme conditions, as illustrated by the widespread SST anomalies[76] above the 90th percentile (1982-2011 baseline) during July 2023 (bottom panel of Box figure). In particular, average North Atlantic (0°-60°N, 0°-80°W) temperatures reached levels of warming that exceeded four standard deviations of the 1980-2011 period during parts of July and September 2023[175], with an annual average ~0.23°C higher than in 2022[176].

What caused this unprecedented warming? The developing El Niño in 2023 can be expected to have caused an increase in radiative heating due to the influence of the El Niño SST pattern on atmospheric static stability and low-level clouds[177]. In addition, El Niño can alter the atmospheric circulation and cause the development of SST anomalies in different regions of the world, like the northeast Pacific[109] and the tropical North Atlantic[178], although warming in the tropical North Atlantic usually occurs after the peak of an El Niño event rather than during its development phase. The pattern of Atlantic warming is consistent with the negative phase of the North Atlantic Oscillation[179], which was indeed strongly negative from mid-April to mid-May and most of July 2023. The concentration of the 2023 warming in near-surface waters[176] suggests that upper ocean stratification, possibly modulated by large-scale climate modes, may have played an important role in preventing the excess heat absorbed by the ocean from being effectively distributed downward, resulting in enhanced surface warming. Other hypotheses regarding the unprecedented 2023 warming include a decreased transport of Saharan dust to the western Atlantic, and a reduction of ship emissions following a 2020 international agreement, leading to an increase in radiative forcing[180], although the influence of these factors on Atlantic warming has yet to be demonstrated. Another hypothesis pertains to the aftermath of the January 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption in Tonga[181]. This eruption emitted aerosols, which had cooling effects, while simultaneously releasing stratospheric water vapor, which had warming effects. However, these factors are estimated to explain, at most, a marginal net cooling of a few hundredths of a degree, rather than a warming[181]. In addition to these mostly natural drivers, the ocean is estimated to have absorbed about 91% of the excess heat associated with global warming[159], causing an average warming of the upper 2000m of the global ocean of ~6.6 10^{21}J/year over 1958-2023[176]. Thus, it is very likely that climate change has contributed to the intensity and widespread coverage of the 2023 MHWs.

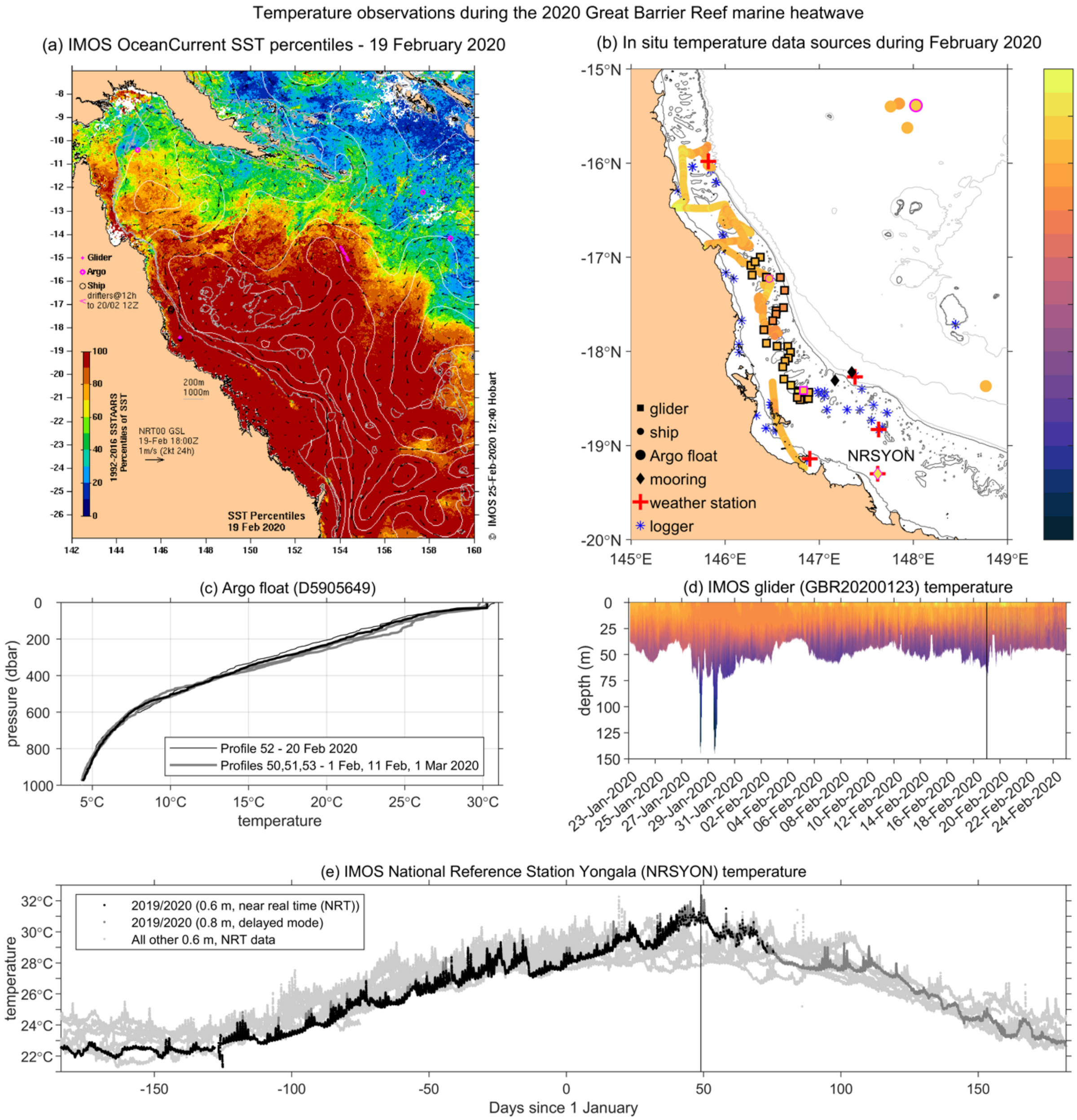

a.
Historical MHWs
BoB
2020/07
2016/08
ECS
KOE
2012/09
GOA
2014/01
NWA
2012/05
Med.
2003/06
SCS
2020/07
NA
2016/03
Niño 3.4
1998/01
Beng.
1995/04
SWIO
2020/07
Tas.
2017/12
WA
2011/02
WSA
2014/02
b.
July 2023
SSTA (°C)
1 2 3 4 5
Beng: Benguela
BoB: Bay of Bengal
ECS: East China Sea
GOA: Gulf of Alaska
KOE: Kuroshio-Oyashio Extension
Med: Mediterranean
Niño 3.4: Niño 3.4 region
NA: Northern Australia
NWA: Northwest Atlantic
SCS: South China Sea
SWIO: Southwestern Indian Ocean
Tas: Tasman Sea
WA: Western Australia
WSA: Western South Atlantic

Box 2. An Integrated Observing System for Monitoring MHWs

Near real time ocean temperature observations and readily accessible visualizations are critical for monitoring MHWs, as they enable responsive activities such as local sampling for research and management. Gliders provide near real time data for a suite of oceanographic variables important for assessing MHW impacts on the marine environment. In Australia, ocean gliders have been used to sample the water column during a MHW over several weeks, through Australia's Integrated Marine Observing System (IMOS) Event Based Sampling sub-facility (panel d of Box figure). In addition, combining different types of temperature observations relative to climatologies over the same reference period offers a comprehensive view of a temporally and spatially evolving MHW[182]. We illustrate the diversity of temperature observations used to monitor a MHW in the Box figure for the 2020 Great Barrier Reef MHW off northeast Australia.

Over the whole Great Barrier Reef, the MHW intensity peaked on 19 February 2020[183,184]. On that day, extremely warm surface waters encompassed a wide extent of the Great Barrier Reef and Coral Sea, based on sea surface temperature (SST) percentiles relative to the 1992-2016 climatological distributions for that day of the year [185,186] (panel a of the Box figure, also indicating the location of other near real time measuring platforms on that day). Several types of monitoring platforms collected temperature data during February 2020 (Panel b of Box figure). The Australian Institute of Marine Science (AIMS) R/V Cape Ferguson measured near-surface water temperatures between 7 February 2020 (north) and 26 February 2020 (south)[187] (small circles shaded with the temperature values). These near-surface temperature measurements were complemented by those from Argo floats (larger circles in panel b, also shaded according to the temperature values), with a pink outline marking the position of one Argo float (5905849) on 20 February 2020[188,189]. The Argo float near -15.4°N, 147.9°E in the Coral Sea also provided subsurface profiles (shown for the upper 1000 m in panel c of the Box figure).

A glider (GBR20200123) was deployed through IMOS Event Based Sampling to monitor the MHW over the shelf[190]. The glider traversed the continental shelf and slope from 23 January 2020 (north) to 24 February 2020 (south), as indicated by the colored (by temperature) track in panel b, measuring subsurface temperature (panel d, same colorbar as in panel b) and a suite of biophysical variables. The glider location on 19 February is indicated by the square with the pink outline (panel b). Finally, the IMOS National Reference Station Yongala (labeled NRSYON in panel b) provided near real time and delayed-mode near-surface temperatures, displayed in panel e of the Box figure relative to 1 January 2020. These measurements during the MHW could be compared against the temperatures recorded at this station from 19 September 2013 to 31 January 2024[191,192], indicating the importance of sustained observations for detecting extremes. These datasets were complemented by in situ water temperature data collected from stationary sources (indicated in panel b) at other IMOS moorings, AIMS reef weather stations[193] and coral reef sites[194]. Together, these temperature measurements provided a comprehensive dataset for assessing the MHW's characteristics and impacts during the 2020 GBR mass coral bleaching event.



Temperature observations during the 2020 Great Barrier Reef marine heatwave
(a) IMOS OceanCurrent SST percentiles - 19 February 2020
Glider
Argo
Ship
drifters@12h to 20/02 12Z
1992-2016 SSTAARS Percentiles of SST
200m
1000m
NRT00 GSL
19-Feb 18:00Z
1m/s (2kt 24h)
SST Percentiles
19 Feb 2020
© IMOS 25-Feb-2020 12:40 Hobart
(b) In situ temperature data sources during February 2020
glider
ship
Argo float
mooring
weather station
logger
NRSYON
(c) Argo float (D5905649)
pressure (dbar)
temperature
Profile 52 - 20 Feb 2020
Profiles 50,51,53 - 1 Feb, 11 Feb, 1 Mar 2020
(d) IMOS glider (GBR20200123) temperature
depth (m)
(e) IMOS National Reference Station Yongala (NRSYON) temperature
2019/2020 (0.6 m, near real time (NRT))
2019/2020 (0.8 m, delayed mode)
All other 0.6 m, NRT data
temperature
Days since 1 January

Figures

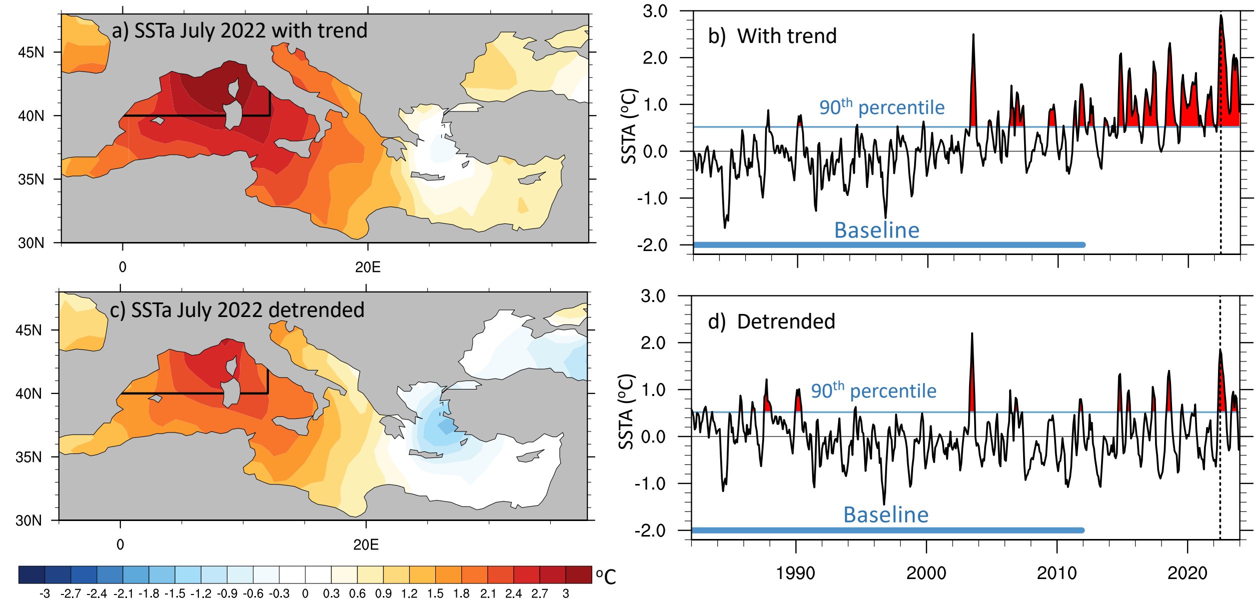


Figure 1. Influence of trends on marine heatwave definition. a) SST anomaly (SSTA, °C) relative to the 1982-2011 climatology over the Mediterranean during July 2022 (dashed line in b) from NOAA-OISSTv2.1[76]. Anomalies include the trend signal. b) SST anomalies averaged over the western Mediterranean (the region bounded by the black lines and the coast, i.e., north of 40°N, and west of 12°E). c) As in a), but with SST anomalies linearly detrended. d) as in b), but with anomalies linearly detrended. In b) and d), the thick blue horizontal line indicates the baseline period used to compute the climatology and to define the 90th percentile (thin horizontal blue lines), which for simplicity is chosen to be seasonally independent. In the presence of a trend, the western Mediterranean tends to be in a quasi-permanent MHW state toward the end of the record, while removal of the trend highlights isolated events since 2015, and also reveals more pronounced extreme events at the beginning of the record. The MHW in the boreal summer of 2003 emerges as an extremely intense event, irrespective of the presence of a trend signal.

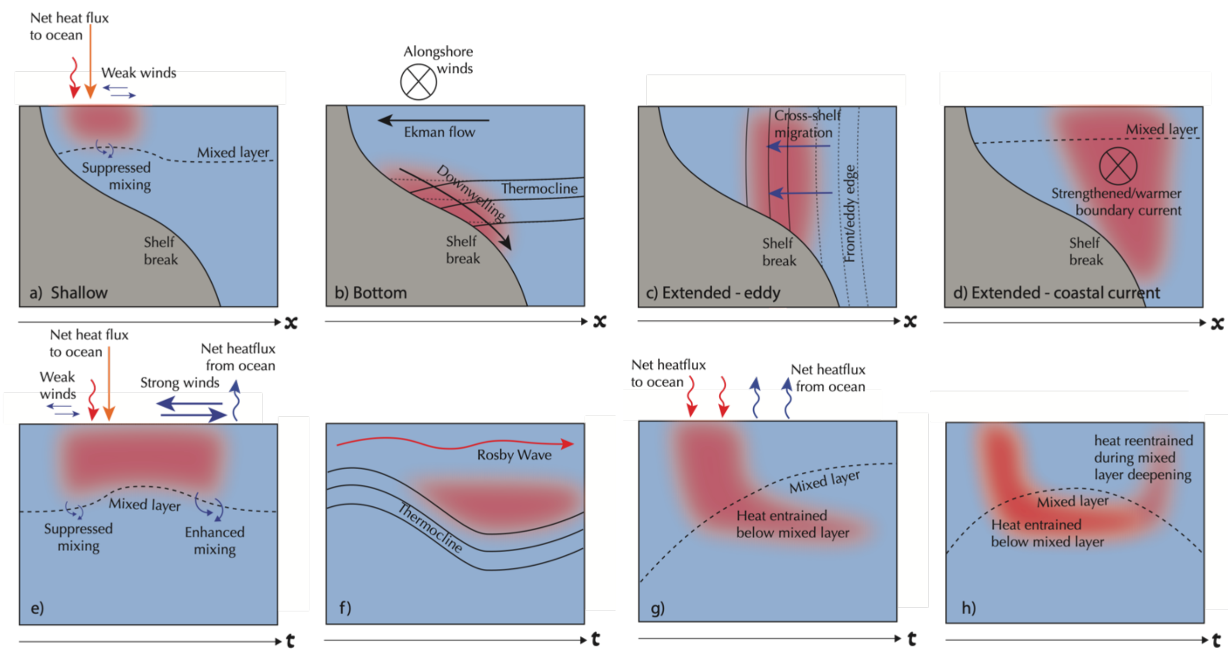


Figure 2. Vertical structures of MHWs. a)-d) Possible vertical structures of MHWs near the shelf, including: "shallow" MHWs which do not penetrate below the mixed layer (a); "Bottom" intensified events due to a downwelling thermocline near the bottom, due, for example to alongshore winds, as illustrated for the Southern Hemisphere (b); "Extended" profiles from the surface to the bottom due to intrusion of warm eddies or western boundary meanders into the shelf (c) or due to warm alongshore advection (d). e)-h) Temporal evolution of subsurface MHWs associated with changes in upper-ocean mixing for shallow events (e); propagation of oceanic Rossby waves causing variations in thermocline depth (f); persistence of deep anomalies with no surface signature due to mixed layer shoaling (g); and re-emergence of deep anomalies at the surface when the mixed layer deepens (h).The subsurface structure of MHWs depends on the processes involved in their formation, as well as the region's stratification and circulation.

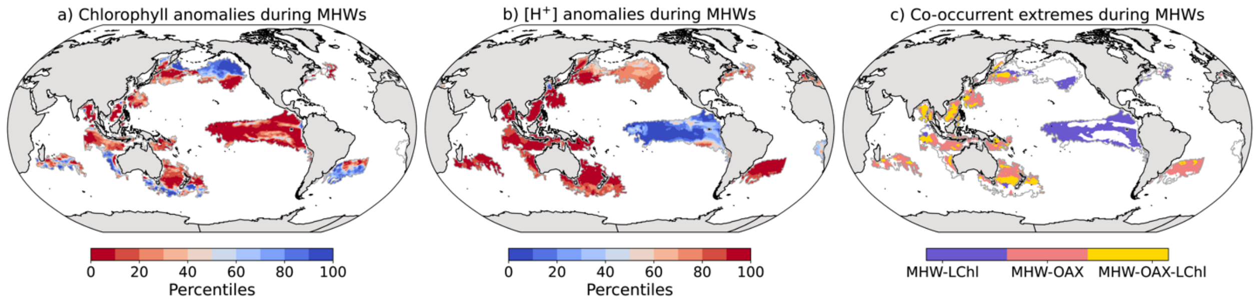


Figure 3. Near-Surface biogeochemical anomalies and compound conditions during some impactful MHWs. The biogeochemical quantities are shown for the month and the area of the MHWs displayed in the top panel of Box1's figure. The footprint of those MHWs is indicated by grey lines. a) Percentile associated with the mean chlorophyll anomaly during the MHWs, compared to the local empirical distribution of chlorophyll monthly anomalies from 1998 to 2018. b) Percentile associated with the mean $[H^+]$ anomaly during the MHWs, compared to the local empirical distribution of $[H^+]$ monthly anomalies from 1982 to 2019, based on observationally-derived data[142]. c) Extent of the MHWs co-occurring with a low chlorophyll extreme event (MHW-LChl, in blue), a high acidity event (MHW-OAX, in red), and both (MHW-LChl-OAX, in yellow). LChl events are defined as events with chlorophyll anomaly percentiles on panel (a) lower than their 10th percentile, and OAX events as events with [H+] anomaly percentiles exceeding their 90th percentile. The chlorophyll data, corresponding to the mean chlorophyll concentration within the mixed layer, are obtained from the NASA Ocean Biogeochemical Model reconstruction[195], and are publicly available for 1998-2021(https://gmao.gsfc.nasa.gov/gmaoftp/rousseaux/Carlos/NOBM/).

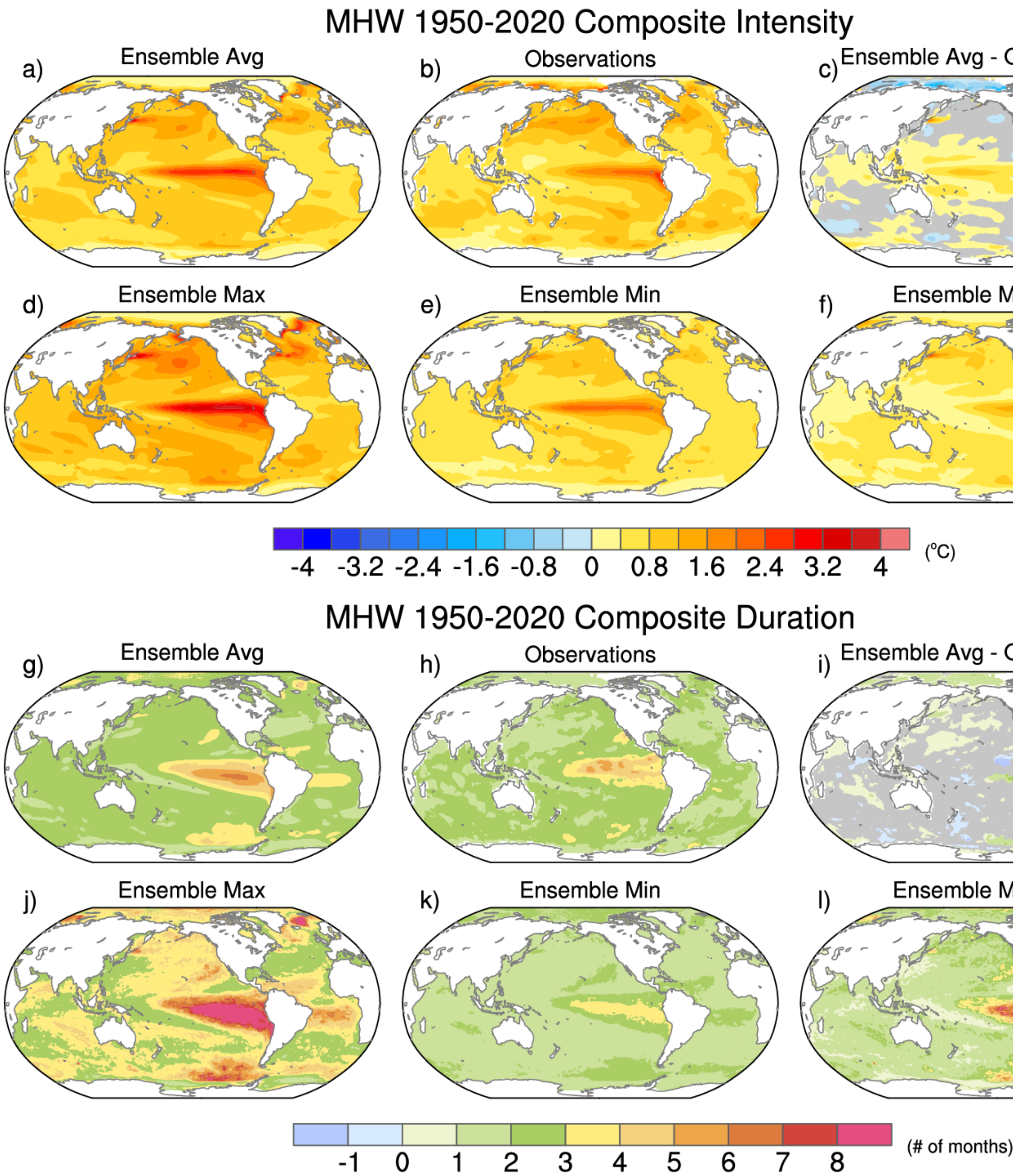


Figure 4. Fidelity in climate models' representation of MHW statistics. (a-f) Composite MHW intensity (ºC) and (g-l) composite MHW duration (months) during 1950-2020 from the 100-member of the Community Earth System Model version 2 (CESM2) SMILE and observations (ERSSTv5)[196]. (a, g) Ensemble average; (b, h) Observations; (c, i) Ensemble average minus Observations; (d, j) Ensemble maximum; (e, k) Ensemble minimum; (f, l) Ensemble maximum minus minimum. Gray shading in (c, i) indicates that observations lie within the 5^{th}-95^{th} percentile range of the CESM2 Large Ensemble. Adapted from Deser et al. (2024)[52].

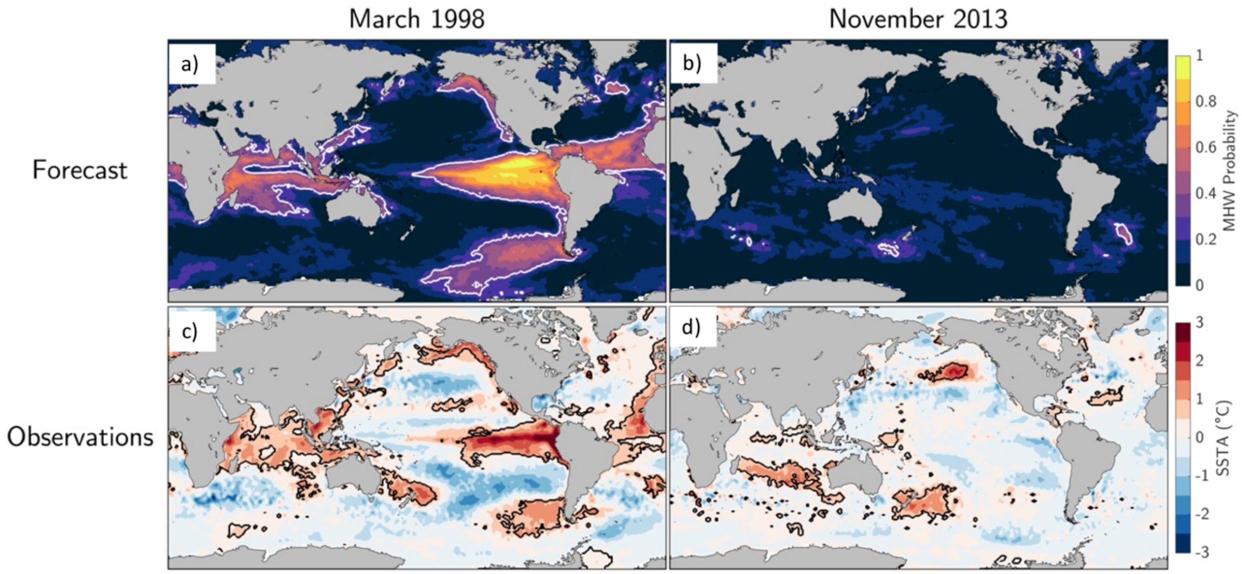


Figure 5. **Dependence of MHW forecast skill on El Niño.** (a-b) Forecasted MHW probabilities for two periods: (a) March 1998, and (b) November 2013, based on probabilistic forecasts of linearly detrended anomalies from the North American Multimodel Ensemble[197] initialized 8.5 months prior (i.e., July 1997 and March 2013, respectively). White contour indicates 30% probability of occurring MHW conditions. (c-d) Observed monthly SST anomalies (°C) for the two forecasted periods. Black contours indicate observed MHW conditions. Adapted from (Jacox et al. 2022)[42].

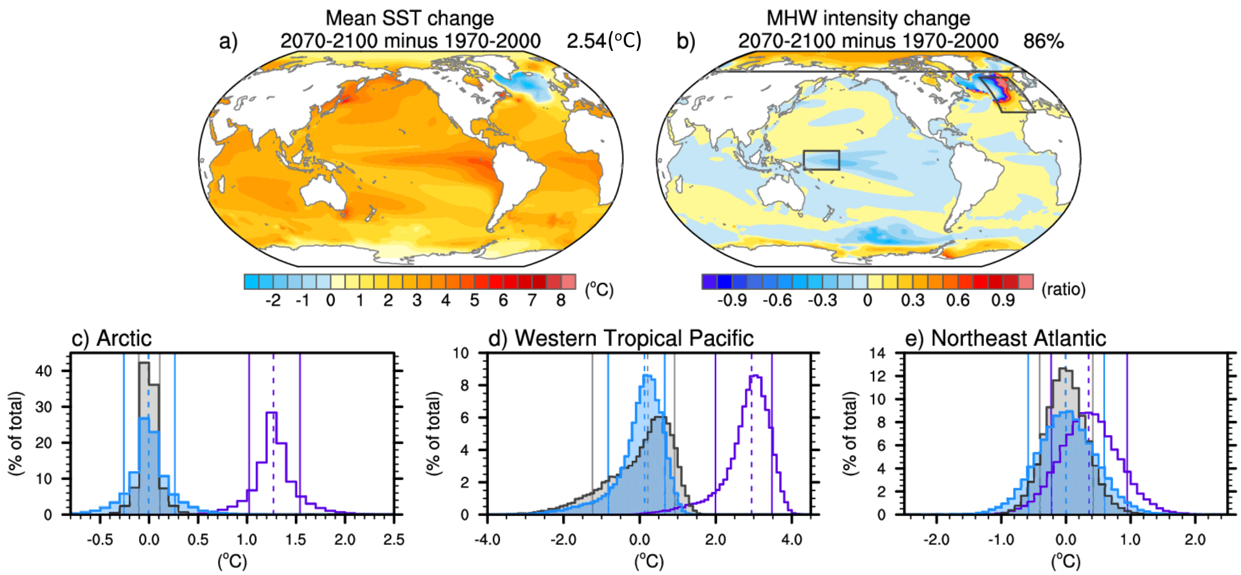


Figure 6. Projected changes in MHWs in one climate model Large Ensemble. a) Changes in mean SST (2070-2100 minus 1970-2000) based on the ensemble mean of the CESM2 large ensemble according to the SSP370 scenario. b) Changes in composite MHW intensity (2070-2100 minus 1970-2000) due to internal variability divided by the intensity changes due to both changes in variability-plus-mean state. (c-e) Histograms of area-averaged SST (°C) from the CESM2 large ensemble for (c) Arctic (poleward of 67°N), (d) western tropical Pacific (8°S–6°N, 155°E–175°W), and (e) northeast Atlantic (35°–62°N, 30°–0°W) based on all months from all 100 ensemble members during 1970–2000 (gray) and 2070–2100 (blue) after removing the ensemble-mean climatological seasonal cycle for each period. The regions considered for computing the histograms are shown by the boxes in panel b). Purple histograms are the same as the blue histograms but with the mean state change (2070–2100 minus 1970–2000) added back in. The 10th and 90th percentiles of each distribution are shown as vertical solid lines, and the 50th percentile is shown as a vertical dashed line. The number in the upper right of panel a) indicates the global mean ocean temperature difference (°C), while the number in the upper right of panel b) indicates the fractional area (%) of values in the range -0.1 and +0.1. (Adapted from Deser et al. 2024)[52].

Competing interests

The authors declare no competing interests.

Acknowledgements

This paper is a product of the CLIVAR “Marine Heatwaves in the Global Ocean” Research Focus Group. The authors thank CLIVAR for their sponsorship and the CLIVAR Program Office for their support. A.C. was supported by the NOAA Climate Program Office’s CVP and MAPP programs, DOE Award #DE-SC0023228, and NASA Physical Oceanography grant #80NSSC21K0556.
N.S.L. was supported by U.S. National Science Foundation (OCE-1752724) and the NOAA CVP program (NA20OAR4310405). CM acknowledges support from Proyecto ANID Fondecyt código 3200621, and Data Observatory Foundation ANID Technology Center No. DO210001. TLF acknowledges funding from AtlantECO (project number: 862923) as well as TipESM, which are

both funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them. NJH acknowledges support from the ARC Centre of Excellence for Climate Extremes (CE170100023) and the National Environmental Science Program Climate Systems Hub. NCAR is sponsored by the National Science Foundation under Cooperative Agreement 1852977. We thank Adam S. Phillips (NCAR) for helping with the preparation of Figs. 4 and 6. Argo data were collected and made freely available by the International Argo Program and the national programs that contribute to it. (https://argo.ucsd.edu, https://www.ocean-ops.org). The Argo Program is part of the Global Ocean Observing System. Data was sourced from Australia's Integrated Marine Observing System (IMOS) - IMOS is enabled by the National Collaborative Research Infrastructure strategy (NCRIS).

Author contributions

A.C. and R.R.R. conceived the study with input from all the authors. A.C., A. S., J.A.B., R.R.R, T.L.F., C.D., and N.S.L. coordinated the writing of various sections. A.C., A.S., J.A.B., N.L., T.X., N.S.L., D.J.A., and C.D. contributed to the preparation of the figures. All authors contributed to the discussion and interpretation of the material and assisted with the writing of the manuscript, led by A.C.

References

1 Smith, K. E. *et al.* Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science* **374**, eabj3593 (2021). https://doi.org:doi:10.1126/science.abj3593

2 Frölicher, T. L. & Laufkötter, C. Emerging risks from marine heat waves. *Nature Communications* **9**, 650 (2018). https://doi.org:10.1038/s41467-018-03163-6

3 Smith, K. E. *et al.* Global impacts of marine heatwaves on shallow coastal foundation species. *Nature Communications*, Accepted (2024).

4 Pearce, A. *et al.* The “Marine Heat Wave” Off Western Australia during the Summer of 2010/11. *Department of Fisheries, Western Australia* **222**, 36pp (2011).

5 Pearce, A. F. & Feng, M. The rise and fall of the “marine heat wave” off Western Australia during the summer of 2010/2011. *Journal of Marine Systems* **111-112**, 139-156 (2013). https://doi.org:https://doi.org/10.1016/j.jmarsys.2012.10.009

6 Saranya, J. S., Roxy, M. K., Dasgupta, P. & Anand, A. Genesis and Trends in Marine Heatwaves Over the Tropical Indian Ocean and Their Interaction With the Indian Summer Monsoon. *Journal of Geophysical Research: Oceans* **127**, e2021JC017427 (2022). https://doi.org:https://doi.org/10.1029/2021JC017427

7 Singh, V. K., Roxy, M. K. & Deshpande, M. Role of warm ocean conditions and the MJO in the genesis and intensification of extremely severe cyclone Fani. *Scientific Reports* **11**, 3607 (2021). https://doi.org:10.1038/s41598-021-82680-9

8 Mawren, D., Hermes, J. & Reason, C. J. C. Marine heat waves and tropical cyclones - Two devastating types of coastal hazard in South-eastern Africa. *Estuarine, Coastal and Shelf Science* **277**, 108056 (2022). https://doi.org:https://doi.org/10.1016/j.ecss.2022.108056

9 Rathore, S. *et al.* Interactions Between a Marine Heatwave and Tropical Cyclone Amphan in the Bay of Bengal in 2020. *Frontiers in Climate* **4** (2022). https://doi.org:10.3389/fclim.2022.861477
10 Roxy, M. K. *et al.* in *The Indian Ocean and its Role in the Global Climate System* (eds Caroline C. Ummenhofer & Raleigh R. Hood) 469-482 (Elsevier, 2024).
11 Jones, T. *et al.* Massive Mortality of a Planktivorous Seabird in Response to a Marine Heatwave. *Geophysical Research Letters* **45**, 3193-3202 (2018). https://doi.org:https://doi.org/10.1002/2017GL076164
12 Garrabou, J. *et al.* Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Global Change Biology* **28**, 5708-5725 (2022). https://doi.org:https://doi.org/10.1111/gcb.16301
13 Smith, K. E. *et al.* Biological Impacts of Marine Heatwaves. *Annual Review of Marine Science* **15**, 119-145 (2023). https://doi.org:10.1146/annurev-marine-032122-121437
14 Eakin, C. M., Sweatman, H. P. A. & Brainard, R. E. The 2014–2017 global-scale coral bleaching event: insights and impacts. *Coral Reefs* (2019). https://doi.org:https://doi.org/10.1007/s00338-019-01844-2
15 Moriarty, T., Leggat, W., Heron, S. F., Steinberg, R. & Ainsworth, T. D. Bleaching, mortality and lengthy recovery on the coral reefs of Lord Howe Island. The 2019 marine heatwave suggests an uncertain future for high-latitude ecosystems. *PLOS Climate* **2**, e0000080 (2023). https://doi.org:10.1371/journal.pclm.0000080
16 Filbee-Dexter, K. *et al.* Marine heatwaves and the collapse of marginal North Atlantic kelp forests. *Scientific Reports* **10**, 13388 (2020). https://doi.org:10.1038/s41598-020-70273-x
17 Smale, D. A. *et al.* Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change* **9**, 306-312 (2019). https://doi.org:10.1038/s41558-019-0412-1
18 Wernberg, T. *et al.* An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Climate Change* **3**, 78-82 (2013). https://doi.org:10.1038/nclimate1627
19 Stuart-Smith, R. D., Brown, C. J., Ceccarelli, D. M. & Edgar, G. J. Ecosystem restructuring along the Great Barrier Reef following mass coral bleaching. *Nature* **560**, 92-96 (2018). https://doi.org:10.1038/s41586-018-0359-9
20 Cheung, W. W. L. *et al.* Marine high temperature extremes amplify the impacts of climate change on fish and fisheries. *Science Advances* **7**, eabh0895 (2021). https://doi.org:doi:10.1126/sciadv.abh0895
21 Holbrook, N. J. *et al.* Keeping pace with marine heatwaves. *Nature Reviews Earth & Environment* **1**, 482-493 (2020). https://doi.org:10.1038/s43017-020-0068-4
22 Oliver, E. C. J. *et al.* Marine Heatwaves. *Annual Review of Marine Science* **13**, 313-342 (2021). https://doi.org:10.1146/annurev-marine-032720-095144
23 Schaeffer, A. & Roughan, M. Subsurface intensification of marine heatwaves off southeastern Australia: The role of stratification and local winds. *Geophysical Research Letters* **44**, 5025-5033 (2017). https://doi.org:https://doi.org/10.1002/2017GL073714
24 Schaeffer, A., Sen Gupta, A. & Roughan, M. Seasonal stratification and complex local dynamics control the sub-surface structure of marine heatwaves in Eastern Australian coastal waters. *Communications Earth & Environment* **4**, 304 (2023). https://doi.org:10.1038/s43247-023-00966-4

25 Sun, D., Li, F., Jing, Z., Hu, S. & Zhang, B. Frequent marine heatwaves hidden below the surface of the global ocean. *Nature Geoscience* **16**, 1099-1104 (2023). https://doi.org:10.1038/s41561-023-01325-w

26 Fragkopoulou, E. *et al.* Marine biodiversity exposed to prolonged and intense subsurface heatwaves. *Nature Climate Change* **13**, 1114-1121 (2023). https://doi.org:10.1038/s41558-023-01790-6

27 Zhang, Y., Du, Y., Feng, M. & Hobday, A. J. Vertical structures of marine heatwaves. *Nature Communications* **14**, 6483 (2023). https://doi.org:10.1038/s41467-023-42219-0

28 Reed, D. *et al.* Extreme warming challenges sentinel status of kelp forests as indicators of climate change. *Nature Communications* **7**, 13757 (2016). https://doi.org:10.1038/ncomms13757

29 Jackson, J. M., Johnson, G. C., Dosser, H. V. & Ross, T. Warming From Recent Marine Heatwave Lingers in Deep British Columbia Fjord. *Geophysical Research Letters* **45**, 9757-9764 (2018). https://doi.org:https://doi.org/10.1029/2018GL078971

30 Yao, Y. & Wang, C. Variations in Summer Marine Heatwaves in the South China Sea. *Journal of Geophysical Research: Oceans* **126**, e2021JC017792 (2021). https://doi.org:https://doi.org/10.1029/2021JC017792

31 Koehlinger, J. A., Newton, J., Mickett, J., Thompson, L. & Klinger, T. Large and transient positive temperature anomalies in Washington's coastal nearshore waters during the 2013–2015 northeast Pacific marine heatwave. *PLOS ONE* **18**, e0280646 (2023). https://doi.org:10.1371/journal.pone.0280646

32 Gruber, N., Boyd, P. W., Frölicher, T. L. & Vogt, M. Biogeochemical extremes and compound events in the ocean. *Nature* **600**, 395-407 (2021). https://doi.org:10.1038/s41586-021-03981-7

33 Hauri, C. *et al.* More Than Marine Heatwaves: A New Regime of Heat, Acidity, and Low Oxygen Compound Extreme Events in the Gulf of Alaska. *AGU Advances* **5**, e2023AV001039 (2024). https://doi.org:https://doi.org/10.1029/2023AV001039

34 Han, W. *et al.* Sea level extremes and compounding marine heatwaves in coastal Indonesia. *Nature Communications* **13**, 6410 (2022). https://doi.org:10.1038/s41467-022-34003-3

35 Martinez-Villalobos, C., Dewitte, B., Garreaud, R. G. & Loyola, L. Extreme coastal El Niño events are tightly linked to the development of the Pacific Meridional Modes. *npj Climate and Atmospheric Science*, In press (2024).

36 Rodrigues, R. R., Taschetto, A. S., Sen Gupta, A. & Foltz, G. R. Common cause for severe droughts in South America and marine heatwaves in the South Atlantic. *Nature Geoscience* **12**, 620-626 (2019). https://doi.org:10.1038/s41561-019-0393-8

37 Dzwonkowski, B. *et al.* Compounding impact of severe weather events fuels marine heatwave in the coastal ocean. *Nature Communications* **11**, 4623 (2020). https://doi.org:10.1038/s41467-020-18339-2

38 Pathmeswaran, C., Sen Gupta, A., Perkins-Kirkpatrick, S. E. & Hart, M. A. Exploring Potential Links Between Co-occurring Coastal Terrestrial and Marine Heatwaves in Australia. *Frontiers in Climate* **4** (2022). https://doi.org:10.3389/fclim.2022.792730

39 Hobday, A. J. *et al.* With the arrival of El Nino, prepare for stronger marine heatwaves. *Nature* **621**, 38-41 (2023). https://doi.org:https://doi.org/10.1038/d41586-023-02730-2

40 Holbrook, N. J. *et al.* A global assessment of marine heatwaves and their drivers. *Nature Communications* **10**, 2624 (2019). https://doi.org:10.1038/s41467-019-10206-z

41 Capotondi, A., Newman, M., Xu, T. & Di Lorenzo, E. An Optimal Precursor of Northeast Pacific Marine Heatwaves and Central Pacific El Niño Events. *Geophysical Research Letters* **49**, e2021GL097350 (2022). https://doi.org:https://doi.org/10.1029/2021GL097350

42 Jacox, M. G. *et al.* Global seasonal forecasts of marine heatwaves. *Nature* **604**, 486-490 (2022). https://doi.org:10.1038/s41586-022-04573-9

43 Hartog, J. R., Spillman, C. M., Smith, G. & Hobday, A. J. Forecasts of marine heatwaves for marine industries: Reducing risk, building resilience and enhancing management responses. *Deep Sea Research Part II: Topical Studies in Oceanography* **209**, 105276 (2023). https://doi.org:https://doi.org/10.1016/j.dsr2.2023.105276

44 Pilo, G. S., Holbrook, N. J., Kiss, A. E. & Hogg, A. M. Sensitivity of Marine Heatwave Metrics to Ocean Model Resolution. *Geophysical Research Letters* **46**, 14604-14612 (2019). https://doi.org:https://doi.org/10.1029/2019GL084928

45 Hayashida, H., Matear, R. J., Strutton, P. G. & Zhang, X. Insights into projected changes in marine heatwaves from a high-resolution ocean circulation model. *Nature Communications* **11**, 4352 (2020). https://doi.org:10.1038/s41467-020-18241-x

46 Guo, X. *et al.* Threat by marine heatwaves to adaptive large marine ecosystems in an eddy-resolving model. *Nature Climate Change* **12**, 179-186 (2022). https://doi.org:10.1038/s41558-021-01266-5

47 Bian, C. *et al.* Oceanic mesoscale eddies as crucial drivers of global marine heatwaves. *Nature Communications* **14**, 2970 (2023). https://doi.org:10.1038/s41467-023-38811-z

48 Collins, M. *et al.* in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (eds H.-O. Portner *et al.*) Ch. Extremes, Abrupt Changes and Managing Risk, pp. 589–655 (Cambridge University Press, 2019).

49 Foc-Kemper, B. *et al.* in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds V. Masson-Delmotte *et al.*) Ch. Ocean, Cryosphere and Sea Level Change., pp. 1211–1362 (Cambridge University Press, 2021).

50 Oliver, E. C. J. *et al.* Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. *Frontiers in Marine Science* **6** (2019). https://doi.org:10.3389/fmars.2019.00734

51 Xu, T. *et al.* An increase in marine heatwaves without significant changes in surface ocean temperature variability. *Nature Communications* **13**, 7396 (2022). https://doi.org:10.1038/s41467-022-34934-x

52 Deser, C. *et al.* Future Changes in the Intensity and Duration of Marine Heat and Cold Waves: Insights from Coupled Model Initial-Condition Large Ensembles. *Journal of Climate* **37**, 1877-1902 (2024). https://doi.org:https://doi.org/10.1175/JCLI-D-23-0278.1

53 Hobday, A. J. *et al.* A hierarchical approach to defining marine heatwaves. *Progress in Oceanography* **141**, 227-238 (2016). https://doi.org:https://doi.org/10.1016/j.pocean.2015.12.014

54 Sun, D., Jing, Z., Li, F. & Wu, L. Characterizing global marine heatwaves under a spatio-temporal framework. *Progress in Oceanography* **211**, 102947 (2023). https://doi.org:https://doi.org/10.1016/j.pocean.2022.102947

55 Scannell, H. A. *et al.* Spatiotemporal evolution of marine heatwaves globally. *ESS Open Archive* (July 23, 2023). https://doi.org:10.22541/essoar.169008275.57053412/v1

56 Perkins, S. E. & Alexander, L. V. On the Measurement of Heat Waves. *Journal of Climate* **26**, 4500-4517 (2013). https://doi.org:https://doi.org/10.1175/JCLI-D-12-00383.1

57 Frölicher, T. L., Fischer, E. M. & Gruber, N. Marine heatwaves under global warming. *Nature* **560**, 360-364 (2018). https://doi.org:10.1038/s41586-018-0383-9

58 Xu, T., Newman, M., Capotondi, A. & Di Lorenzo, E. The Continuum of Northeast Pacific Marine Heatwaves and Their Relationship to the Tropical Pacific. *Geophysical Research Letters* **48**, 2020GL090661 (2021). https://doi.org:https://doi.org/10.1029/2020GL090661

59 Amaya, D. J., Miller, A. J., Xie, S.-P. & Kosaka, Y. Physical drivers of the summer 2019 North Pacific marine heatwave. *Nature Communications* **11**, 1903 (2020). https://doi.org:10.1038/s41467-020-15820-w

60 Cael, B. B., Burger, F. A., Henson, S. A., Britten, G. L. & Frölicher, T. L. Historical and future maximum sea surface temperatures. *Science Advances* **10**, eadj5569 (2024). https://doi.org:doi:10.1126/sciadv.adj5569

61 Glynn, P. W. & D'Croz, L. Experimental evidence for high temperature stress as the cause of El Niño-coincident coral mortality. *Coral Reefs* **8**, 181-191 (1990). https://doi.org:10.1007/BF00265009

62 Liu, G. *et al.* Reef-Scale Thermal Stress Monitoring of Coral Ecosystems: New 5-km Global Products from NOAA Coral Reef Watch. *Remote Sensing* **6**, 11579-11606 (2014).

63 Langlais, C. E. *et al.* Coral bleaching pathways under the control of regional temperature variability. *Nature Climate Change* **7**, 839-844 (2017). https://doi.org:10.1038/nclimate3399

64 Kajtar, J. B. *et al.* A stakeholder-guided marine heatwave hazard index for fisheries and aquaculture. *Climatic Change* **177**, 26 (2024). https://doi.org:10.1007/s10584-024-03684-8

65 Oliver, E. C. J. *et al.* Longer and more frequent marine heatwaves over the past century. *Nature Communications* **9**, 1324 (2018). https://doi.org:10.1038/s41467-018-03732-9

66 Wulff, C. O., Vitart, F. & Domeisen, D. I. V. Influence of trends on subseasonal temperature prediction skill. *Quarterly Journal of the Royal Meteorological Society* **148**, 1280-1299 (2022). https://doi.org:https://doi.org/10.1002/qj.4259

67 Jacox, M. G. Marine heatwaves in a changing climate. *Nature* **571**, 485-487 (2019).

68 Amaya, D. J. *et al.* Marine heatwaves need clear definitions so coastal community can adapt. *Nature* **616**, 29-32 (2023).

69 Mignot, A. *et al.* Decrease in air-sea CO2 fluxes caused by persistent marine heatwaves. *Nature Communications* **13**, 4300 (2022). https://doi.org:10.1038/s41467-022-31983-0

70 Laufkötter, C., Zscheischler, J. & Frölicher, T. L. High-impact marine heatwaves attributable to human-induced global warming. *Science* **369**, 1621-1625 (2020). https://doi.org:doi:10.1126/science.aba0690

71 Bonino, G., Masina, S., Galimberti, G. & Moretti, M. Southern Europe and western Asian marine heatwaves (SEWA-MHWs): a dataset based on macroevents. *Earth Syst. Sci. Data* **15**, 1269-1285 (2023). https://doi.org:10.5194/essd-15-1269-2023

72 Prochaska, J. X., Beaulieu, C. & Giamalaki, K. The rapid rise of severe marine heat wave systems. *Environmental Research: Climate* **2**, 021002 (2023). https://doi.org:10.1088/2752-5295/accd0e

73 Desmet, F., Münnich, M. & Gruber, N. Spatiotemporal heterogeneity in the increase in ocean acidity extremes in the northeastern Pacific. *Biogeosciences* **20**, 5151-5175 (2023). https://doi.org:10.5194/bg-20-5151-2023

74 Donlon, C. J. *et al.* The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system. *Remote Sensing of Environment* **116**, 140-158 (2012). https://doi.org:https://doi.org/10.1016/j.rse.2010.10.017

75 Good, S. *et al.* The Current Configuration of the OSTIA System for Operational Production of Foundation Sea Surface Temperature and Ice Concentration Analyses. *Remote Sensing* **12**, 720 (2020).

76 Huang, B. *et al.* Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1. *Journal of Climate* **34**, 2923-2939 (2021). https://doi.org:https://doi.org/10.1175/JCLI-D-20-0166.1

77 Cook, F. *et al.* Marine heatwaves in shallow coastal ecosystems are coupled with the atmosphere: Insights from half a century of daily in situ temperature records. *Frontiers in Climate* **4** (2022). https://doi.org:10.3389/fclim.2022.1012022

78 Goebeler, N., Norkko, A. & Norkko, J. Ninety years of coastal monitoring reveals baseline and extreme ocean temperatures are increasing off the Finnish coast. *Communications Earth & Environment* **3**, 215 (2022). https://doi.org:10.1038/s43247-022-00545-z

79 Hemming, M., Roughan, M. & Schaeffer, A. Exploring multi-decadal time series of temperature extremes in Australian coastal waters. *Earth Syst. Sci. Data* **16**, 887-901 (2024). https://doi.org:10.5194/essd-16-887-2024

80 Hu, S. *et al.* Observed strong subsurface marine heatwaves in the tropical western Pacific Ocean. *Environmental Research Letters* **16**, 104024 (2021). https://doi.org:10.1088/1748-9326/ac26f2

81 Elzahaby, Y. & Schaeffer, A. Observational Insight Into the Subsurface Anomalies of Marine Heatwaves. *Frontiers in Marine Science* **6** (2019). https://doi.org:10.3389/fmars.2019.00745

82 Johnson, G. C. *et al.* Argo—Two Decades: Global Oceanography, Revolutionized. *Annual Review of Marine Science* **14**, 379-403 (2022). https://doi.org:https://doi.org/10.1146/annurev-marine-022521-102008

83 Bond, N. A., Cronin, M. F., Freeland, H. & Mantua, N. Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters* **42**, 3414-3420 (2015). https://doi.org:https://doi.org/10.1002/2015GL063306

84 Capotondi, A., Sardeshmukh, P. D., Di Lorenzo, E., Subramanian, A. C. & Miller, A. J. Predictability of US West Coast Ocean Temperatures is not solely due to ENSO. *Scientific Reports* **9**, 10993 (2019). https://doi.org:10.1038/s41598-019-47400-4

85 Jean-Michel, L. *et al.* The Copernicus Global 1/12° Oceanic and Sea Ice GLORYS12 Reanalysis. *Frontiers in Earth Science* **9** (2021). https://doi.org:10.3389/feart.2021.698876

86 Amaya, D. J. *et al.* Bottom marine heatwaves along the continental shelves of North America. *Nature Communications* **14**, 1038 (2023). https://doi.org:10.1038/s41467-023-36567-0

87 Fredston, A. L. *et al.* Marine heatwaves are not a dominant driver of change in demersal fishes. *Nature* **621**, 324-329 (2023). https://doi.org:10.1038/s41586-023-06449-y

88 Zinke, J. *et al.* Coral record of southeast Indian Ocean marine heatwaves with intensified Western Pacific temperature gradient. *Nature Communications* **6**, 8562 (2015). https://doi.org:10.1038/ncomms9562

89 Lane, M. K. *et al.* Planktonic foraminiferal assemblages reflect warming during two recent mid-latitude marine heatwaves. *Frontiers in Marine Science* **10** (2023). https://doi.org:10.3389/fmars.2023.1155761

90 Penland, C. & Sardeshmukh, P. D. The Optimal Growth of Tropical Sea Surface Temperature Anomalies. *Journal of Climate* **8**, 1999-2024 (1995). https://doi.org:https://doi.org/10.1175/1520-0442(1995)008<1999:TOGOTS>2.0.CO;2

91 Sen Gupta, A. *et al.* Drivers and impacts of the most extreme marine heatwave events. *Scientific Reports* **10**, 19359 (2020). https://doi.org:10.1038/s41598-020-75445-3

92 Perkins-Kirkpatrick, S. E. *et al.* The Role of Natural Variability and Anthropogenic Climate Change in the 2017/18 Tasman Sea Marine Heatwave. *Bulletin of the American Meteorological Society* **100**, S105-S110 (2019). https://doi.org:https://doi.org/10.1175/BAMS-D-18-0116.1

93 Kajtar, J. B., Bachman, S. D., Holbrook, N. J. & Pilo, G. S. Drivers, Dynamics, and Persistence of the 2017/2018 Tasman Sea Marine Heatwave. *Journal of Geophysical Research: Oceans* **127**, e2022JC018931 (2022). https://doi.org:https://doi.org/10.1029/2022JC018931

94 Salinger, M. J. *et al.* The unprecedented coupled ocean-atmosphere summer heatwave in the New Zealand region 2017/18: drivers, mechanisms and impacts. *Environmental Research Letters* **14**, 044023 (2019). https://doi.org:10.1088/1748-9326/ab012a

95 Gregory, C. H., Holbrook, N. J., Marshall, A. G. & Spillman, C. M. Atmospheric Drivers of Tasman Sea Marine Heatwaves. *Journal of Climate* **36**, 5197-5214 (2023). https://doi.org:https://doi.org/10.1175/JCLI-D-22-0538.1

96 Carrasco, D., Pizarro, O., Jacques-Coper, M. & Narváez, D. A. Main drivers of marine heat waves in the eastern South Pacific. *Frontiers in Marine Science* **10** (2023). https://doi.org:10.3389/fmars.2023.1129276

97 Dasgupta, P., Nam, S., Saranya, J. S. & Roxy, M. K. Marine Heatwaves in the East Asian Marginal Seas Facilitated by Boreal Summer Intraseasonal Oscillations. *Journal of Geophysical Research: Oceans* **129**, e2023JC020602 (2024). https://doi.org:https://doi.org/10.1029/2023JC020602

98 Amaya, D. J. *et al.* Are Long-Term Changes in Mixed Layer Depth Influencing North Pacific Marine Heatwaves? *Bulletin of the American Meteorological Society* **102**, S59-S66 (2021). https://doi.org:https://doi.org/10.1175/BAMS-D-20-0144.1

99 Vogt, L., Burger, F. A., Griffies, S. M. & Frölicher, T. L. Local Drivers of Marine Heatwaves: A Global Analysis With an Earth System Model. *Frontiers in Climate* **4** (2022). https://doi.org:10.3389/fclim.2022.847995

100 Feng, M., McPhaden, M. J., Xie, S.-P. & Hafner, J. La Niña forces unprecedented Leeuwin Current warming in 2011. *Scientific Reports* **3**, 1277 (2013). https://doi.org:10.1038/srep01277

101 Benthuysen, J., Feng, M. & Zhong, L. Spatial patterns of warming off Western Australia during the 2011 Ningaloo Niño: Quantifying impacts of remote and local forcing. *Continental Shelf Research* **91**, 232-246 (2014). https://doi.org:https://doi.org/10.1016/j.csr.2014.09.014

102 Oliver, E. C. J. *et al.* The unprecedented 2015/16 Tasman Sea marine heatwave. *Nature Communications* **8**, 16101 (2017). https://doi.org:10.1038/ncomms16101

103 Li, Z., Holbrook, N. J., Zhang, X., Oliver, E. C. J. & Cougnon, E. A. Remote Forcing of Tasman Sea Marine Heatwaves. *Journal of Climate* **33**, 5337-5354 (2020). https://doi.org:https://doi.org/10.1175/JCLI-D-19-0641.1

104 Elzahaby, Y., Schaeffer, A., Roughan, M. & Delaux, S. Oceanic Circulation Drives the Deepest and Longest Marine Heatwaves in the East Australian Current System.

Geophysical Research Letters **48**, e2021GL094785 (2021). https://doi.org:https://doi.org/10.1029/2021GL094785

105 Jin, F.-F. An Equatorial Ocean Recharge Paradigm for ENSO. Part I: Conceptual Model. *Journal of the Atmospheric Sciences* **54**, 811-829 (1997). https://doi.org:https://doi.org/10.1175/1520-0469(1997)054<0811:AEORPF>2.0.CO;2

106 Capotondi, A. ENSO diversity in the NCAR CCSM4 climate model. *Journal of Geophysical Research: Oceans* **118**, 4755-4770 (2013). https://doi.org:https://doi.org/10.1002/jgrc.20335

107 Bian, C., Jing, Z., Wang, H. & Wu, L. Scale-Dependent Drivers of Marine Heatwaves Globally. *Geophysical Research Letters* **51**, e2023GL107306 (2024). https://doi.org:https://doi.org/10.1029/2023GL107306

108 Mogen, S. C. *et al.* Multi-month forecasts of marine heatwaves and ocean acidification extremes. *Nature Geoscience*, Revised (2024).

109 Capotondi, A. *et al.* Observational Needs Supporting Marine Ecosystems Modeling and Forecasting: From the Global Ocean to Regional and Coastal Systems. *Frontiers in Marine Science* **6** (2019). https://doi.org:10.3389/fmars.2019.00623

110 Ren, X., Liu, W., Capotondi, A., Amaya, D. J. & Holbrook, N. J. The Pacific Decadal Oscillation modulated marine heatwaves in the Northeast Pacific during past decades. *Communications Earth & Environment* **4**, 218 (2023). https://doi.org:10.1038/s43247-023-00863-w

111 Wang, Y., Holbrook, N. J. & Kajtar, J. B. Predictability of Marine Heatwaves off Western Australia Using a Linear Inverse Model. *Journal of Climate* **36**, 6177-6193 (2023). https://doi.org:https://doi.org/10.1175/JCLI-D-22-0692.1

112 Wang, C. Three-ocean interactions and climate variability: a review and perspective. *Climate Dynamics* **53**, 5119-5136 (2019). https://doi.org:10.1007/s00382-019-04930-x

113 Cai, W. *et al.* Pantropical climate interactions. *Science* **363**, eaav4236 (2019). https://doi.org:doi:10.1126/science.aav4236

114 Yao, Y., Wang, C. & Wang, C. Record-breaking 2020 summer marine heatwaves in the western North Pacific. *Deep Sea Research Part II: Topical Studies in Oceanography* **209**, 105288 (2023). https://doi.org:https://doi.org/10.1016/j.dsr2.2023.105288

115 Song, Q., Yao, Y. & Wang, C. Response of Future Summer Marine Heatwaves in the South China Sea to Enhanced Western Pacific Subtropical High. *Geophysical Research Letters* **50**, e2023GL103667 (2023). https://doi.org:https://doi.org/10.1029/2023GL103667

116 Song, Q., Wang, C., Yao, Y. & Fan, H. Unraveling the Indian monsoon's role in fueling the unprecedented 2022 Marine Heatwave in the Western North Pacific. *npj Climate and Atmospheric Science* **7**, 90 (2024). https://doi.org:10.1038/s41612-024-00645-x

117 Chiang, J. C. H. & Vimont, D. J. Analogous Pacific and Atlantic Meridional Modes of Tropical Atmosphere–Ocean Variability. *Journal of Climate* **17**, 4143-4158 (2004). https://doi.org:https://doi.org/10.1175/JCLI4953.1

118 Zhang, H., Clement, A. & Di Nezio, P. The South Pacific Meridional Mode: A Mechanism for ENSO-like Variability. *Journal of Climate* **27**, 769-783 (2014). https://doi.org:https://doi.org/10.1175/JCLI-D-13-00082.1

119 Gregory, C. H., Holbrook, N. J., Marshall, A. G. & Spillman, C. M. Sub-seasonal to seasonal drivers of regional marine heatwaves around Australia. *Climate Dynamics* (2024). https://doi.org:10.1007/s00382-024-07226-x

120 Köhn, E. E., Vogt, M., Münnich, M. & Gruber, N. On the Vertical Structure and Propagation of Marine Heatwaves in the Eastern Pacific. *Journal of Geophysical Research: Oceans* **129**, e2023JC020063 (2024). https://doi.org:https://doi.org/10.1029/2023JC020063

121 Alexander, M. A., Deser, C. & Timlin, M. S. The Reemergence of SST Anomalies in the North Pacific Ocean. *Journal of Climate* **12**, 2419-2433 (1999). https://doi.org:https://doi.org/10.1175/1520-0442(1999)012<2419:TROSAI>2.0.CO;2

122 Scannell, H. A., Johnson, G. C., Thompson, L., Lyman, J. M. & Riser, S. C. Subsurface Evolution and Persistence of Marine Heatwaves in the Northeast Pacific. *Geophysical Research Letters* **47**, e2020GL090548 (2020). https://doi.org:https://doi.org/10.1029/2020GL090548

123 Richaud, B. *et al.* Drivers of Marine Heatwaves in the Arctic Ocean. *Journal of Geophysical Research: Oceans* **129**, e2023JC020324 (2024). https://doi.org:https://doi.org/10.1029/2023JC020324

124 Zscheischler, J. *et al.* Future climate risk from compound events. *Nature Climate Change* **8**, 469-477 (2018). https://doi.org:10.1038/s41558-018-0156-3

125 Seneviratne, S. I. *et al.* in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds V. Masson-Delmotte *et al.*) Ch. Weather and Climate Extreme Events in a Changing Climate, 1513-1766 (Cambridge University Press, 2021).

126 Peng, Q., Xie, S.-P., Wang, D., Zheng, X.-T. & Zhang, H. Coupled ocean-atmosphere dynamics of the 2017 extreme coastal El Niño. *Nature Communications* **10**, 298 (2019). https://doi.org:10.1038/s41467-018-08258-8

127 Hauri, C., Gruber, N., McDonnell, A. M. P. & Vogt, M. The intensity, duration, and severity of low aragonite saturation state events on the California continental shelf. *Geophysical Research Letters* **40**, 3424-3428 (2013). https://doi.org:https://doi.org/10.1002/grl.50618

128 Negrete-García, G., Lovenduski, N. S., Hauri, C., Krumhardt, K. M. & Lauvset, S. K. Sudden emergence of a shallow aragonite saturation horizon in the Southern Ocean. *Nature Climate Change* **9**, 313-317 (2019). https://doi.org:10.1038/s41558-019-0418-8

129 Burger, F. A., John, J. G. & Frölicher, T. L. Increase in ocean acidity variability and extremes under increasing atmospheric CO2. *Biogeosciences* **17**, 4633-4662 (2020). https://doi.org:10.5194/bg-17-4633-2020

130 Burger, F. A. & Frölicher, T. L. Drivers of Surface Ocean Acidity Extremes in an Earth System Model. *Global Biogeochemical Cycles* **37**, e2023GB007785 (2023). https://doi.org:https://doi.org/10.1029/2023GB007785

131 Köhn, E. E., Münnich, M., Vogt, M., Desmet, F. & Gruber, N. Strong Habitat Compression by Extreme Shoaling Events of Hypoxic Waters in the Eastern Pacific. *Journal of Geophysical Research: Oceans* **127**, e2022JC018429 (2022). https://doi.org:https://doi.org/10.1029/2022JC018429

132 Le Grix, N., Zscheischler, J., Laufkötter, C., Rousseaux, C. S. & Frölicher, T. L. Compound high-temperature and low-chlorophyll extremes in the ocean over the satellite period. *Biogeosciences* **18**, 2119-2137 (2021). https://doi.org:10.5194/bg-18-2119-2021

133 Le Grix, N., Zscheischler, J., Rodgers, K. B., Yamaguchi, R. & Frölicher, T. L. Hotspots and drivers of compound marine heatwaves and low net primary production extremes. *Biogeosciences* **19**, 5807-5835 (2022). https://doi.org:10.5194/bg-19-5807-2022

134 Boyd, P. W. & Brown, C. J. Modes of interactions between environmental drivers and marine biota. *Frontiers in Marine Science* **2** (2015). https://doi.org:10.3389/fmars.2015.00009

135 Pörtner, H. O. & Knust, R. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science (New York, N.Y.)* **315**, 95-97 (2007). https://doi.org:10.1126/science.1135471

136 Deutsch, C., Ferrel, A., Seibel, B., Pörtner, H.-O. & Huey, R. B. Climate change tightens a metabolic constraint on marine habitats. *Science* **348**, 1132-1135 (2015). https://doi.org:doi:10.1126/science.aaa1605

137 Morée, A. L., Clarke, T. M., Cheung, W. W. L. & Frölicher, T. L. Impact of deoxygenation and warming on global marine species in the 21st century. *EGUsphere* **2022**, 1-36 (2022). https://doi.org:10.5194/egusphere-2022-1364

138 Bednaršek, N. *et al.* Natural Analogues in pH Variability and Predictability across the Coastal Pacific Estuaries: Extrapolation of the Increased Oyster Dissolution under Increased pH Amplitude and Low Predictability Related to Ocean Acidification. *Environmental Science & Technology* **56**, 9015-9028 (2022). https://doi.org:10.1021/acs.est.2c00010

139 Hoegh-Guldberg, O. *et al.* Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science* **318**, 1737-1742 (2007). https://doi.org:doi:10.1126/science.1152509

140 Le Grix, N., Cheung, W. L., Reygondeau, G., Zscheischler, J. & Frölicher, T. L. Extreme and compound ocean events are key drivers of projected low pelagic fish biomass. *Global Change Biology* **29**, 6478-6492 (2023). https://doi.org:https://doi.org/10.1111/gcb.16968

141 Cavole, L. M. *et al.* Biological Impacts of the 2013–2015 Warm-Water Anomaly in the Northeast Pacific

Winners, Losers, and the Future. *Oceanography* **29**, 273-285 (2016).

142 Burger, F. A., Terhaar, J. & Frölicher, T. L. Compound marine heatwaves and ocean acidity extremes. *Nature Communications* **13**, 4722 (2022). https://doi.org:10.1038/s41467-022-32120-7

143 Wyatt, A. M., Resplandy, L. & Marchetti, A. Ecosystem impacts of marine heat waves in the northeast Pacific. *Biogeosciences* **19**, 5689-5705 (2022). https://doi.org:10.5194/bg-19-5689-2022

144 Mogen, S. C. *et al.* Ocean Biogeochemical Signatures of the North Pacific Blob. *Geophysical Research Letters* **49**, e2021GL096938 (2022). https://doi.org:https://doi.org/10.1029/2021GL096938

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

146 Kwiatkowski, L. *et al.* Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. *Biogeosciences* **17**, 3439-3470 (2020). https://doi.org:10.5194/bg-17-3439-2020

147 Kwiatkowski, L. & Orr, J. C. Diverging seasonal extremes for ocean acidification during the twenty-first century. *Nature Climate Change* **8**, 141-145 (2018). https://doi.org:10.1038/s41558-017-0054-0

148 Kwiatkowski, L., Torres, O., Aumont, O. & Orr, J. C. Modified future diurnal variability of the global surface ocean CO2 system. *Global Change Biology* **29**, 982-997 (2023). https://doi.org:https://doi.org/10.1111/gcb.16514

149 Deser, C. *et al.* Insights from Earth system model initial-condition large ensembles and future prospects. *Nature Climate Change* **10**, 277-286 (2020). https://doi.org:10.1038/s41558-020-0731-2

150 Alexander, M. A. *et al.* Projected sea surface temperatures over the 21st century: Changes in the mean, variability and extremes for large marine ecosystem regions of Northern Oceans. *Elementa: Science of the Anthropocene* **6** (2018). https://doi.org:10.1525/elementa.191

151 McAdam, R., Masina, S. & Gualdi, S. Seasonal forecasting of subsurface marine heatwaves. *Communications Earth & Environment* **4**, 225 (2023). https://doi.org:10.1038/s43247-023-00892-5

152 de Boisseson, E. & Balmaseda, M. Predictability of Marine Heatwaves: assessment based on the ECMWF seasonal forecast system. *EGUsphere* **2023**, 1-19 (2023). https://doi.org:10.5194/egusphere-2023-2232

153 Hu, Z.-Z., Kumar, A., Jha, B., Zhu, J. & Huang, B. Persistence and Predictions of the Remarkable Warm Anomaly in the Northeastern Pacific Ocean during 2014–16. *Journal of Climate* **30**, 689-702 (2017). https://doi.org:https://doi.org/10.1175/JCLI-D-16-0348.1

154 Amaya, D. J., Bond, N. A., Miller, A. J. & De Florio, M. J. The evolution and known atmospheric forcing mechanisms behind the 2013-2015 North Pacific warm anomalies. *US CLIVAR Variations* **14** (2016).

155 Wang, Y., Kajtar, J. B., Alexander, L. V., Pilo, G. S. & Holbrook, N. J. Understanding the Changing Nature of Marine Cold-Spells. *Geophysical Research Letters* **49**, e2021GL097002 (2022). https://doi.org:https://doi.org/10.1029/2021GL097002

156 Park, J.-Y., Stock, C. A., Dunne, J. P., Yang, X. & Rosati, A. Seasonal to multiannual marine ecosystem prediction with a global Earth system model. *Science* **365**, 284-288 (2019). https://doi.org:doi:10.1126/science.aav6634

157 Frölicher, T. L., Ramseyer, L., Raible, C. C., Rodgers, K. B. & Dunne, J. Potential predictability of marine ecosystem drivers. *Biogeosciences* **17**, 2061-2083 (2020). https://doi.org:10.5194/bg-17-2061-2020

158 Mogen, S. C. *et al.* Skillful Multi-Month Predictions of Ecosystem Stressors in the Surface and Subsurface Ocean. *Earth's Future* **11**, e2023EF003605 (2023). https://doi.org:https://doi.org/10.1029/2023EF003605

159 Forster, P. M. *et al.* Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence. *Earth Syst. Sci. Data* **15**, 2295-2327 (2023). https://doi.org:10.5194/essd-15-2295-2023

160 Yao, Y., Wang, C. & Fu, Y. Global Marine Heatwaves and Cold-Spells in Present Climate to Future Projections. *Earth's Future* **10**, e2022EF002787 (2022). https://doi.org:https://doi.org/10.1029/2022EF002787

161 Frankignoul, C., Gastineau, G. & Kwon, Y.-O. Estimation of the SST Response to Anthropogenic and External Forcing and Its Impact on the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation. *Journal of Climate* **30**, 9871-9895 (2017). https://doi.org:https://doi.org/10.1175/JCLI-D-17-0009.1

162 Wills, R. C. J., Battisti, D. S., Armour, K. C., Schneider, T. & Deser, C. Pattern Recognition Methods to Separate Forced Responses from Internal Variability in Climate Model

Ensembles and Observations. *Journal of Climate* **33**, 8693-8719 (2020). https://doi.org:https://doi.org/10.1175/JCLI-D-19-0855.1

163 Capotondi, A., Alexander, M. A., Bond, N. A., Curchitser, E. N. & Scott, J. D. Enhanced upper ocean stratification with climate change in the CMIP3 models. *Journal of Geophysical Research: Oceans* **117** (2012). https://doi.org:https://doi.org/10.1029/2011JC007409

164 Cai, W. *et al.* Changing El Niño–Southern Oscillation in a warming climate. *Nature Reviews Earth & Environment* **2**, 628-644 (2021). https://doi.org:10.1038/s43017-021-00199-z

165 Geng, T., Yang, Y. & Wu, L. On the Mechanisms of Pacific Decadal Oscillation Modulation in a Warming Climate. *Journal of Climate* **32**, 1443-1459 (2019). https://doi.org:https://doi.org/10.1175/JCLI-D-18-0337.1

166 O'Brien, J. P. & Deser, C. Quantifying and Understanding Forced Changes to Unforced Modes of Atmospheric Circulation Variability over the North Pacific in a Coupled Model Large Ensemble. *Journal of Climate* **36**, 19-37 (2023). https://doi.org:https://doi.org/10.1175/JCLI-D-22-0101.1

167 Song, S.-Y., Yeh, S.-W., Kim, H. & Holbrook, N. J. Arctic warming contributes to increase in Northeast Pacific marine heatwave days over the past decades. *Communications Earth & Environment* **4**, 25 (2023). https://doi.org:10.1038/s43247-023-00683-y

168 Maher, N. *et al.* The future of the El Niño–Southern Oscillation: using large ensembles to illuminate time-varying responses and inter-model differences. *Earth Syst. Dynam.* **14**, 413-431 (2023). https://doi.org:10.5194/esd-14-413-2023

169 Zhao, Y. & Yu, J.-Y. Two Marine Heatwave (MHW) Variants under a Basinwide MHW Conditioning Mode in the North Pacific and Their Atlantic Associations. *Journal of Climate* **36**, 8657-8674 (2023). https://doi.org:https://doi.org/10.1175/JCLI-D-23-0156.1

170 Shi, J. *et al.* Northeast Pacific warm blobs sustained via extratropical atmospheric teleconnections. *Nature Communications* **15**, 2832 (2024). https://doi.org:10.1038/s41467-024-47032-x

171 Ross, A. C. *et al.* A high-resolution physical–biogeochemical model for marine resource applications in the northwest Atlantic (MOM6-COBALT-NWA12 v1.0). *Geosci. Model Dev.* **16**, 6943-6985 (2023). https://doi.org:10.5194/gmd-16-6943-2023

172 Cheeseman, T. *et al.* Bellwethers of change: population modelling of North Pacific humpback whales from 2002 through 2021 reveals shift from recovery to climate response. *Royal Society Open Science* **11** (2024). https://doi.org:10.1098/rsos.231462

173 Myers, T. A., Mechoso, C. R., Cesana, G. V., DeFlorio, M. J. & Waliser, D. E. Cloud Feedback Key to Marine Heatwave off Baja California. *Geophysical Research Letters* **45**, 4345-4352 (2018). https://doi.org:https://doi.org/10.1029/2018GL078242

174 Ripple, W. J. *et al.* The 2023 state of the climate report: Entering uncharted territory. *BioScience* **73**, 841-850 (2023). https://doi.org:10.1093/biosci/biad080

175 Kuhlbrodt, T., Swaminathan, R., Ceppi, P. & Wilder, T. A Glimpse into the Future: The 2023 Ocean Temperature and Sea Ice Extremes in the Context of Longer-Term Climate Change. *Bulletin of the American Meteorological Society* **105**, E474-E485 (2024). https://doi.org:https://doi.org/10.1175/BAMS-D-23-0209.1

176 Cheng, L. *et al.* New Record Ocean Temperatures and Related Climate Indicators in 2023. *Advances in Atmospheric Sciences* (2024). https://doi.org:10.1007/s00376-024-3378-5

177 Ceppi, P. & Fueglistaler, S. The El Niño–Southern Oscillation Pattern Effect. *Geophysical Research Letters* **48**, e2021GL095261 (2021). https://doi.org:https://doi.org/10.1029/2021GL095261

178 Zhang, W., Jiang, F., Stuecker, M. F., Jin, F.-F. & Timmermann, A. Spurious North Tropical Atlantic precursors to El Niño. *Nature Communications* **12**, 3096 (2021). https://doi.org:10.1038/s41467-021-23411-6

179 Deser, C., Alexander, M. A., Xie, S.-P. & Phillips, A. S. Sea Surface Temperature Variability: Patterns and Mechanisms. *Annual Review of Marine Science* **2**, 115-143 (2010). https://doi.org:https://doi.org/10.1146/annurev-marine-120408-151453

180 Diamond, M. S. Detection of large-scale cloud microphysical changes within a major shipping corridor after implementation of the International Maritime Organization 2020 fuel sulfur regulations. *Atmos. Chem. Phys.* **23**, 8259-8269 (2023). https://doi.org:10.5194/acp-23-8259-2023

181 Schoeberl, M. R. *et al.* The Estimated Climate Impact of the Hunga Tonga-Hunga Ha'apai Eruption Plume. *Geophysical Research Letters* **50**, e2023GL104634 (2023). https://doi.org:https://doi.org/10.1029/2023GL104634

182 Benthuysen, J. A., Oliver, E. C. J., Feng, M. & Marshall, A. G. Extreme Marine Warming Across Tropical Australia During Austral Summer 2015–2016. *Journal of Geophysical Research: Oceans* **123**, 1301-1326 (2018). https://doi.org:https://doi.org/10.1002/2017JC013326

183 Benthuysen, J. A., Steinberg, C., Spillman, C. M. & Smith, G. A. Oceanographic drivers of bleaching in the GBR: from observations to prediction. Volume 4: Observations and predictions of marine heatwaves. *Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns* (47pp). Accessed from: https://nesptropical.edu.au/wp-content/uploads/2021/2006/2024.2022-Volume-2024-Final-Report_COMPLETE.pdf (2021).

184 Benthuysen, J. A., Smith, G. A., Spillman, C. M. & Steinberg, C. R. Subseasonal prediction of the 2020 Great Barrier Reef and Coral Sea marine heatwave. *Environmental Research Letters* **16**, 124050 (2021). https://doi.org:10.1088/1748-9326/ac3aa1

185 Wijffels, S. E. *et al.* A fine spatial-scale sea surface temperature atlas of the Australian regional seas (SSTAARS): Seasonal variability and trends around Australasia and New Zealand revisited. *Journal of Marine Systems* **187**, 156-196 (2018). https://doi.org:https://doi.org/10.1016/j.jmarsys.2018.07.005

186 IMOS2024a. IMOS - SRS - SST - L3S - Multi Sensor - 6 day - night time - Australia. https://portal.aodn.org.au/search?uuid=e1908591-b3cf-42aa-a32f-424322b28165. Accessed 17 March 2024

187 IMOS2024b. Sensors on Tropical Research Vessels: Enhanced Measurements from Ships of Opportunity (SOOP). https://portal.aodn.org.au/search?uuid=8af21108-c535-43bf-8dab-c1f45a26088c. Accessed 22 March 2024

188 Argo2020. Argo float data and metadata from Global Data Assembly Centre (Argo GDAC) - Snapshot of Argo GDAC of February 10st 2020. SEANOE. https://doi.org/10.17882/42182#70590

189 IMOS2024c. IMOS – Argo Profiles – core data. https://portal.aodn.org.au/search?uuid=4402cb50-e20a-44ee-93e6-4728259250d2. Accessed 26 March 2024

190 IMOS2024d. IMOS - Australian National Facility for Ocean Gliders (ANFOG) - delayed mode glider deployments. https://portal.aodn.org.au/search?uuid=c317b0fe-02e8-4ff9-96c9-563fd58e82ac. Accessed 18 March 2024

191 IMOS2024e. IMOS - ANMN National Reference Stations - Darwin and Yongala - Near real-time meteorology and oceanographical data. https://portal.aodn.org.au/search?uuid=006bb7dc-860b-4b89-bf4c-6bd930bd35b7. Accessed 17 March 2024

192 IMOS2024f. IMOS NRS. IMOS - Australian National Mooring Network (ANMN) Facility - WQM and CTD burst averaged data products. https://portal.aodn.org.au/search?uuid=8964658c-6ee1-4015-9bae-2937dfcc6ab9. Accessed 19 March 2024

193 AIMS2009. Northern Australia Automated Marine Weather and Oceanographic Stations. https://doi.org/10.25845/5c09bf93f315d. Accessed 17 March 2024

194 AIMS2017. AIMS Sea Water Temperature Observing System (AIMS Temperature Logger Program). https://doi.org/10.25845/5b4eb0f9bb848. Accessed 28 November 2023

195 Watson, G. & Rousseaux, C. S. NASA Ocean Biogeochemical Model assimilating satellite chlorophyll global data daily VR2017, Goddard Earth Sciences Data and Information Services Center (GES DISC), Greenbelt, MD, USA, https://doi.org/10.5067/PT6TXZKSHBW9. (2017). https://doi.org:

196 Huang, B. *et al.* Extended Reconstructed Sea Surface Temperature, Version 5 (ERSSTv5): Upgrades, Validations, and Intercomparisons. *Journal of Climate* **30**, 8179-8205 (2017). https://doi.org:https://doi.org/10.1175/JCLI-D-16-0836.1

197 Kirtman, B. P. *et al.* The North American Multimodel Ensemble: Phase-1 Seasonal-to-Interannual Prediction; Phase-2 toward Developing Intraseasonal Prediction. *Bulletin of the American Meteorological Society* **95**, 585-601 (2014). https://doi.org:https://doi.org/10.1175/BAMS-D-12-00050.1