

Keeping pace with marine heatwaves

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Abstract | Marine heatwaves (MHWs) are prolonged extreme oceanic warm water events. They can have devastating impacts on marine ecosystems — for example, causing mass coral bleaching and substantial declines in kelp forests and seagrass meadows — with implications for the provision of ecological goods and services. Effective adaptation and mitigation efforts by marine managers can benefit from improved MHW predictions, which at present are inadequate. In this Perspective, we explore MHW predictability on short-term, interannual to decadal, and centennial timescales, focusing on the physical processes that offer prediction. While there may be potential predictability of MHWs days to years in advance, accuracy will vary dramatically depending on the regions and drivers. Skilful MHW prediction has the potential to provide critical information and guidance for marine conservation, fisheries and aquaculture management. However, to develop effective prediction systems, better understanding is needed of the physical drivers, subsurface MHWs, and predictability limits.

Prolonged extreme oceanic warm water events — also known as marine heatwaves (MHWs) — can severely impact marine ecosystems and the services they provide^{1–6}. Yet, despite their significance, dedicated and coordinated research into MHWs only became prominent following the extreme event off Western Australia in 2011 (REFS^{7,8}). Indeed, it was during this event that the term ‘marine heatwave’ was first used to characterize an extensive, persistent and extreme ocean-temperature event⁹ (BOX 1), spurring a new wave of research into their physical processes and corresponding impacts.

Since 2011, MHWs have been observed and analysed both retrospectively and contemporaneously and are now recognized to occur over various spatio-temporal scales. For example, given the ocean’s heat capacity and dynamical scales, MHW events can persist for weeks to years^{10–16}. They further vary in spatial extent and depth, depending on the processes that cause and maintain them, as well as the geometry of the regions in which they occur. For instance, MHWs can be locally confined to individual bays¹⁷, around small islands or along short sections of coastline, or be broadly distributed over

regional seas^{10,18}, ocean basins^{15,19} or even spanning multiple oceans^{20,21} (for a map of major MHW events, see FIG. 1).

As well as the physical drivers, the ecological impacts of MHWs have been studied in some depth. The effects include biodiversity loss and changes in species behaviour or performance^{3,7}, loss of genetic diversity and adaptive capacity²², economic impacts from changes in fishery catch rates^{1,23–25} and mortality or altered performance of farmed aquaculture species¹³. The impacts of MHWs are particularly evident on coral reefs (promoting widespread bleaching, including pan-tropical events²⁶), kelp forests (driving significant loss of kelp forest habitats off the coast of Western Australia, New Zealand, Mexico and the North Atlantic^{7,27–29}) and seagrass meadows (wherein substantial declines have been observed³⁰). At higher trophic levels, MHWs have impacted economically important species, including lobster and snow crab in the northwest Atlantic^{1,31}, lobster, crabs, abalone and scallops off Western Australia^{24,32} and numerous species in the northeast Pacific³³. In some cases, MHWs have even been linked with increased whale entanglements³⁴.

Given the evidence for potentially devastating impacts resulting from MHWs, there is a need for skilful prediction to inform effective response and adaptation strategies. This need is amplified by anthropogenic warming, which has increased MHW occurrences by 50% over the past several decades³⁵, a change that is also projected to increase in the future^{36,37} (FIG. 2). However, despite improved process-based understanding¹⁴, knowledge of MHW predictability and present MHW-prediction systems are in their infancy. Hence, there is a compelling need to understand and improve MHW predictability in order to guide marine conservation, fisheries management and aquaculture practices in a warming world.

In this Perspective, we explore the mechanisms and potential for MHW predictability across a range of timescales. We first consider the physical mechanisms that cause MHWs, before then exploring the importance of MHW-event monitoring as an activity to improve understanding of MHW precursors, processes and forecasts. Using this knowledge, we subsequently outline the potential for MHW predictability. Finally, we address future challenges and opportunities for MHW research, including those arising from climate change.

Physical mechanisms

A range of physical mechanisms can lead to anomalously warm ocean waters (FIG. 3). These include enhanced solar radiation into the ocean, suppressed latent and sensible heat losses from the ocean to the atmosphere, shoaling of the mixed layer from increased stratification, increased horizontal transport (advection) of heat, reduced vertical heat transport associated with suppressed mixing and reduced coastal upwelling or Ekman pumping (see REF.¹⁴ for an in-depth discussion). Elevated upper ocean heat content, or the re-emergence of warm anomalies from the subsurface, can also precondition the ocean for increased likelihood of MHW occurrence. The amplification or suppression of these processes, either in isolation or collectively, can promote or inhibit MHW development driven by local air–sea interactions and feedbacks, and large-scale modes of climate variability acting locally or remotely. Here, we detail these physical processes, the

Box 1 | Defining marine heatwaves

'Heatwave' is a well-recognized term, broadly indicating to society the risks associated with thermal stresses on people and the environment. The atmospheric-research community uses qualitative descriptors and quantitative metrics to express heatwave events, with a widely used definition describing a heatwave as at least three consecutive days of air temperatures above the 90th percentile of climatological, seasonally varying norms¹²⁹.

In 2015, an analogous definition was developed for marine heatwaves (MHWs). Compared with the atmospheric definition, it was recommended that a threshold of at least 5 days above the seasonally varying 90th percentile¹²⁴ is needed to acknowledge longer thermal persistence timescales in the ocean. MHWs have also been defined as sea surface temperatures exceeding the 99th percentile^{36,109} — a definition applied in the Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere (SROCC¹¹⁷). In fact, the SROCC defines a MHW as "an event at a particular place and time of the year that is rare and predominately, but not exclusively, defined with a relative threshold; that is, an event rarer than 90th or 99th percentile of a probability density function."

understanding of which has substantial bearing on MHW predictability, as discussed subsequently.

Coupled air–sea interactions and

atmospheric preconditioning. Many of the iconic extratropical MHWs (for example, The Blob, central South Pacific) have been associated with persistent high-pressure systems (or blocking highs) over the ocean and their resulting air–sea interactions. Atmospheric blocking reduces cloud cover, enhances insolation and suppresses surface wind speeds, resulting in hot, dry weather. Collectively, these conditions reduce sensible and latent ocean heat loss and increase solar radiative heating, in turn, warming sea surface temperatures (SSTs)^{14,19,38,39} (FIG. 3). Given that blocking highs have large spatial scales and can persist for weeks to months, they have the potential to substantially raise ocean temperatures over a large geographic region for a considerable duration, as reflected in the characteristics of MHWs they promote. For example, key events occurred during 2003 in the Mediterranean Sea^{10,40}, 2009/10 in the central South Pacific¹⁹, 2012 in the northwest Atlantic^{12,41}, 2013/14 in the northeast Pacific³⁸ and 2017/18 in the Tasman Sea^{42,43}.

While these events are related to atmospheric blocking, the specific mechanisms vary. The 2009/10 MHW in the central South Pacific, for example, was generated by Rossby wave-related atmospheric anomalies arising from the central Pacific El Niño¹⁹. By contrast, the 2003 Mediterranean Sea^{10,44} and 2017/18 Tasman Sea MHWs^{42,43} formed through enhanced radiative heat fluxes caused by concurrent atmospheric heatwaves. For the 2012 northwest Atlantic^{12,41} and 2013/14 northeast Pacific MHWs^{15,38}, atmospheric preconditioning was important. Specifically, persistent atmospheric weather patterns through the winter reduced wintertime

heat loss from the ocean to the atmosphere, keeping the upper ocean warmer and preconditioning it to increased MHW likelihood in the following seasons. The 2013 North Pacific blocking pattern was so extreme and persistent that it was given the nickname the 'Ridiculously Resilient Ridge' (REF.⁴⁵), referring to a large and unusual region of high sea-level pressure that was unprecedented since at least the 1980s³⁸.

Oceanic preconditioning. Oceanic preconditioning of warm temperature anomalies can result from the process of re-emergence⁴⁶. If heat anomalies form during winter when the mixed layer is deep, subsurface anomalies can become uncoupled from the surface ocean in summer when the mixed layer shoals. When the mixed layer deepens again during the subsequent winter, the persistent subsurface anomalies are re-entrained into the mixed layer, making the surface ocean warmer⁴⁶. Mixed-layer depths are also important for modulating the response of the surface ocean to heat fluxes. For example, when mixed layers are shallower than normal, they will warm more quickly for a given input of heat⁴⁷. Indeed, an anomalously shallow mixed layer when net heat fluxes are into the ocean could increase the likelihood of summer MHWs, even in the absence of anomalously large surface heat fluxes⁴⁸. Ocean circulation changes can also precondition the ocean for MHW development over longer timescales and at greater depths, whereby ocean heat content increases reduce surface heating requirements for MHW generation⁴⁹.

Modulation by climate modes and teleconnections. Modes of climate variability — which operate on timescales from intraseasonal (Madden–Julian Oscillation (MJO)), through interannual (El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole), to decadal — are known

to modulate the frequency, intensity and duration of MHWs^{14,35,50}. These modes can influence ocean temperatures, including the development of regional MHWs, directly or remotely via atmospheric or oceanic teleconnections, which reverberate the effects globally^{14,51}.

On intraseasonal timescales, for instance, the MJO influences atmospheric circulation by suppressing convection and increasing Ekman pumping off northwest Australia, specifically during MJO phases 2–5 (REF.⁵²). This process preferentially supports warmer SSTs and increases the likelihood of MHWs off Western Australia⁵³. Conversely, the MJO has been associated with enhanced convection, capable of exciting a Rossby wave train through to the extratropics that effectively sets up a blocking high, which forces MHWs in the southwest Atlantic Ocean³⁹.

On interannual timescales, ENSO events play a substantial role in influencing MHW likelihood, not only in the tropical Pacific but also in regions remote to ENSO's centre of action. El Niño events are associated with increased SSTs in the central and eastern tropical Pacific, resulting in MHWs through the dynamic response of the thermocline to wind stress changes at the surface, Kelvin wave propagation across the Pacific and reduced upwelling¹⁴. El Niño events have also been associated with reduced strength of the subtropical north-easterly trade winds, which, in turn, reduce evaporation, increase local SSTs and trigger a positive thermodynamic wind–evaporation–SST feedback¹⁵. This feedback subsequently activates meridional modes, which propagate and amplify SST from the subtropics into the central equatorial Pacific. There, the positive SST anomalies favour the development of El Niño and tropical convection, exciting atmospheric Rossby waves that teleconnect to the extratropics, which aid persistence¹⁵. Conversely, La Niña events can remotely elevate SSTs off Western Australia via the propagation of oceanic Kelvin waves and by strengthening heat transport through the Leeuwin Current, increasing the likelihood of MHWs^{47,54}. Thus, the phase of ENSO (along with other modes) is important in enhancing or suppressing MHWs in different regions across the globe^{14,35}.

On multi-year timescales, oceanic Rossby waves can propagate westwards for years to decades across ocean basins and modulate ocean heat content and the local vertical structure along their path. In particular, it has been shown that oceanic Rossby waves generated by wind changes

in the interior South Pacific can modulate poleward transport through the Tasman Sea⁵⁵ and enhance MHW event likelihoods there⁵⁶. This likelihood is increased despite the fact that the East Australian Current Extension region is eddy-rich, with eddy variability typically occurring on timescales of weeks to months. This oceanic Rossby wave teleconnection process provides an additional modulation mechanism to effectively 'load the dice' for increased MHW potential predictability in the Tasman Sea up to several years in advance.

Monitoring marine heatwaves

Coupled with understanding the physical processes contributing to MHW development, ocean temperature

monitoring programmes are crucial for their identification and categorization. The near real-time monitoring of MHWs requires resources to deliver temperature data on a range of spatial scales and depths. In this regard, satellite sensors provide a suite of global and regional ocean surface information, including SST, sea level, currents and winds. Near real-time in situ data from Argo floats, gliders and moorings provide information on subsurface conditions, such as mixed-layer depth and heat content.

Integrated ocean data systems that incorporate these multiple data streams can offer region-specific information for monitoring MHWs. For example, Australia's [Integrated Marine Observing](#)

[System](#) (IMOS) provides near real-time summaries of surface currents and SST, which, when referenced against climatology data, indicates the presence of MHWs around Australia — representing valuable information for the public, aquaculture industries, tourism operators in the marine environment and local communities.

Event-based monitoring. Event-based monitoring can offer targeted information for marine stakeholders once a MHW event has commenced. For example, identifying properties of a MHW, such as its vertical extent, can provide information on its persistence or potential disruption to marine ecosystems (TABLE 1); a shallow MHW might

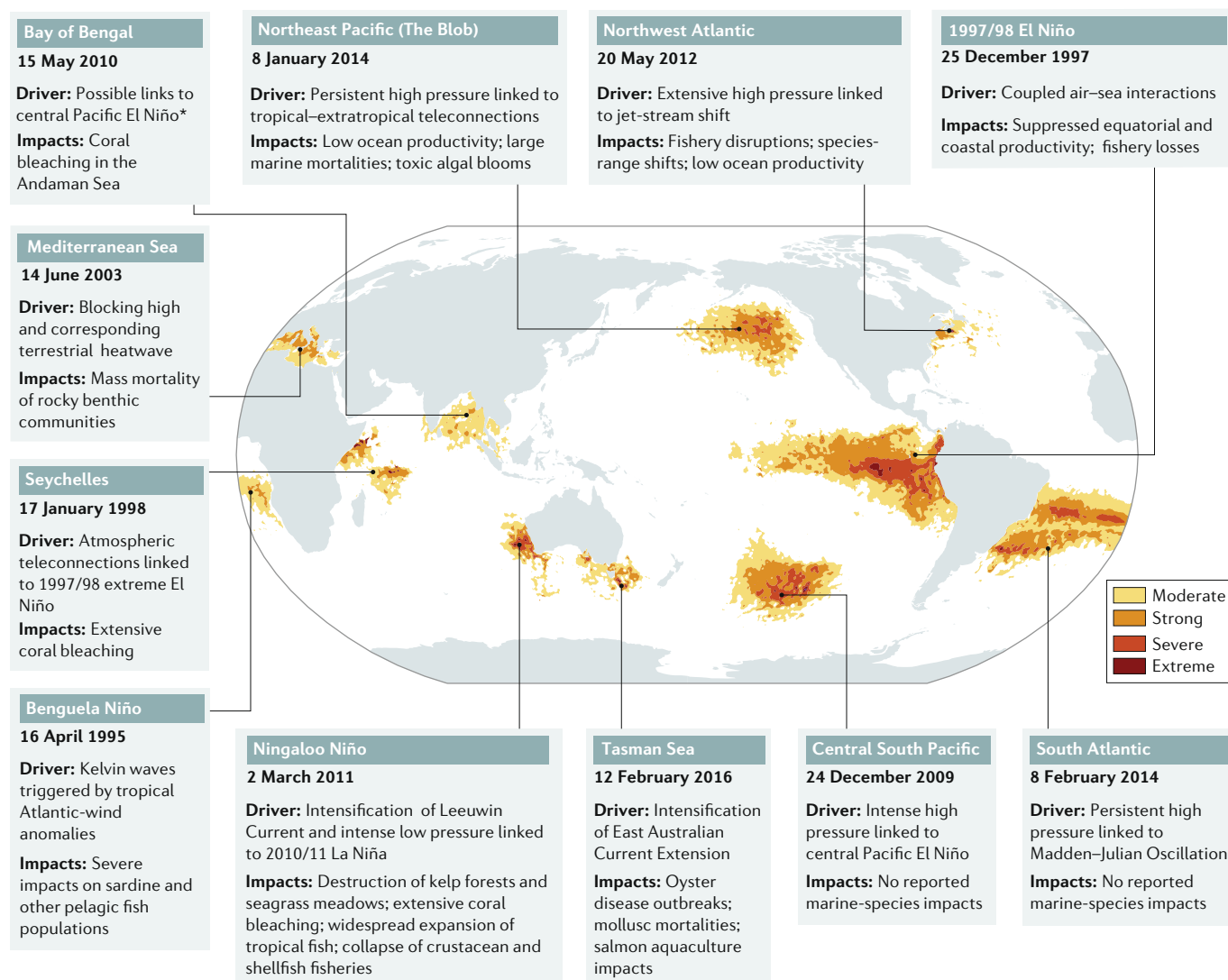


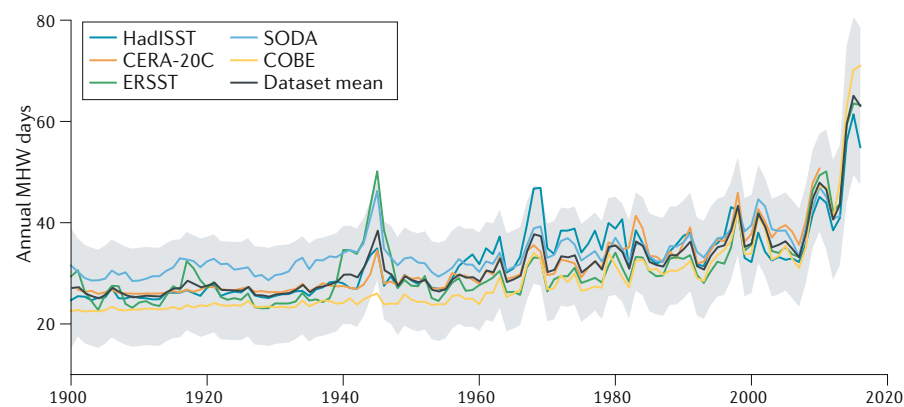
Fig. 1 | Drivers and ecological impacts of major marine heatwave events. A subset of major marine heatwave (MHW) events since 1995. The MHW intensity scale, from moderate to extreme, represents conditions corresponding to the peak date of the event, with categories identified successively as multiples of the 90th percentile¹⁰¹. The spatial scale, intensity and ecological impacts of MHWs can be substantial, as observed for the Benguela Niño¹¹², Seychelles¹¹³, Ningaloo Niño^{27,111}, Tasman Sea¹³, central South Pacific¹⁹, South Atlantic³⁹, 1997/98 El Niño¹¹⁴, northwest Atlantic^{1,12}, The Blob^{15,38}, Bay of Bengal^{115,116} and the Mediterranean Sea^{10,44}. Figure inspired by schematics in REFS^{109,117,118}. *While the Bay of Bengal MHW co-occurred with a major central Pacific El Niño event, there have been no studies to confirm or reject a causal link.

be more likely to weaken if strengthening winds lead to deep mixing, whereas a deep MHW offshore would persist even if winds intensified.

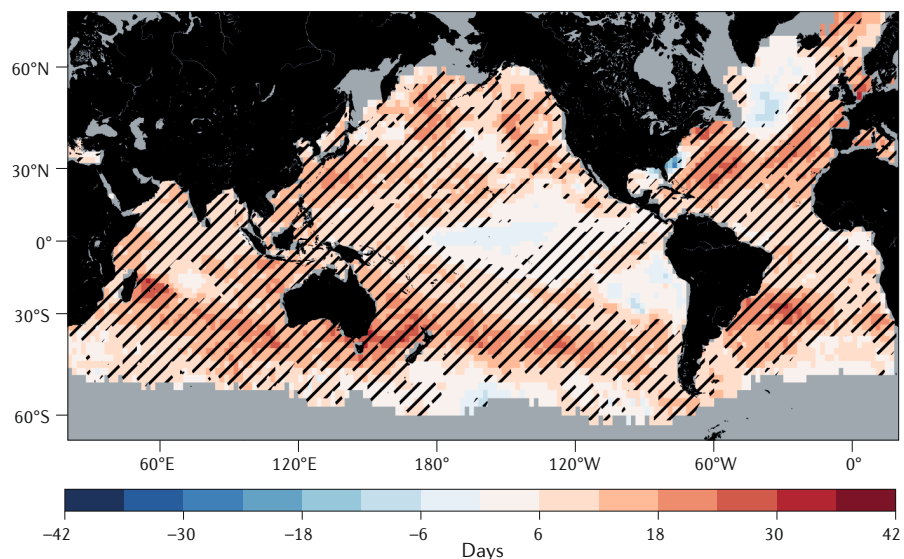
During a MHW, rapid deployment of specific equipment can augment standard and integrated systems, and can target regions where infrastructure is not present

or does not meet the needs for near real-time monitoring. For instance, existing technology such as autonomous underwater vehicles, vertical-profiling instruments and undulating towed vehicles can be manoeuvred to resolve a MHW's vertical structure and investigate contributing physical processes. An IMOS programme to examine the emergence, maintenance and decay phases of the 2018/19 Tasman Sea MHW, for example, revealed the potential for such monitoring approaches. During this programme, Slocum gliders deployed off Tasmania provided high temporal and spatial sampling over the continental shelf, informing the depth and characteristics of the anomalously warm-water event (FIG. 4). Near real-time data were shared with regional stakeholders, including local marine industries such as salmon and oyster aquaculture, stimulating interest and intensifying demand for predictive capability. Indeed, such real-time information, achieved through event-based monitoring, can inform adaptive management responses relevant

a Globally averaged annual MHW days



b Change in MHW days (1987–2016 minus 1925–1954)



c Change in MHW days (2031–2060 minus 1961–1990)

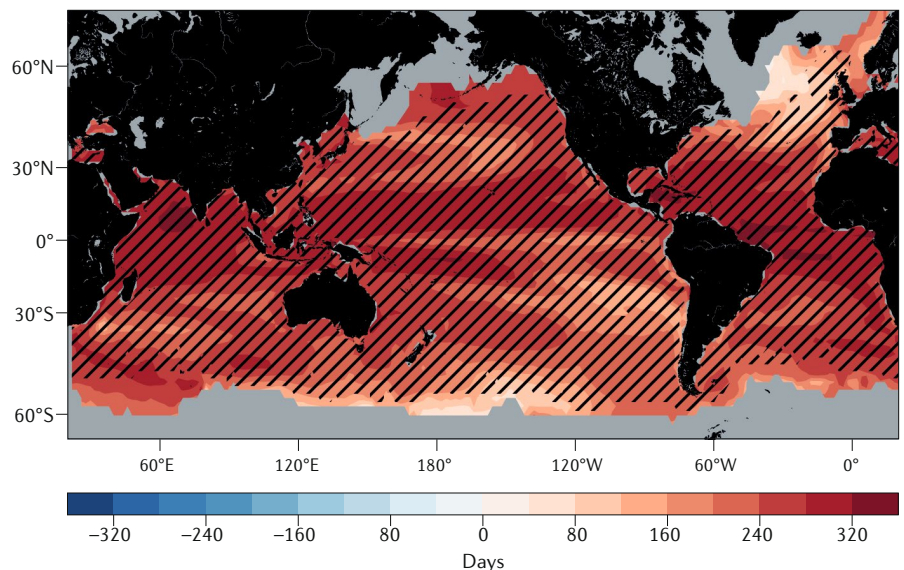


Fig. 2 | Trends in global marine heatwave occurrence. **a** | Globally averaged changes in the annual number of marine heatwave (MHW) days based on the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST)¹¹⁹, Extended Reconstructed Sea Surface Temperature (ERSST)¹²⁰, COBE¹²¹, CERA-20C¹²² and Simple Ocean Data Assimilation (SODA) datasets¹²³. Grey shading indicates the 95% confidence interval. **b** | Changes in the annual number of MHW days from the period 1925–1954 to 1987–2016, based on the same data as in panel **a**. Hatching indicates statistically significant changes ($P < 0.05$). **c** | Changes in the annual number of MHW days from the period 1961–1990 to 2031–2060, based on six Climate Model Inter-comparison Project (CMIP5) global climate models under the Representative Concentration Pathway (RCP) 8.5 emissions scenario. Hatching indicates grid points in which all six models agree on the sign of the change. Grey areas in panels **b** and **c** reflect missing data, primarily due to seasonal ice cover. In panels **a** and **b**, the effect of natural variability (the Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation and El Niño–Southern Oscillation) has been removed following REF.³⁵. MHW days are defined as the number of days when sea-surface-temperature anomalies exceed a daily climatological 90th percentile threshold, for at least 5 days¹²⁴. The annual count of MHW days has increased substantially since the early twentieth century, and this increase has only accelerated up to the present day. This rise is projected to continue increasing in the future, with annual MHW days approaching a full year by the late twenty-first century. Panel **a** adapted from REF.³⁵, CC BY 4.0. Panel **c** reprinted from REF.³⁷, CC BY 4.0.

to multiple stakeholders, demonstrating the importance of translating raw data streams into visual results.

Monitoring subsurface marine heatwaves.

While remote sensing, in combination with surface drifting buoys and ship underway data, provides high resolution SST data for both historical and real-time analyses of MHW surface characteristics, it is not only surface properties that need attention. MHWs can exhibit considerable depth penetration, or exist at depth with no surface expression, necessitating subsurface data^{57,58}. Yet, the ability to characterize subsurface MHWs in both the open ocean⁵⁸ and coastal regions⁵⁷ is challenged by the sparsity of observations and the absence of continuous, long-term time series in the historical record (such as data from eXpendable BathyThermographs (XBTs), CTDs (conductivity, temperature and depth), gliders and Argo profiles).

These challenges hinder the development of robust and spatially complete subsurface temperature climatologies needed for

statistical assessments of MHWs. Indeed, while some datasets exist^{59,60}, they do not extend to coastal regions, owing to an absence of Argo profiles⁶¹. Nevertheless, analyses of MHW vertical structure and corresponding processes have been attempted through the use of long-term mooring sites^{20,57}, autonomous floats in regional seas (such as the western Tasman Sea⁵⁸) and dynamical ocean models or reanalyses that assimilate ocean observations^{62,63}. Each of these approaches have known limitations; mooring sites provide information for single points in space and reanalysis data are based on model-synthesized sparse observations, meaning the products are only as good as the quality and quantity of observations they assimilate, and their distribution. Consideration of how to identify MHWs using suboptimal data is, therefore, important for future work⁶⁴. Better understanding of the relevant timescales of subsurface MHWs, which can be longer than those at the surface⁵⁸, can alleviate some of the demands on high-frequency

sampling. It is clear, however, that without improved subsurface characterization of MHWs — with bearing on surface recharge, heat storage and mixing — their prediction potential remains limited.

Predicting marine heatwaves

As discussed previously, MHW occurrences can depend on modes of climate variability^{14,35,50}, the background ocean state (heat content, mixed-layer depth)^{48,49}, ocean circulation¹³, remote teleconnections^{14,15,39,56} and the presence of weather systems such as atmospheric blocking^{38,39,42}. In many instances, these drivers are themselves at least partially predictable, especially in regard to climate modes⁶⁵, suggesting that certain MHW events are potentially predictable many months ahead^{14,18,56}. Here, we outline the need for understanding MHW predictability, their timescales and the development of forecast systems.

The benefit of and need for marine heatwave prediction. Skilful prediction of MHW events, and their intensity, duration, depth

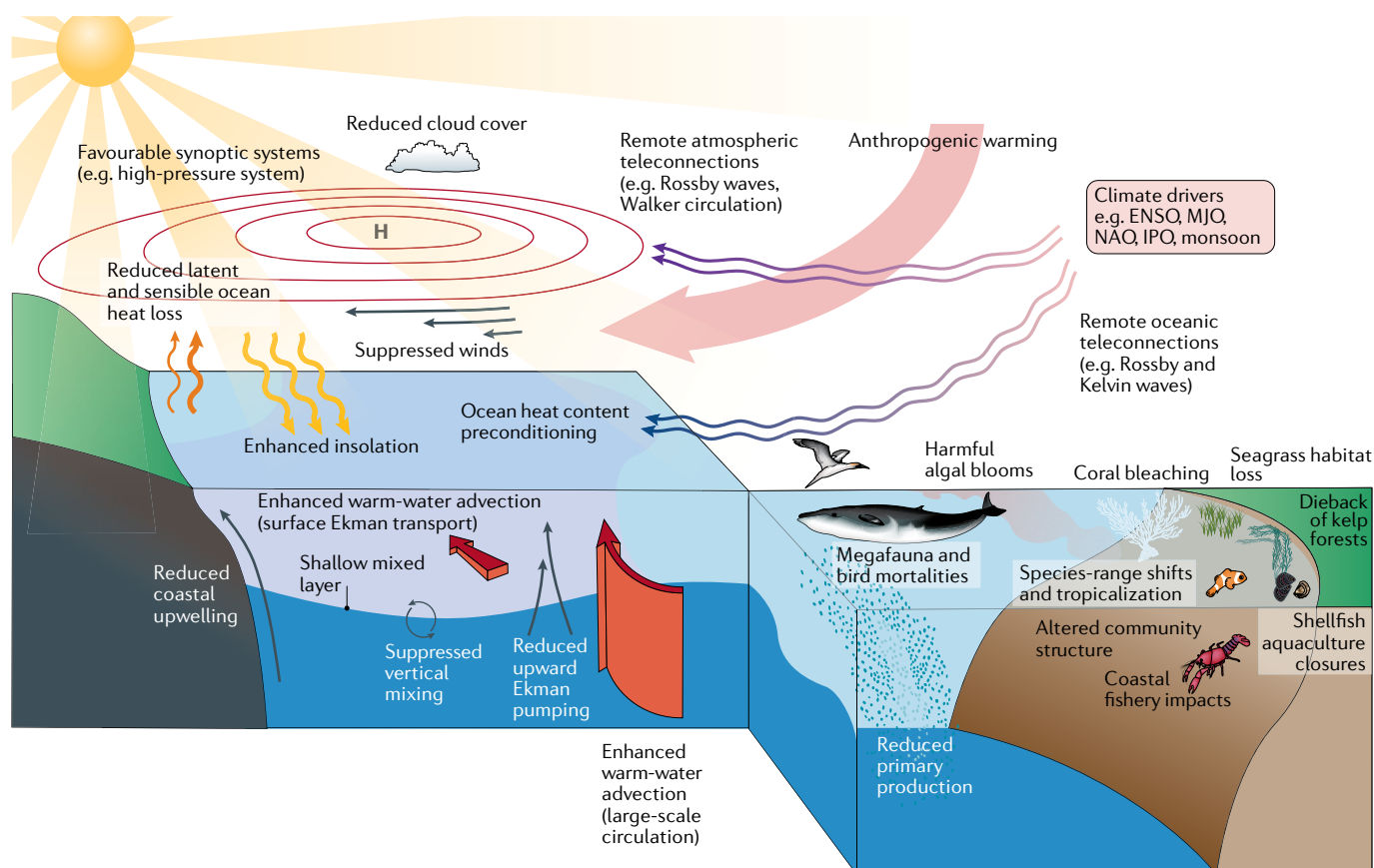


Fig. 3 | Marine heatwave drivers and impacts. Schematic of the drivers of marine heatwaves (left) and their impacts on oceanic and coastal ecosystems (right). Surface marine heatwaves are caused by local ocean and atmosphere heat fluxes affecting the surface mixed layer. These processes are controlled by local synoptic systems that can be modulated by large-scale climate oscillations and anthropogenic warming. Impacts range across trophic levels often affecting human systems. ENSO, El Niño–Southern Oscillation; H, high pressure; IPO, Interdecadal Pacific Oscillation; MJO, Madden–Julian Oscillation; NAO, North Atlantic Oscillation.

Table 1 | Marine heatwave potential predictability lead times, scales, and potential and example impacts

Condition	Predictability lead time	Predictability source	Persistence	Vertical scale	Horizontal scale	Impacted ecosystems	Impact severity	Example
Strong atmospheric and oceanic contributions ^a	Months (at least)	Local and remote climate forcing	Months	Up to 100s of metres	1,000s of kilometres	Surface to benthic (possibly)	Potentially substantial	2011 Western Australia MHW ^{17,111}
Strong atmospheric and weak oceanic contributions ^a	~1–2 weeks or season ahead	Atmospheric preconditioning and/or teleconnections	Months	Up to 10s of metres	1,000s of kilometres	Within mixed layer	Moderate to substantial	2014 NE Pacific + 2013/14 SW Atlantic + 2017/18 eastern Tasman Sea MHW ^{38,39,42,43}
Weak atmospheric and strong oceanic contributions ^a	Months to years	Oceanic preconditioning and/or teleconnections	Months	Up to 100s of metres	100s of kilometres	Surface to benthic (possibly)	Moderate to substantial	2015/16 Tasman Sea MHW ^{13,49,56}
Weak atmospheric and oceanic contributions ^a	Days	Transitory weather or eddies	Hours to days	Up to 10s of metres	Local	Minimal	Minor	Heat spikes

^aContributions refer to those from local atmospheric sources and those arising from oceanic advection. MHW, marine heatwave.

and spatial extent, is expected to be of great value to marine resource users and managers of fisheries, aquaculture and conservation^{65–67}. For instance, short-term forecasts of a few days to weeks⁶⁸ would allow for active management strategies to be implemented, such as harvesting or relocating farmed species in aquaculture industries that would likely suffer mortality under MHW conditions. With predictive capabilities, it might be possible to ameliorate stressful conditions through short-term active interventions such as cooling or shading, as is currently implemented in Australian fishery and aquaculture sectors in response to seasonal forecasts of adverse conditions (for example, water temperature, rainfall and air temperature)⁶⁹. Indeed, on seasonal timescales, forecasts can be used to inform strategic fisheries management decisions (target species, quotas and timings) or to implement temporary protected areas. While most applications of MHW predictions seek to support mitigation of detrimental ecological consequences, short-term to medium-term prediction of MHWs could also bring opportunities. For example, the 2011 MHW in Western Australia led to the temporary appearance of marine megafauna (whale sharks, manta rays, tiger sharks, turtles) and recreationally important fish species well outside their normal range⁹, providing a short-term business opportunity for local tour operators.

Anticipating regions that might be affected by decadal and longer-term MHW intensification would also guide placement of fully protected areas⁷⁰, as well as inform

fisheries management approaches by future-proofing target species for fisheries and aquaculture²⁴. Moreover, longer-term prediction can help focus conservation efforts such as assisted evolution or early restoration in sensitive habitats and regions³⁰. Skilful prediction can identify areas where mitigation strategies might have limited utility, as it may not be economically feasible or technically possible to mitigate all the impacts on marine ecosystems⁷¹.

Predictability timescales. The degree to which MHWs are predictable requires knowledge of how the relevant physical drivers and processes interact in time, from days (SST persistence), to weeks (blocking systems and atmospheric teleconnections), to months (oceanic preconditioning) and years (low-frequency climate modes and oceanic teleconnections). Given that the heat capacity, persistence and propagation timescales of oceanic processes (such as from oceanic Rossby waves) are much greater than those for the atmosphere (for instance, from blocking), MHW development is expected to have longer predictability lead times in regions where oceanic processes dominate (TABLE 1, FIG. 5).

For example, MHW forecasts with lead times of 7–10 days might be possible when air–sea interactions (such as from a blocking event) dominate MHW development. However, at weeks-to-months leads, preconditioning factors from mixed-layer depth or ocean heat content enhance predictability potential^{48,49}. For example, if the mixed-layer depth in boundary current and extension regions is relatively shallow

leading into summer, anomalously warm SSTs might be expected in the summer season⁴⁸. Information on ocean advection processes and internal variability (from large-scale eddies, for example) might improve MHW forecast potential on similar timescales, as has been found for seasonal forecasts⁷² (TABLE 1). Atmospheric and oceanic circulations are recognized in describing MHW types along the eastern Tasmanian shelf region, where persistence and intensity are related to the relative contribution of the East Australian Current and atmospheric heat input⁶².

Climate modes and their teleconnections are expected to influence MHW predictability on subseasonal to seasonal^{18,39,53,73} and interannual to decadal timescales^{14,56}. Most climate modes have some degree of predictability, or at least persistence, and can, therefore, provide potential sources of MHW predictability. For example, ENSO can be predicted ~6 months in advance, and, given strong connections to MHWs off Western Australia, some degree of predictability on seasonal timescales might be possible in that region.

Moreover, atmospheric blocking events at midlatitudes via remote teleconnections also offer some predictability, albeit at much shorter timescales³⁹. While blocking can be influential to MHW development, the realistic simulation of blocking is a challenge, as is the forecasting of these blocking events^{74–77}. Specifically, although atmospheric blocking can increase the likelihood of MHW event occurrence, other short-term oceanic processes can work against the blocking such that the event does

not occur, creating significant uncertainty around MHW event likelihood.

Other processes can also offer predictive potential. The clustering of ocean eddies in western boundary currents⁷⁸, for example, contribute potentially predictable changes in ocean temperature extremes^{62,79,80}. Remotely forced oceanic Rossby wave teleconnections — which take months to many years to propagate westwards across ocean basins — also hold considerable promise for multi-year prediction of MHW likelihood in the Tasman Sea region⁵⁶.

Developing forecast systems. Marine managers can gain valuable information from seasonal MHW forecasts. However, skilful forecasts are not easily achieved. For example, a recent assessment of seasonal forecast skill from the US National Centers for Environmental Prediction's Climate Forecast System in 'The Blob' region had little success⁸¹. Meanwhile, a separate assessment of seasonal MHW forecasts of the California Current System in eight global climate-forecast systems indicated that large ensemble forecasts were potentially beneficial, with MHWs being more or less predictable, depending on the forcing mechanisms¹⁸. In Australia, ocean 'weather' forecasts (7–10 days) are already available through *BlueLink*, but these have not yet specifically addressed MHWs.

Testing and developing the aforementioned relationships and timescales for forecast systems can benefit from using data-learning algorithms or through process-based ocean model experiments, including single-model or multi-model ensembles. Such examples have been shown for coral-bleaching events⁸². MHW-forecast systems that use large ensembles of weather and/or climate model simulations are expected to be the most promising, in line with similar ensemble numerical modelling techniques applied to forecast extreme events such as tropical cyclones. The use of machine learning to synthesize datasets is also a promising avenue towards sequential time series forecasting. For example, neural networks composed of gated recurrent units might hold promise for learning seasonal patterns in SST and predicting extremes when trained with MHW-relevant climate features⁸³. Data to train such models should be relevant to the phenomena being forecasted, for example, the NINO3.4 index, regional sea-level pressure and upper ocean heat content. It is clear, however, that, whichever method is used, forecast systems must be developed for different regions given the spatial heterogeneity of predictability processes.

Forecasting MHWs comes with the opportunity and challenge of communicating these forecasts with stakeholders, including fishery managers and the public⁸⁴. Choosing thresholds and timescales for forecasts that are relevant to marine ecosystem response and planning requires identifying who the forecast system will inform and the desired criteria or metrics that will facilitate decision-making, and will require considerable efforts towards stakeholder engagement.

Future perspectives

MHWs have emerged as one of the grand challenges facing marine ecosystems and the sustainability of marine resources, demanding progress in understanding the physical phenomena; improved prediction systems; increased collaboration between marine scientists, climate scientists, marine industries and managers; and the efficient,

accessible and consistent dissemination of new knowledge. We expand here on specific areas that warrant attention.

Developing improved understanding of physical processes. Heat budgets provide a valuable tool for understanding processes that cause MHWs^{13,14,41,47,48,73}. However, fixed-region budget approaches are limited to analysing the drivers of MHWs locally, while remote forcing and atmospheric and oceanic teleconnections can also be important contributors to the development and decline of MHWs. Hence, there is merit in considering large-scale dynamical frameworks that connect remote drivers to MHW events, which might benefit predicting MHW onset, persistence, decay, spatial extent, depth and intensity. There has been some success in understanding the physical mechanisms of atmospheric heatwave development through Lagrangian back-trajectory analysis^{85,86}, a technique also used in the ocean to investigate the influences of microbial exposure to ocean-temperature variability as they drift⁸⁷. A beneficial addition for the analysis of MHW predictability will be the use of adjoint models to explain the fundamental dynamics of back-trajectory teleconnections⁸⁸.

Marine ecosystem and fisheries-management implications. The management of marine species, habitats and ecosystems can be seriously affected by MHW impacts on

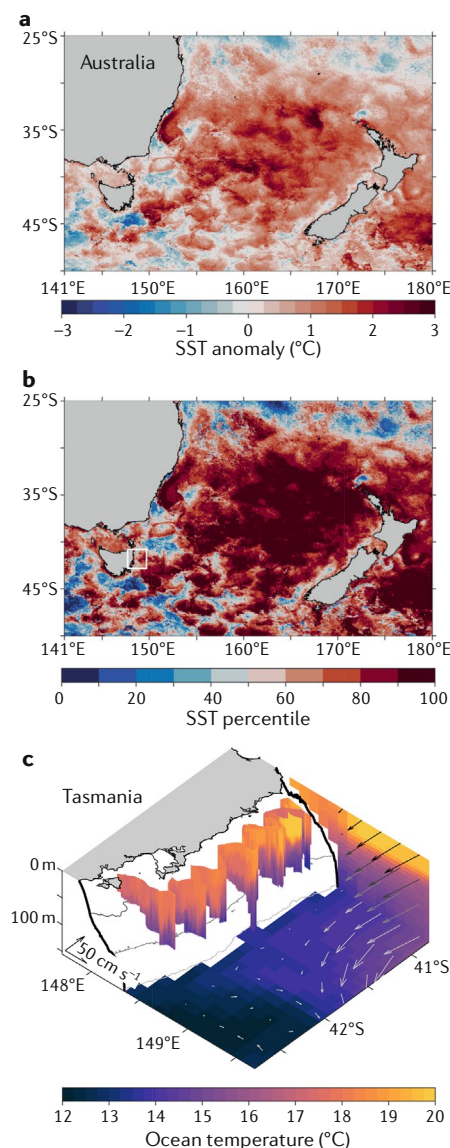


Fig. 4 | Integrated approaches for monitoring marine heatwaves. **a** | February 2019 mean sea surface temperature (SST)¹²⁵ anomalies during the 2018/19 Tasman Sea marine heatwave. SST represents monthly mean, multisensor, night-time-only readings at 0.2 m depth. Anomalies are calculated with respect to the 50th percentile February climatology from the SST Atlas of Australian Regional Seas (SSTAARS¹²⁶). **b** | February 2019 SSTAARS SST percentiles, where the percentiles are centred on mid-February and constructed over 60 days. The region off eastern Tasmania is shown by a white box. **c** | Subsurface temperature measured by a Slocum glider, deployed 13 February 2019 in the north and recovered 9 March 2019 in the south. The temperatures and ocean-current velocities (subsampling) along 40.8°S and along 155 m depth are the 13–28 February 2019 means derived from the 10-km resolution *BlueLink* ReAnalysis (BRAN)-2015 (REF.¹²⁷). The current velocities are shaded according to their depth and consistent with the shading of isobaths plotted every 50 m (black to light grey). SST data in panel **a** and Slocum glider data in panel **b** are from the Australian Ocean Data Network (AODN) Portal (<https://portal.aodn.org.au/>). Coastline data in panel **c** are from REF.¹²⁸.

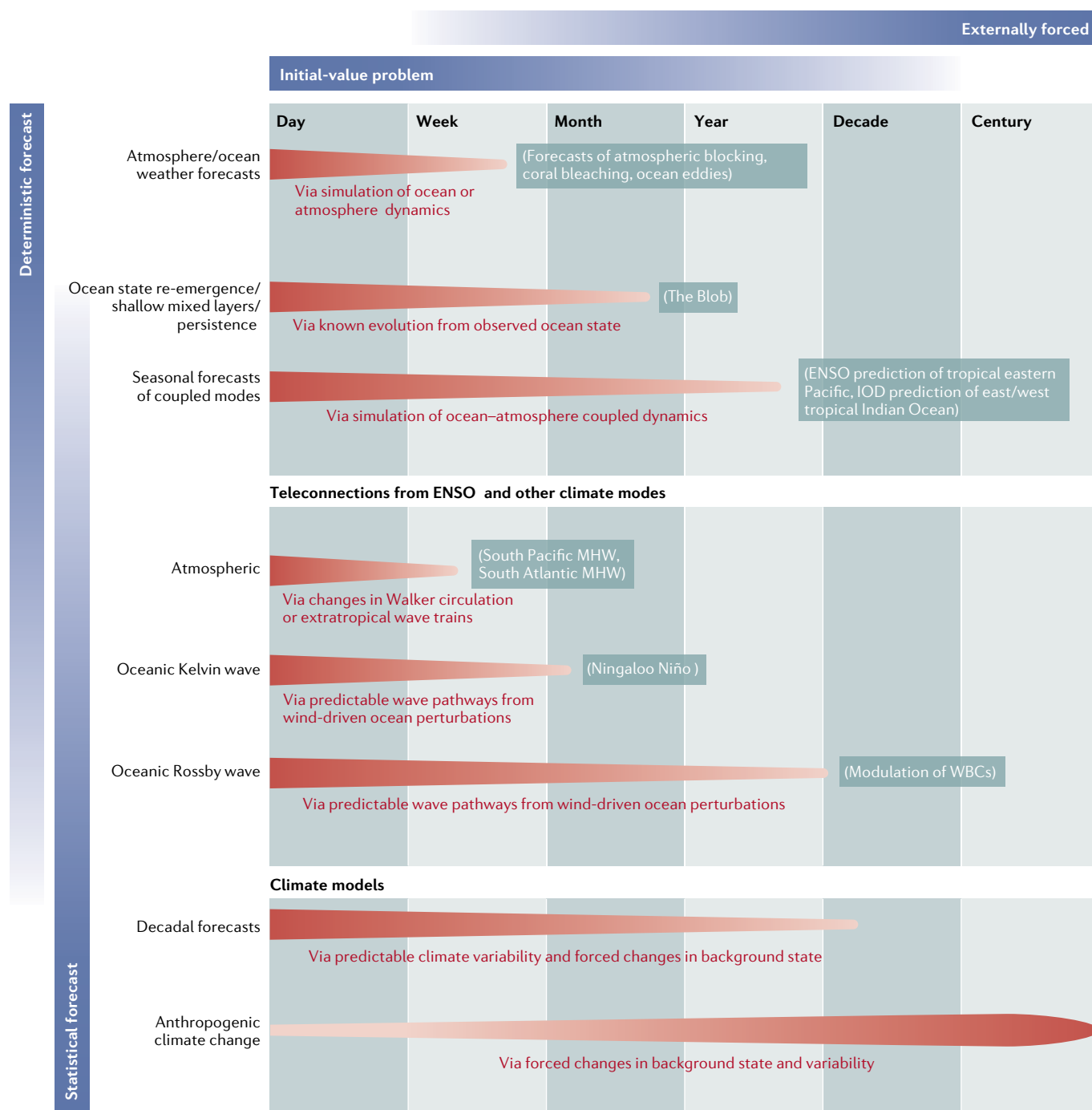


Fig. 5 | **Marine heatwave potential predictability and forecast timescales.** A spectrum of marine heatwave (MHW) prediction timescales and types ranging from initialized forecasts, which predict specific events (deterministic forecasts), through to externally forced projections, in which scenarios can be used to explore changed statistical probabilities of MHW likelihoods (statistical forecasts). The red horizontal bars provide indicative timescales of predictability for each prediction system type, where increasing opacity corresponds to increasing confidence in the prediction skill for that lead time. ENSO, El Niño–Southern Oscillation; IOD, Indian Ocean Dipole; WBCs, western boundary currents.

fisheries and aquaculture, recreational activities and biodiversity conservation³. However, marine governance and management practices for responding to a rapidly changing climate are in early stages of development⁸⁹, and a wider range of tools and strategies will be needed to adapt to and mitigate against future MHWs⁹⁰.

Although a reactive response can limit the damage to some industries, such as aquaculture, in other cases, it might be too late. For example, wild abalone in a MHW would likely be in poor condition and unable to be harvested.

Proactive responses to these extreme events — which include passive approaches

such as catchment management, fishing restrictions and identification of marine protected areas — can be implemented by marine managers if sufficient warning is provided⁹¹. These approaches aim to increase the resilience of marine ecosystems by limiting exposure to stressors that compound the impact of warming, such as

overfishing, eutrophication and pollution^{92,93}, or protecting natural ecological processes such as predation and herbivory, which confer ecosystem resistance to change^{94,95}. However, passive approaches can be slow or inefficient⁹⁶.

By contrast, active interventions seek to maintain or re-establish ecosystems or key ecosystem services through direct manipulation, ranging from habitat rehabilitation and restoration through to assisted migration, species replacements and assisted evolution^{97–99}. Although some of these options are ethically contentious, they may be essential for ensuring the long-term survival of vulnerable marine ecosystems¹⁰⁰, which are under threat from increased MHWs.

The performance of many marine industries is related to the occurrence of favourable environmental conditions, including suitable habitats. Aquaculture requires water temperatures to remain within tolerance limits of the farmed species, while fisheries often rely on species that relocate in response to changing

environmental conditions. Warm waters can lead to the arrival of new species, providing opportunity for commercial and recreational fishers. Marine habitats that support fisheries and tourism activities might be damaged or enhanced by anomalous conditions, with coral bleaching a well-known detrimental example. Extreme conditions such as MHWs shock systems and present challenges for managing economic enterprises dependent on the ocean (BOX 2). Information about the likelihood of MHW occurrence is, therefore, valuable to a wide range of marine communities, and decisions can be made to take advantage of opportunities or minimize losses. Importantly, the availability of future environmental information can differentially advantage some groups over others, so decisions about information dissemination should be made with this in mind¹⁸⁴. One way to minimize differences between stakeholders is to provide transparent and equitable access to information.

Experience to date suggests that three elements assist stakeholders in making the best decisions with forecasts. First,

proactive planning of responses enables end users of the forecasts to evaluate different response options depending on factors such as lead time. This process can allow clear options to be considered when a forecast for undesirable conditions is issued and can be undertaken as part of business-planning cycles. Second, dedicated training and information sessions are essential to understand the skill and uncertainty requirements for users⁸⁴. Such sessions could potentially involve simulation activities to explore different responses to extreme events to build the capacity of stakeholders, including those from industry. Finally, implementation of risk-based responses must be considered when skill is low and uncertainty is high. For example, a forecasted MHW that might impact production could be met with a partial early harvest of the vulnerable species, rather than a full harvest⁸⁴.

Communication and engagement. While awareness about MHWs is rapidly increasing in the scientific community,

Box 2 | Marine heatwaves as a stress test for management systems

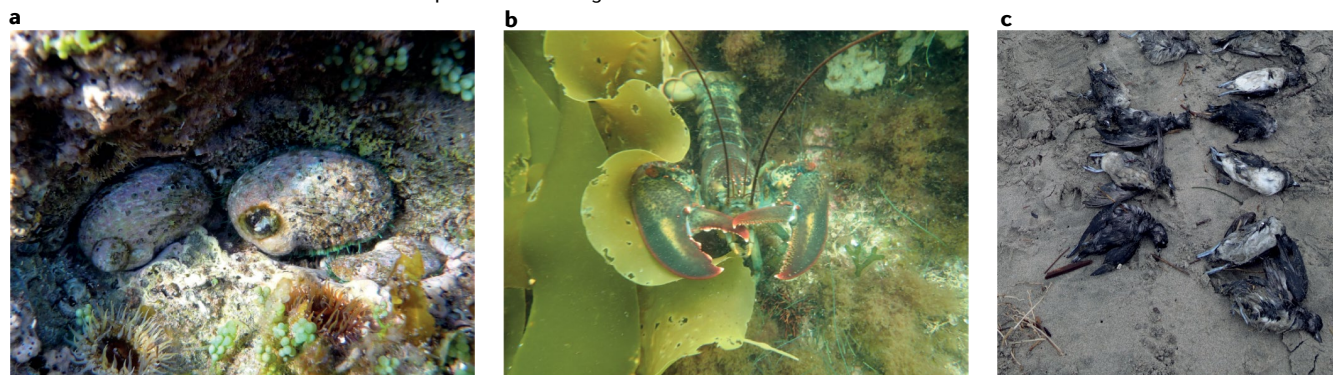
Three well-known marine heatwaves (MHWs) challenged existing management approaches owing to their intensity, duration and rapid onset. The 2011 Western Australia MHW resulted in mass mortality of Roe's abalone, and, in response, managers closed the fishery and instituted an outplanting approach in the years following the event. Scallop fisheries in the region affected by the MHW were closed for 3–5 years, while the Shark Bay crab fishery was closed for 18 months²⁴. This event tested assessment and management responses and showed that flexible harvest strategies (as well as early detection and monitoring of the MHW) allowed for early management intervention²⁴.

The 2012 Gulf of Maine MHW revealed unexpected connections between the natural and human components of the ecosystem¹³⁰. Early and above-average landings in a valuable lobster fishery led to a backlog in the supply chain and a drop in lobster price; exacerbating the supply chain bottleneck was the fact that the Canadian lobster fishery also had unusually high spring landings. The joint impact was low prices on both sides of the border, accompanied by Canadian protests and blockades of lobster imports coming from Maine. The management system was unable to respond to the 2012 event but made changes that meant another MHW in 2016 did not cause the same impacts. These changes

included the development of seasonal forecasting approaches to provide warning of future events.

A large MHW in the northeast Pacific ('The Blob') appeared off the coast of Alaska in the winter of 2013/14 and subsequently stretched south to Baja California. This event persisted through to the end of 2015. Mass strandings of marine mammals and seabirds occurred along the west coast of the United States and Canada³³. Several thousand California sea lions died on beaches following shortages of forage fish. More than 50,000 Cassin's auklets were estimated to have starved and been washed ashore beginning in September 2014. These dying and dead animals stressed animal-rescue arrangements, pathology testing and management responses.

All the examples of MHWs above required rapid and novel responses, which can be difficult if policy or legislative barriers exist. In the cases where flexible instruments were already in place, such as in Western Australia, the management system coped better, even under persistent impacts. In other cases, improvements were not realized until the next event. Learning from these stress tests will improve management under climate variability and change and better prepare marine managers for the future when more extreme ocean temperatures will be the 'new normal'.



Figure, part a, Roe's abalone: image courtesy of Anthony Hart, DPIRD-Mollusc Science; part b Maine lobster: image courtesy of Andrew Pershing-Gulf, Maine Research Institute; part c Cassin's auklets: image courtesy of L. Doyle/COASST, Julia Parrish.

much of the information can be considered technical and relatively inaccessible to stakeholders in fisheries, aquaculture, tourism and biodiversity conservation. The full potential of increased predictive capacity will be contingent on rapid dissemination and uptake across these relevant stakeholders. The first step towards rapid dissemination is streamlining and simplifying the information given. In this context, experience from other types of extreme events such as tropical cyclones and earthquakes shows that consistent naming conventions and intuitive classification schemes for attributing relative magnitude can be effective¹⁰¹. To this end, the MHW severity-classification scheme¹⁰¹ and information provided by this approach is already seeing uptake^{24,102}, and we recommend that this framework be used in communicating MHWs to stakeholders. The second step towards dissemination is to generate a central repository for MHW information and news, which can serve as an interface between stakeholders and scientists. The [MHW website](#) is one such example, and other regional engagement websites are also emerging. Such initiatives need to be expanded to include information targeting specific stakeholders — so-called targeted forecasts. Finally, using available temperature products, near real-time visualization of ongoing MHWs allows intuitive understanding of the dynamics of near-future and ongoing MHWs. Although a ‘[Marine Heatwave Tracker](#)’ is currently available in a web-based format, additional stakeholder-suited delivery mechanisms, such as smartphone applications, may be needed. With all these elements in place, predictable MHW events will allow proactive responses by potentially affected marine stakeholders, leading to improved marine management.

Establishing baselines. Globally, the increased frequency of MHWs is due primarily to the warming trend^{35,103}. It has been suggested that baselines should also shift when analysing MHW events under climate change¹⁰⁴. While using a shifting baseline period can be beneficial for analysing the underlying variability in MHW occurrence over time and its dynamics, ecosystem impacts from climate change are likely to be best understood if we consider changes against a fixed baseline. A baseline that shifts in line with a species’ adaptive capabilities may be suitable in some cases, as the impact of MHWs on marine species often critically depends on the rate of change in absolute temperature, above

the species’ thermal limits¹⁰⁵. It might be that some species have no capacity to adapt on short timescales, given the rapidity of temperature change, while other species can adapt either fully or perhaps partially. These differences in adaptation rates should be taken into consideration when designing baselines as fixed or shifting, and when interpreting the impacts of rapid temperature change.

Conversely, future advances in our understanding of shifts in dynamical processes might require subsequent updates of the baseline period. One way of at least partially addressing these issues is the use of MHW categories¹⁰¹, where the introduction of new extreme categories can be considered and analysed with respect to their drivers, even when the baseline remains fixed. Whether to fix or shift baselines depends on the key questions being asked and is the subject of ongoing discussion and debate¹⁰⁴, and remains a fertile area for research and consideration.

Keeping pace with climate change. The rapidly growing awareness of MHWs and their increasing impact is a harbinger of the pace of climate change. In the Tasman Sea alone, three of the four summers between 2015/16 and 2018/19 have seen substantial MHW events, two of which were driven by the presence of large and persistent high-pressure blocking events. Given that blocking events are apparently becoming more frequent and pervasive as a result of climate change^{106,107}, we can expect blocking to remain a critical mechanism for driving large-scale MHWs into the future.

Over the coming decades, MHWs will become more frequent, longer in duration and/or more intense across much of the globe^{36,37}. These projected changes represent threats to the health and sustainability of marine ecosystems globally^{3,108,109}. Addressing this challenge will require significant action. It will require not only coordinated global commitment to reduce greenhouse-gas emissions but also governance arrangements that support novel adaptation strategies, including protecting refugia for foundation marine species of coral, kelp and seagrass that provide essential habitats to marine ecosystems. Although skilful MHW prediction will require improved process-based understanding of MHWs and their drivers, forecasting ecosystem impacts¹¹⁰ requires physiological understanding of species’ thermal sensitivity and critical thresholds, and how these link to other stressors. Coupling action between mitigation and adaptation will require

creative solutions, spanning traditional disciplinary boundaries to protect and sustain our marine ecosystems and the services they provide. The utility of proactive decision-making will be facilitated by skilful MHW prediction and approaches will need to be adaptive to keep pace with MHW changes in a warming world.

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Author contributions

N.J.H. led the overall conceptual design, led the activity and coordinated the writing. A.S.G. generated Figs 1, 3 and 5. E.C.J.O. generated Fig. 2. J.A.B. generated Fig. 4. A.J.H. led the conceptual design for Box 2 and Table 1. All authors discussed the concepts presented and contributed to the writing.

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