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Marine Heatwaves

Eric C.J. Oliver,[1] Jessica A. Benthuysen,[2] Sofia Darmaraki,[1] Markus G. Donat,[3] Alistair J. Hobday,[4] Neil J. Holbrook,[5,6] Robert W. Schlegel,[1,7] and Alex Sen Gupta[8,9]

[1]Department of Oceanography, Dalhousie University, Halifax, Nova Scotia B3H 4R2, Canada; email: eric.oliver@dal.ca

[2]Australian Institute of Marine Science, Crawley, Western Australia 6009, Australia

[3]Barcelona Supercomputing Center, 08034 Barcelona, Spain

[4]CSIRO Oceans and Atmosphere, Hobart, Tasmania 7000, Australia

[5]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania 7001, Australia

[6]Australian Research Council Centre of Excellence for Climate Extremes, University of Tasmania, Hobart, Tasmania 7001, Australia

[7]Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA

[8]Climate Change Research Centre, The University of New South Wales, Sydney, New South Wales 2052, Australia

[9]Australian Research Council Centre of Excellence for Climate Extremes, The University of New South Wales, Sydney, New South Wales 2052, Australia

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Keywords

climate extremes, sea surface temperature, climate change, mixed-layer dynamics, ocean circulation, air–sea heat flux, climate variability

Abstract

Ocean temperature variability is a fundamental component of the Earth's climate system, and extremes in this variability affect the health of marine ecosystems around the world. The study of marine heatwaves has emerged as a rapidly growing field of research, given notable extreme warm-water events that have occurred against a background trend of global ocean warming. This review summarizes the latest physical and statistical understanding of marine heatwaves based on how they are identified, defined, characterized, and monitored through remotely sensed and in situ data sets. We describe the physical mechanisms that cause marine heatwaves, along with their global distribution, variability, and trends. Finally, we discuss current issues in this developing research area, including considerations related to the

choice of climatological baseline periods in defining extremes and how to communicate findings in the context of societal needs.

1. INTRODUCTION

Marine heatwaves (MHWs)—a term first used by Pearce et al. (2011)—are anomalous warm seawater events that can substantially affect marine ecosystems. An MHW is qualitatively defined as a discrete period of prolonged anomalously warm water at a particular location, and quantitative definitions are based on ocean temperatures exceeding a fixed (Frölicher et al. 2018), seasonally varying (Hobday et al. 2016), or cumulative (Eakin et al. 2010) threshold. MHWs are caused by a combination of local oceanic and atmospheric processes, including air–sea heat flux and horizontal temperature advection, and may be modulated by large-scale climate variability, including remote sources via teleconnections (Holbrook et al. 2019). MHWs have been identified primarily using ocean surface temperatures, although they may also extend below the surface (Schaeffer & Roughan 2017). The global count of MHW days per year has risen over the historical record due to increases in MHW duration and frequency (Oliver et al. 2018a). This trend is projected to increase further under climate change (Frölicher et al. 2018, Oliver et al. 2019) as a consequence of long-term ocean warming.

Marine heatwave (MHW): a discrete period of prolonged anomalously warm water at a particular location

Threshold: a temperature value, which may be fixed or vary over time and/or space, above which temperatures are considered anomalously warm in defining MHWs

Air–sea heat flux: turbulent (sensible and latent) and radiative (longwave and shortwave) exchanges of heat between the ocean and atmosphere

Temperature advection: a local temperature change due to the action of ocean currents in the presence of a spatial gradient in temperature, which may act in the horizontal (e.g., geostrophic boundary currents, wind-driven Ekman flows) or the vertical (e.g., upwelling/downwelling)

MHW duration: the time from the start date to the end date of an MHW

The study of MHWs as discrete events is motivated largely by their ecological and socioeconomic impacts. The study of sea surface temperature (SST) variability has a long history in physical oceanography and climate science (Philander 1983, Deser et al. 2010), and understanding the effects of warm ocean temperature extremes on marine ecosystems is vitally important (Garrabou et al. 2009, Mills et al. 2013, Wernberg et al. 2013, Smale et al. 2019, Benthuysen et al. 2020). Specifically, studies of MHWs are set apart from studies of SST variability more broadly in that they examine the aspects of SST variability that affect marine ecosystems, rather than just the physical and climatic properties of ocean temperature variability.

Here, we critically review our current understanding of MHWs from a physical and climatological perspective. We review the definitions of MHWs, data sets useful for monitoring them, the physical processes causing MHWs, and their statistical properties. We examine the global distribution of MHWs, including characteristics of their variability and trends, and the role of anthropogenic change. The field of MHWs has grown as events continue to occur that have broad impacts across marine ecosystems and socioeconomic systems, raising issues of how best to communicate about MHWs and the most appropriate way to define MHWs in a warming ocean.

2. A BRIEF HISTORY OF RECENT HIGH-IMPACT EVENTS

While anomalously warm seawater events are not a new phenomenon, they have occurred with increasing frequency and duration over the past century (Oliver et al. 2018a) and have had significant impacts on marine ecosystems. The global-scale coral bleaching events of 1998, 2010, and most recently 2014–2017 occurred with El Niño conditions and globally elevated ocean temperatures (Eakin et al. 2019). The increased occurrence of extreme warm-water events across the globe has focused efforts toward examining events within a common framework. Over the past two decades, analyses of prominent MHW events (**Figure 1**) have revealed that they are often caused by compounding influences of atmospheric forcing and/or oceanic processes. Furthermore, the phase of climate modes of variability can act to increase or decrease the likelihood of MHW occurrence regionally (Holbrook et al. 2019). Here, we highlight notable events that have been attributed to local changes in air–sea heat fluxes, ocean heat transport, or remote forcing via teleconnections.

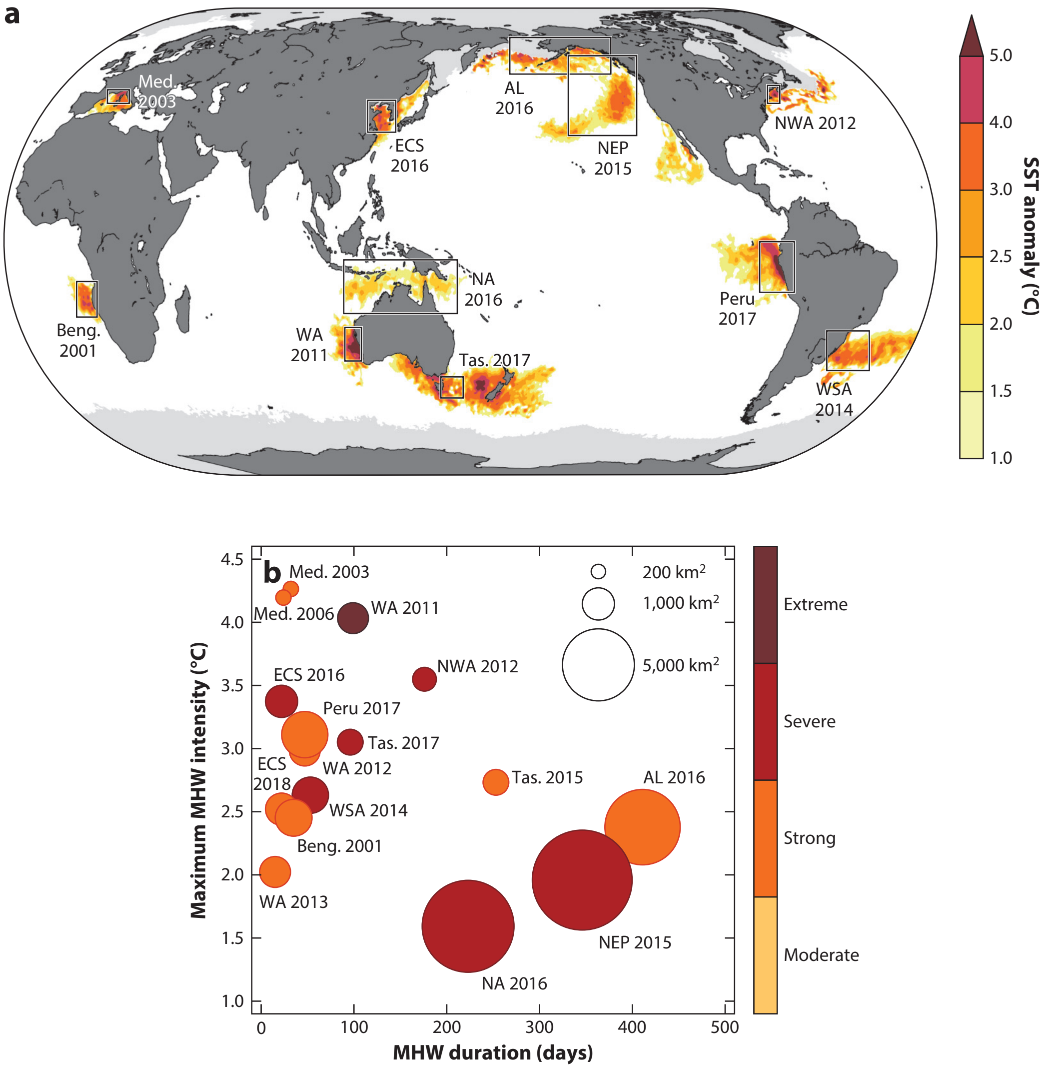

Figure 1

Key historical MHWs. (*a*) SST anomalies on the day of peak MHW intensity. MHW intensity was defined based on the time series of SST averaged over the regions indicated by the black boxes. Light gray indicates areas of sea ice influence. (*b*) MHW properties for key historical events. The MHW intensity (*y* axis), MHW duration (*x* axis), and category (*color*; see Hobday et al. 2018a) were determined from the spatially averaged time series, as in panel *a*. The MHW area (*circle size*) is the total contiguous area reaching at least category 2 (strong). All events shown in panel *b* are referenced in Section 2. Abbreviations: AL, Gulf of Alaska and Bering Sea; Beng., Benguela; ECS, East China Sea; Med., Mediterranean; NA, northern Australia; MHW, marine heatwave; NEP, northeast Pacific; NWA, northwest Atlantic; SST, sea surface temperature; Tas., Tasman Sea; WA, Western Australia; WSA, western South Atlantic. Panel *a* inspired by a schematic from Frölicher & Laufkötter (2018).

Record-breaking MHWs have been documented where the atmospheric state played a central role in their development and maintenance. Examples of such events include those in the Mediterranean Sea during the summers of 2003 (Olita et al. 2007) and 2006 (Bensoussan et al. 2010), off the northeast coast of the United States in 2012 (Chen et al. 2014, 2015), from the southeast tropical Indian Ocean to the Coral Sea in 2015–2016 (Benthuysen et al. 2018), in the East China Sea in

2016 (Tan & Cai 2018), along the southwest Atlantic shelf in 2017 (Manta et al. 2018), off coastal Peru in 2017 (Echevin et al. 2018), and in the Tasman Sea in 2017–2018 (Perkins-Kirkpatrick et al. 2019, Salinger et al. 2019). In these cases, the anomalously warm ocean temperatures were related to abnormally high air–sea heat fluxes into the ocean.

Climate modes of variability: recurrent spatial patterns of specific climate variables, often quasi-periodic or broad-banded and occurring on subseasonal, interannual, decadal, multidecadal, centennial, millennial, or longer timescales

MHW intensity: the temperature anomaly (based on the maximum or mean value) during an MHW

Anomaly: a deviation of temperature from the climatological mean

Other MHWs have been found to be caused primarily by anomalous ocean heat transport, such as the MHWs in the Angola Benguela Upwelling System in 2001 (Rouault et al. 2007), off Western Australia in early 2011 (Feng et al. 2013, Benthuysen et al. 2014), in the Tasman Sea in 2015–2016 (Oliver et al. 2017), and in the Middle Atlantic Bight (Gawarkiewicz et al. 2019) and off Japan (Sugimoto et al. 2020) in 2017. In addition, large-scale MHWs have developed through a combination of multiple interacting mechanisms. Most notably, the 2014–2016 MHW affected the Pacific and was linked to tropical–extratropical teleconnections (Bond et al. 2015, Di Lorenzo & Mantua 2016, Hu et al. 2017, Tseng et al. 2017). Other events have been associated with substantial retreat in Arctic sea ice (e.g., the Gulf of Alaska and the Bering Sea in 2016; Walsh et al. 2018, Oliver et al. 2018b). There is an increasing interest in such events that span across systems, including the ocean, atmosphere, land, and cryosphere (e.g., Ruthrof et al. 2018).

While these recent MHWs had varying intensities, durations, and spatial extents (**Figure 1*b***), they have all been linked with disruptive changes in marine ecosystems (Wernberg et al. 2016, Hughes et al. 2017, Smale et al. 2019) and commercial fisheries (Mills et al. 2013, Caputi et al. 2016, Jacox et al. 2019). It should be noted that MHWs are distinct from otherwise anomalously warm years. Smale et al. (2019) pointed out that, while most recent research has been on the ecological effects of mean climate variables, discrete events have emerged as critical factors driving rapid shifts in ecosystems. These issues highlight the need for consistent MHW detection methods, frameworks for understanding their physical drivers, and accurate dynamical and statistical models for predicting future events.

3. DEFINING AND MONITORING MARINE HEATWAVES

3.1. Defining a Marine Heatwave

Extreme events are climate anomalies that are rare and have magnitudes that deviate significantly from typical conditions in a region. The statistics of extremes, those that describe the tails of a probability distribution, have traditionally been examined using extreme value theory (Gumbel 1958, Leadbetter et al. 1983, Coles 2001). Extreme value theory examines the distribution of extreme values in a time series by assuming the data are distributed according to certain probability distributions, such as the generalized extreme value (for block-maxima extremes, e.g., the annual maxima in **Figure 2**) or the generalized Pareto distribution (for peak-over-threshold extremes). The fitted distribution can be used to estimate the return periods or return levels of extreme events. Extreme value theory has not been widely applied to study temperature extremes in the ocean (e.g., Oliver et al. 2014a,b).

More recently, methods for detecting ocean temperature extremes have used a threshold above which any contiguous days of temperature are considered to be a single event. In this analysis, the important choice is in defining the threshold, either fixed in time or allowed to vary seasonally or on longer timescales. Fixed thresholds can be defined by an absolute temperature (**Figure 2*a***), informed by marine species' upper thermal limits (the temperatures above which biological functions become impaired). For example, cumulative temperatures above an absolute threshold have been used for coral bleaching studies (e.g., degree heating days, weeks, and months; Liu et al. 2014). Temporally fixed thresholds can be defined using a relative measure of the temperature variance (e.g., quantiles). While these thresholds are fixed in time, similar

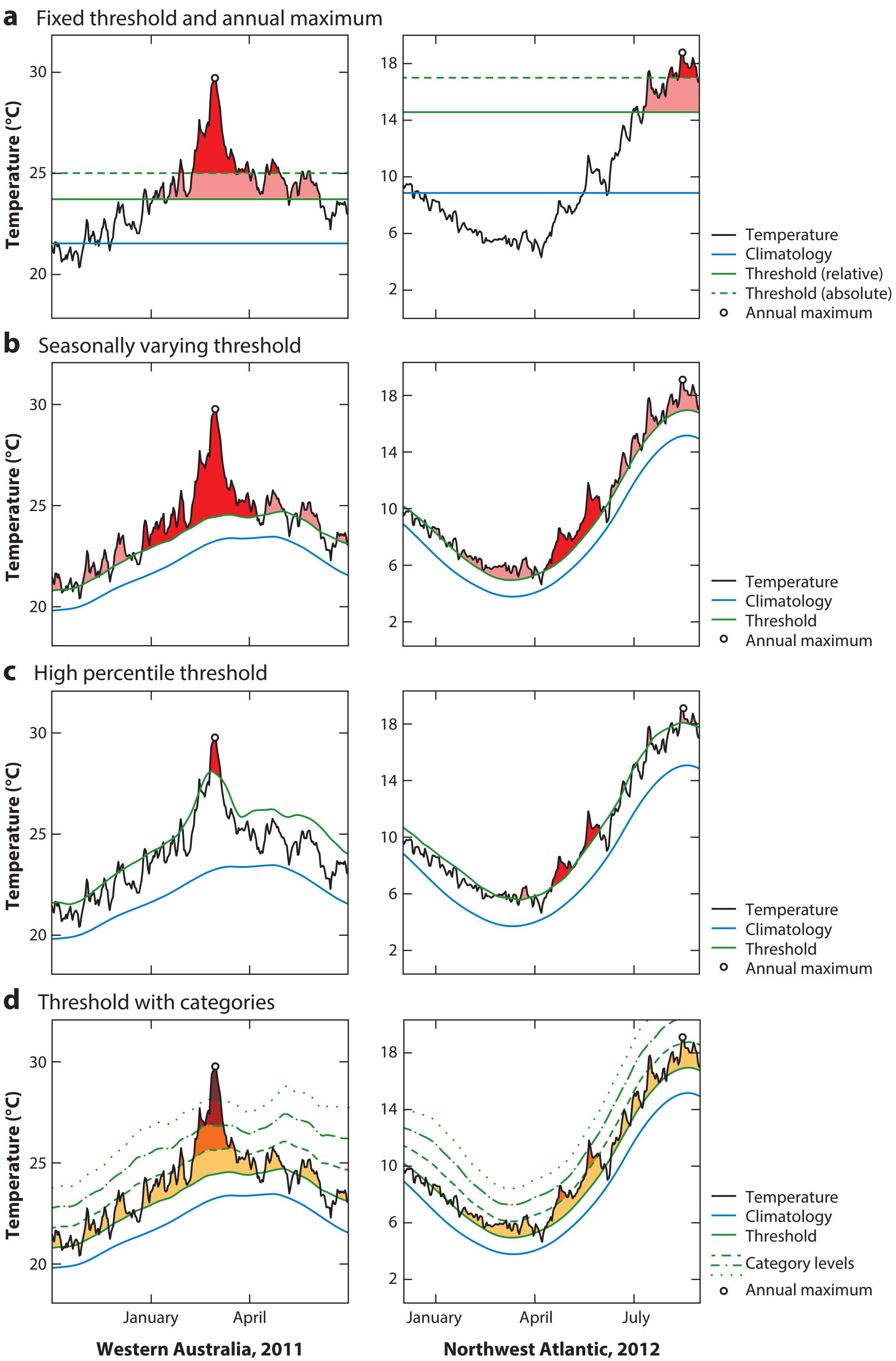

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Figure 2 (*Figure appears on preceding page*)

Different methods of detecting extreme temperatures for the 2011 Western Australia MHW (Pearce & Feng 2013) (*left column*) and 2012 northwest Atlantic MHW (Mills et al. 2013) (*right column*). (*a*) Fixed thresholds—defined either by an absolute temperature (here set at 25°C for Western Australia and 17°C for the northwest Atlantic; *dashed green lines*) or a fixed percentile threshold (here the 90th percentile; *solid green lines*)—and annual maximum temperature values (*white circles*) work well for detecting events during the warm season (as in Western Australia in 2011) but are poor indicators of anomalous conditions during other seasons (as in the northwest Atlantic in 2012). (*b*) Seasonally varying percentile thresholds, such as the Hobday et al. (2016) definition using the 90th percentile, allow detection of MHWs as anomalously warm temperatures during warm and cool seasons (including both the 2011 Western Australia MHW and the 2012 northwest Atlantic MHW). (*c*) Increasing the threshold—for example, by using the 99th percentile instead of the 90th—isolates only the most extreme events. (*d*) The categorization scheme, proposed by Hobday et al. (2018a), permits the use of a lower percentile threshold while identifying category levels of increasing intensity. The climatology was calculated using NOAA OI SST V2.0 data with a baseline period of 30 years (1983–2012). Abbreviations: MHW, marine heatwave; NOAA OI SST V2.0, National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature version 2.0.

to the absolute thresholds, this measure allows the definition of extreme to come from the time series data distribution itself (**Figure 2*a***). This approach may be less applicable to a single species, but the results represent a more general quantification of what is extreme in the local context. Fixed thresholds typically only identify warm-season MHWs (e.g., coral bleaching thresholds; Fordyce et al. 2019). However, extremely warm temperatures in other seasons may have important consequences for the life cycle and survival of marine species (e.g., the survival of invasive warm-water species in winter; Ling et al. 2009). Temperatures below a lower threshold are known as marine cold spells (see the sidebar titled Marine Cold Spells).

Climatology: the statistical properties of a time series defined over an extended period (e.g., 30 years), including the mean, seasonal cycle, variance, and quantiles

Baseline period: the time period used to calculate a climatology, traditionally taken to be a 30-year period, following World Meteorological Organization recommendations

A more versatile method to identify MHWs uses a seasonally varying climatological threshold (**Figure 2*b***). The climatology is calculated over a chosen baseline period, preferably a 30-year temperature time series (WMO 2018). The method defined by Hobday et al. (2016) uses a local daily upper-percentile climatology as the threshold above which MHWs are detected, consistent with atmospheric heatwave definitions (Perkins & Alexander 2013). A 90th-percentile threshold results in a relatively large number of MHW events, and some weak, short-lived events may not result in ecological consequences. One solution is to use a higher threshold, such as the 99th percentile (Frölicher et al. 2018, Collins et al. 2019) (**Figure 2*c***). This method identifies more intense MHWs but requires a longer observational record to estimate the threshold in a robust way, which can be problematic given the limitations of many observational records (see Section 3.2).

MARINE COLD SPELLS

Prolonged ocean temperatures in the lower tail of the temperature distribution are known as marine cold spells (MCSs) and may be defined analogously to MHWs by their exceedance of temperatures below a percentile threshold for a prolonged period (Schlegel et al. 2017). MCSs can be driven by intense upwelling or atmospheric forcing (e.g., cold-air outbreaks or storm-induced mixing). Severe MCSs can cause fish kills and invertebrate mortality and can pose risks to coral reefs (Gunter 1951, Roberts et al. 1982, Holt & Holt 1983, Firth et al. 2011, Paz-García et al. 2012). Higher-latitude systems have some resilience (Tuckett & Wernberg 2018), and MCSs may have historically inhibited the tropicalization of temperate ecosystems (Leriorato & Nakamura 2019). MCSs have also been implicated as a controlling factor in ecosystem shifts between salt marshes and mangroves (Cavanaugh et al. 2019).

Hobday et al. (2018a) provided a refined definition that categorizes the severity of an MHW and allows for the identification of the more extreme events. Categories are delineated by the number of times the maximum observed temperature anomaly is greater than the difference between the climatological mean and the 90th-percentile threshold (**Figure 2*d***). This approach results in a simple numbered system from category 1 (moderate) to 4 (extreme) that can be used to monitor an ongoing event or applied retrospectively given the maximum value reached.

Once a definition is chosen, a suite of metrics defines characteristics of each event. These metrics include intensity (e.g., temperature anomaly relative to the climatological mean), duration (time between start and end dates), and cumulative intensity (the intensity integrated over the duration of the event, analogous to degree heating days).

There are limitations with each type of MHW definition. The research questions and their application are important factors for selecting a definition, and the availability of long time series data is important for determining reference periods and thresholds.

3.2. Available Data Sets

Temperature data with daily resolution are ideal to identify and characterize MHWs in a consistent way. In addition, the data time period needs to be sufficiently long for estimating a climatology (ideally a minimum of 30 years; e.g., WMO 2018). However, Schlegel et al. (2019) showed that as few as 10 years of data may be sufficient for constraining the climatology, and recent studies have used fewer data, from short records or those with temporal gaps, to identify MHWs (e.g., Oliver et al. 2017).

Most studies have characterized MHWs using available SST products (see **Table 1**). Satellite-based SST data sets provide global, continuous, multidecadal, and near-real-time products for the study of MHWs. On local to regional scales, high-frequency subsurface ocean temperatures can be used to construct climatologies and analyze MHW characteristics (e.g., Schaeffer & Roughan 2017, Benthuysen et al. 2018, Elzahaby & Schaeffer 2019). However, subsurface measurements are generally available only in select locations (i.e., long-term moorings) or at a lower temporal resolution from depth-profiling drifting floats (e.g., Argo) or gliders. In fact, little is known about the characteristics of MHWs below the ocean surface due to sparsely collected data. Therefore, despite the notable importance of these events for benthic ecosystems, systematic studies of subsurface MHWs are difficult to undertake robustly.

When daily temperature data are not available (e.g., some seasonal forecasts and climate models save only monthly data), the ability to apply the formal MHW definitions is limited, given the necessity for daily measurements. However, such data have been used to examine longer-lasting MHWs in order to monitor coral bleaching risk (e.g., Donner et al. 2005) and perform seasonal forecasting of major events (Doi et al. 2013, Spillman et al. 2013, Jacox et al. 2019). In addition, the monthly temperature variations offer statistical insight into the frequency of extremes, a property that has been used to develop centennial-scale proxies of MHW properties globally (Oliver et al. 2018a).

In global ocean and climate models, SSTs and MHW estimates may have biases if subgrid-scale processes are not represented (e.g., Pilo et al. 2019) or do not include feedback from air–sea heat coupling (e.g., Frankignoul 1985). While data sets derived from observations, even coarsely resolved ones, inherently represent the physical processes of the natural world, coarse-resolution ocean models are challenged in representing ocean temperatures at the local scale. In global climate models, issues in representing boundary currents, eddies, teleconnections, coastal processes, and interannual-to-decadal variability will affect SST patterns (e.g., Cai & Cowan 2013, Taschetto

Table 1 Ocean temperature data types along with their temporal coverage, spatial resolution, general strengths and weaknesses, and example products

Data set type	Earliest start date	Spatial resolution	Strengths	Weaknesses	Examples
Observations					
In situ (stationary)	Around 1900	Local	Accurate representation of local temperatures; several long records available; includes surface and subsurface measurements (in some cases)	Representation very spatially restricted; subject to missing data or changes in technology over time; some records too short to constrain a climatology	Scripps Shore Stations Program (USA), British Columbia Shore Station Oceanographic Program (Canada), Arendal Institute of Marine Research (Norway), South African Coastal Temperature Network
In situ (passive movement)	Late twentieth century	Local to basin scale	Large spatial coverage; includes surface and subsurface measurements	Lagrangian in nature, which complicates analysis; instruments cannot be directed to sample a specific area of interest	Surface drifting buoys, Argo floats
In situ (active movement)	Early twenty-first century	Local to basin scale	Missions can target events as they occur; includes surface and subsurface measurements; other physical and biogeochemical parameters also typically measured	Data lack the spatiotemporal context outside the mission period and location; requires many missions to build up a time series for a particular location	Gliders, ships of opportunity (various missions and groups worldwide)
Remotely sensed (satellite: infrared, microwave)	1979	1–25 km	Global; continuous; near real time; high frequency (daily to weekly)	May not accurately resolve coastal temperatures	NOAA OI SST, CoralTemp, CCI-SST, GHRSST
Statistically analyzed observations (bin averaged)	Late nineteenth century	5°	Global; long records; quantification of uncertainty	Low frequency (monthly); missing data in space and time	HadSST3, HadSST4
Statistically analyzed observations (interpolated)	Late nineteenth century	1–2°	Global; continuous; long records; quantification of uncertainty (in some cases)	Low frequency (monthly); data values in the absence of observations are weakly constrained	HadISST, ERSST, COBE2
Reanalyses					
Eddy-resolving ocean reanalysis	1993	1/12–1/4°	Global; continuous; quantification of uncertainty (in some cases); complete three-dimensional ocean state estimated (temperature, salinity, and velocities)	Data values in the absence of observations are weakly constrained	GLORYS, HYCOM, BRAN

(*Continued*)

Table 1 (*Continued*)

Data set type	Earliest start date	Spatial resolution	Strengths	Weaknesses	Examples
Coarse-scale ocean reanalyses	Around 1900	1/2–1°	Global; continuous; long records; quantification of uncertainty (in some cases); complete three-dimensional ocean state estimated (temperature, salinity, and velocities)	Subgrid-scale physical processes are not resolved; data in the absence of observations, most notably in earlier time periods, are only very weakly constrained	SODA, CERA-20C, GODAS
Numerical models					
Eddy-permitting and eddy-resolving ocean models	Various	1/4° or finer	Dynamically consistent data allow for an accurate exploration of physical processes; resolves important physical processes, including eddies and coastal processes	Free running models are not constrained to represent the timing of the observational record	Many modeling groups worldwide
Coarse-scale ocean models	Various	Coarser than 1/4°	Dynamically consistent data allow for an accurate exploration of physical processes	Free running models are not constrained to represent the timing of the observational record; subgrid-scale physical processes are not resolved	Many modeling groups worldwide
Global and regional climate models	Various	1/2–2°	Dynamically consistent data allow for an accurate exploration of physical processes, including a representation of the complete, coupled climate system (ocean, atmosphere, cryosphere, etc.); can separate the natural and anthropogenic influences on MHWs	Free running models are not constrained to represent the timing of the observational record; subgrid-scale physical processes are not resolved	CMIP5, CMIP6, CORDEX

Beggs (2020) provides further details on many specific observational SST data sets. Abbreviations: BRAN, Bluelink Reanalysis; CCI-SST, Climate Change Initiative Sea Surface Temperature; CERA-20C, Coupled Ocean-Atmosphere Reanalysis of the 20th Century; CMIP5/6, Coupled Model Intercomparison Project Phase 5/6; COBE2, Centennial In Situ Observation-Based Estimates 2; ERSST, Extended Reconstructed Sea Surface Temperature; GHRSST, Group for High Resolution Sea Surface Temperature; GLORYS, Global Ocean Reanalysis and Simulation; GODAS, Global Ocean Data Assimilation System; HadISST, Hadley Centre Sea Ice and Sea Surface Temperature; HadSST3, Hadley Centre Sea Surface Temperature; HYCOM, Hybrid Coordinate Ocean Model; MHW, marine heatwave; NOAA OI SST, National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature; SODA, Simple Ocean Data Assimilation; SST, sea surface temperature.

et al. 2014, Sen Gupta et al. 2016, Power et al. 2017). These shortcomings may be mitigated by bias correction of the SST time series (e.g., Oliver et al. 2017, Pilo et al. 2019), but such an approach corrects only for the statistical aspects of the bias and not the underlying issues of poorly captured or unrepresented physical processes. Increases in model resolution and process parameterization may provide some improvements in this regard [e.g., Coupled Model Intercomparison Project Phase 6 (CMIP6); Eyring et al. 2016].

Surface mixed layer: the upper layer of the ocean, in contact with the atmosphere, which has a nearly uniform density over its depth due to turbulent mixing

Mixed-layer temperature budget: the theoretical balance of physical processes that cause temperature changes in the surface mixed layer

4. MARINE HEATWAVE MECHANISMS

4.1. Dynamical Understanding

The physical processes responsible for MHWs can be explored through the analysis of the heat sources and sinks within the surface mixed layer, which are reflected in SST variations (Alexander et al. 2000, Deser et al. 2010). A mixed-layer temperature budget has been used to describe the processes of MHW formation, evolution, and decay (Benthuysen et al. 2014, Chen et al. 2014, Kataoka et al. 2017). This approach relates temperature changes in the surface mixed layer with physical processes, including horizontal temperature transport and air–sea heat fluxes.

Generally, changes in mixed-layer temperatures arise from a combination of air–sea exchanges, advection by mean currents and eddies, horizontal and vertical mixing, and entrainment of water into the mixed layer. The rate of change of vertically averaged seawater temperature in the mixed layer, or the temperature tendency, is given by (Moisan & Niiler 1998)

$$\underbrace{\frac{\partial \overline{T}}{\partial t}}_{\text{Temperature tendency}} = -\underbrace{\overline{\mathbf{u}}\cdot\nabla\overline{T}}_{\text{Horizontal advection}} + \underbrace{\overline{\nabla\cdot(\kappa_{\mathrm{h}}\nabla T)}}_{\text{Horizontal mixing}} - \underbrace{\frac{1}{h}\kappa_z\left.\frac{\partial T}{\partial z}\right|_{-h}}_{\text{Vertical mixing}}$$
$$\underbrace{-\left(\frac{\overline{T}-T_{-h}}{h}\right)\left(\underbrace{\frac{\partial h}{\partial t}}_{\text{MLD tendency}} + \underbrace{\mathbf{u}_{-h}\cdot\nabla h}_{\text{Lateral induction}} + \underbrace{w_{-h}}_{\text{Vertical advection}}\right)}_{\text{Entrainment}}$$
$$+\underbrace{\frac{Q_{\mathrm{SW}}-Q_{\mathrm{SW}(-h)}+Q_{\mathrm{LW}}+Q_{\mathrm{sens}}+Q_{\mathrm{lat}}}{\rho c_{\mathrm{p}} h}}_{\text{Air–sea heat flux}}, \qquad 1.$$

where T is the temperature in the surface mixed layer, t is time, $\mathbf{u} = (u, v)$ is the two-dimensional horizontal (x, y) velocity vector, w is vertical (z) velocity, ∇ is the horizontal gradient operator, Q comprises various components of the air–sea heat flux (see details below), ρ is the seawater density, c_{p} is the specific heat capacity of seawater, h is the mixed-layer depth (MLD), and κ_{h} and κ_z are the horizontal and vertical diffusivity coefficients. Quantities have been vertically averaged over the mixed layer, and the vertical average of any quantity x is defined to be $\overline{x} = h^{-1}\int_{-h}^{0} x\mathrm{d}z$; a subscript x_{-h} indicates that the quantity is evaluated at the base of the mixed layer, i.e., at $z = -h$. Note that Equation 1 neglects second-order correlation terms (for the full form of the budget, see Moisan & Niiler 1998).

Equation 1 describes how the rate of change of surface mixed-layer temperature is related to the transfer of heat by horizontal advection, air–sea heat flux, lateral and vertical mixing, and entrainment of deeper waters into the mixed layer (**Figure 3*a***). Horizontal temperature advection can drive local temperature changes through horizontal flows across a temperature gradient; examples include strong poleward geostrophic flows in a western boundary current extension region and strong Ekman flows associated with changes in wind stress (Rebert et al. 1985). Anomalous ocean currents—or, less often, anomalous temperature gradients—are responsible for

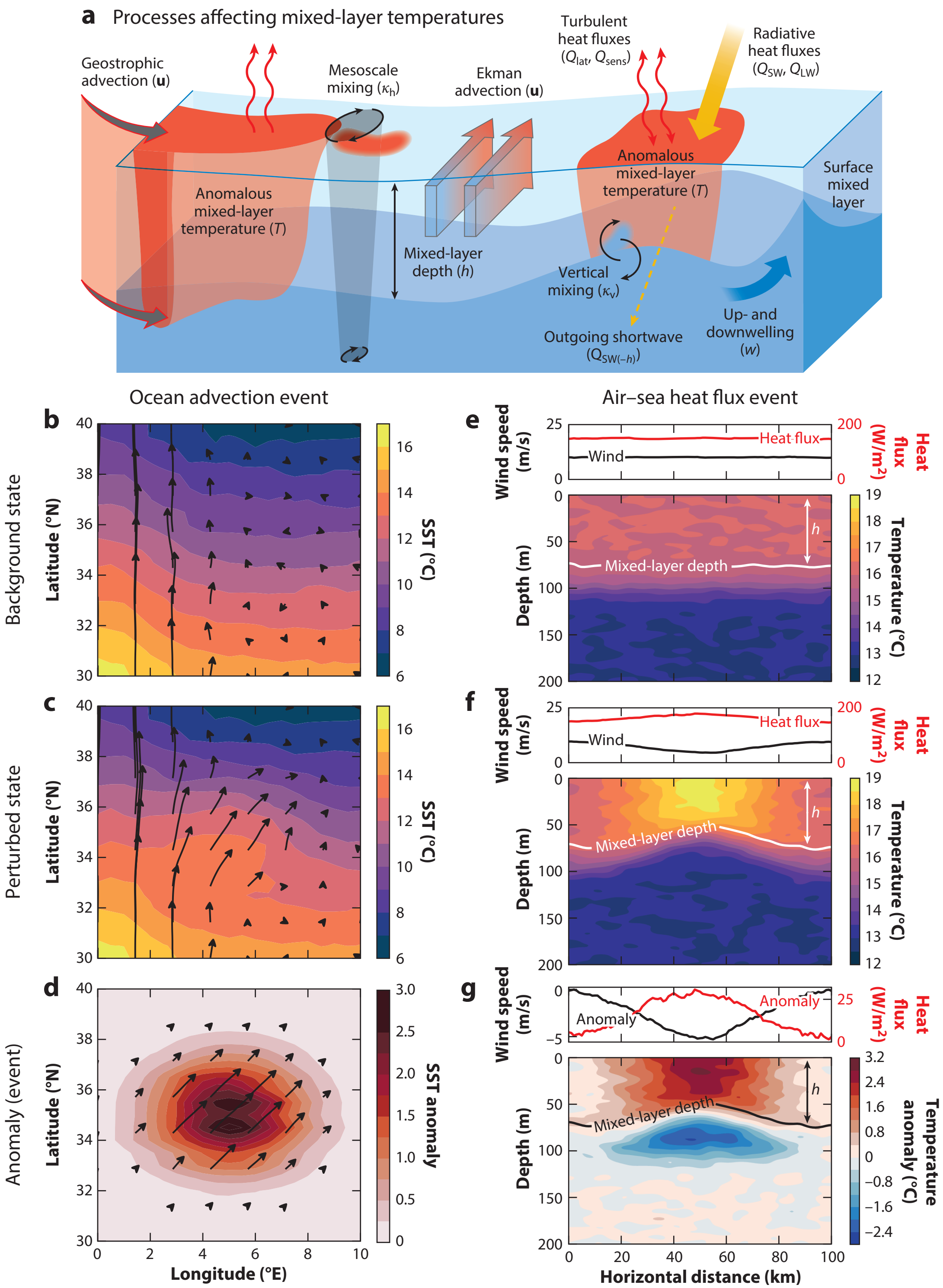

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Figure 3 (*Figure appears on preceding page*)

Physical processes affecting mixed-layer temperatures. (*a*) Relevant physical processes in a mixed-layer temperature budget. (*b–g*) Idealized examples of MHW events where the budget is dominated by (*b–d*) horizontal advection and (*e–g*) air–sea heat flux. For the advection event, we have (*b*) a background state consisting of a poleward ocean current **u** (*arrows*) across a temperature gradient ∇T (*colors*; e.g., a western boundary current), which is (*c*) perturbed by an anomalous flow to the northeast, resulting in (*d*) anomalously high SSTs. For the air–sea heat flux event, we have (*e*) a background state consisting of stratification with a constant mixed-layer depth (*h*), wind forcing, and air–sea heat flux (*Q*). This state is (*f*) perturbed by an atmospheric event that acts to weaken the surface winds, increase the air–sea heat flux, and shoal the mixed-layer depth, resulting in (*g*) anomalously high temperatures in the mixed layer (and anomalously low temperatures immediately below the mixed layer, consistent with Sparnocchia et al. 2006). Abbreviations: MHW, marine heatwave; SST, sea surface temperature. Panel *a* adapted from Holbrook et al. (2019).

advective-type MHWs (**Figure 3*b–d***), such as the 2015–2016 Tasman Sea MHW (Oliver et al. 2017) (**Figure 4*a–g***). Vertical temperature advection results from vertical flows in the presence of thermal stratification and is often related to upwelling and downwelling processes. Schaeffer & Roughan (2017) showed subsurface coastal warming associated with downwelling-favorable winds, and Benthuysen et al. (2018) showed warm anomalies and a subsurface MHW owing to anomalous downwelling via a reduction in the expected upwelling for that time of year. Upwelling

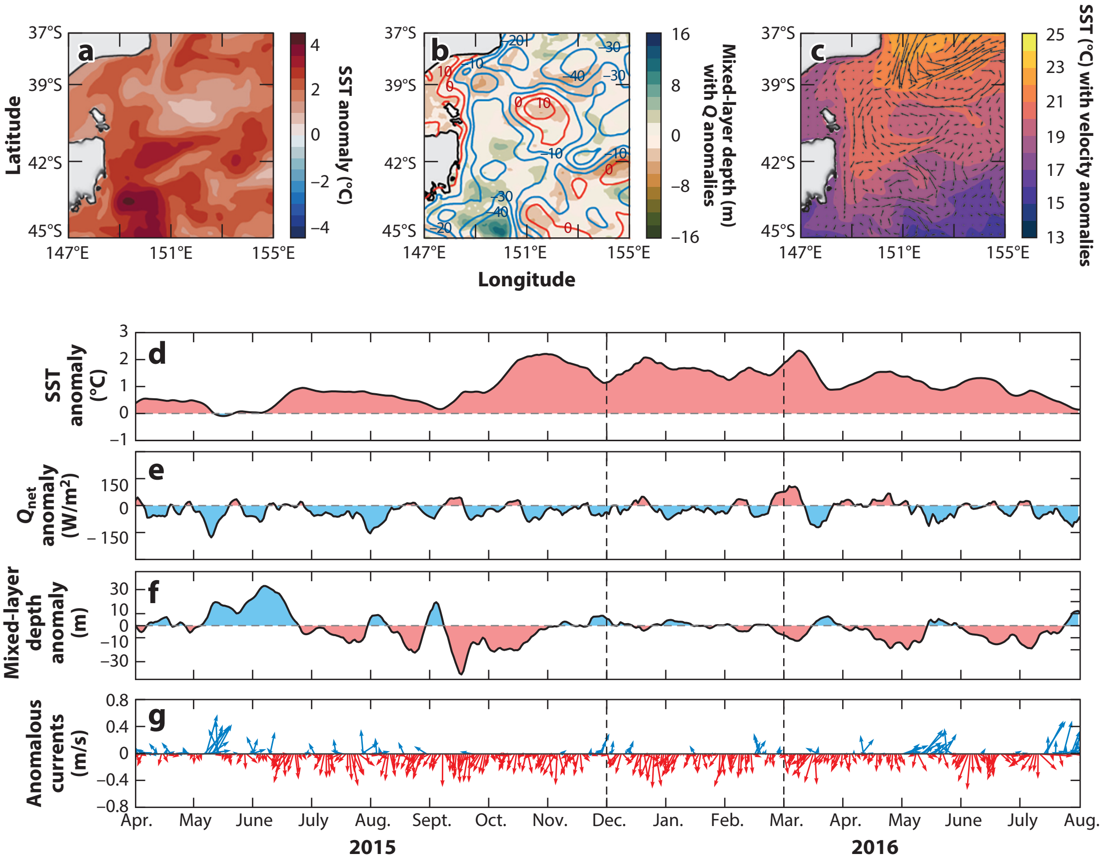

Figure 4

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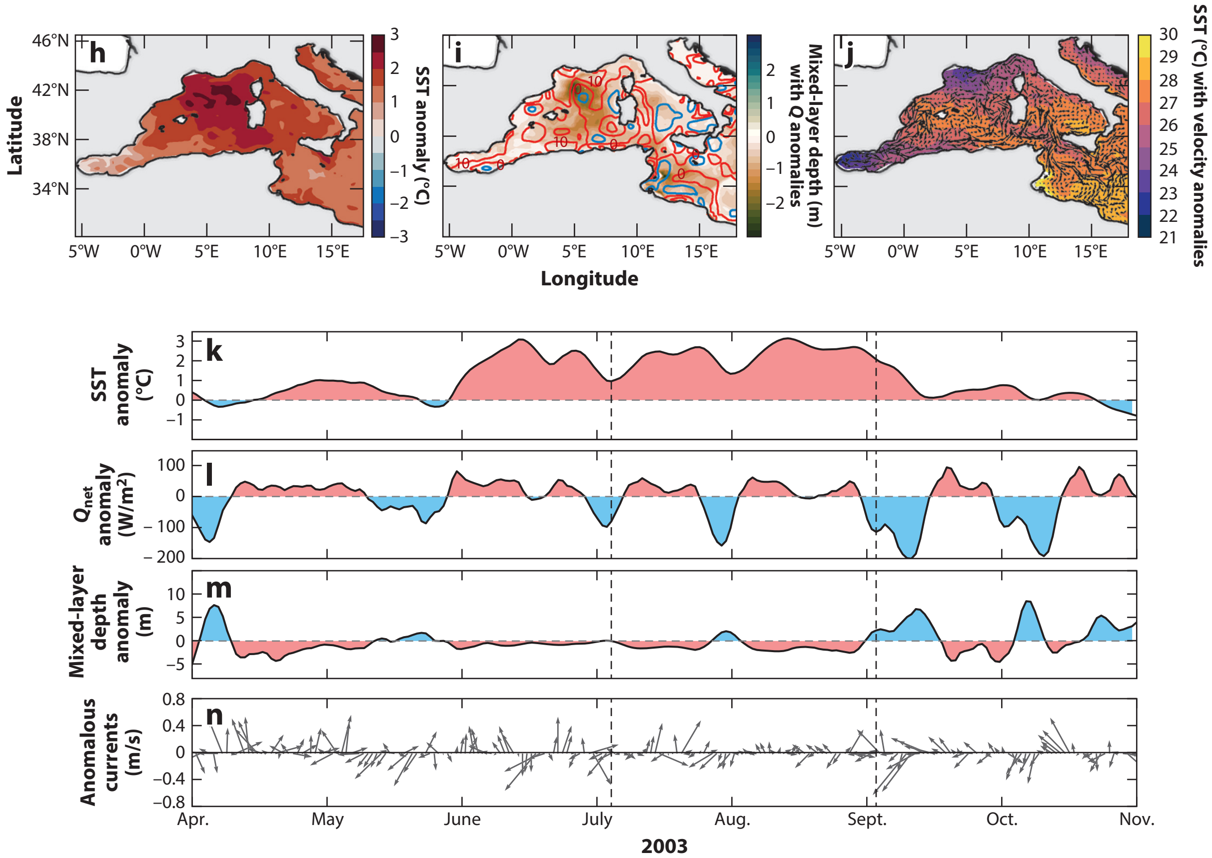


Figure 4

Anomalous contributions to the mixed-layer temperature budget during the (*a–g*) 2015–2016 Tasman Sea MHW and (*h–n*) 2003 Mediterranean Sea MHW. The maps show (*a*, *h*) SST anomaly, (*b*, *i*) mixed-layer depth (*shading*) and air–sea heat flux (Q) (*contours*, where *red* indicates a positive flux into the ocean) anomalies, and (*c*, *j*) velocity anomalies (*arrows*) and SST (*shading*) averaged over the peak duration of each event (December 1, 2015–February 29, 2016, for the Tasman Sea, and July 3–September 3, 2003, for the Mediterranean Sea). The time series show (*d*, *k*) SST anomaly, (*e*, *l*) Q anomaly, (*f*, *m*) mixed-layer depth anomaly, and (*g*, *n*) eastward and northward velocity anomalies spatially averaged. The time series are shaded or (in the case of velocities) the arrows colored according to the sign of the anomaly, with red and blue indicating a tendency to increase and decrease the mixed-layer temperature, respectively. Note that during the 2015–2016 Tasman Sea MHW, Q and the mixed-layer depth were variable but the velocities were predominantly southward, indicating that poleward advection of heat was a dominant contribution to the MHW. During the 2003 Mediterranean Sea MHW, the velocities were variable and weak, but the mixed-layer depths were anomalously shallow and Q tended to be positive, indicating a dominance of air–sea heat fluxes in the MHW development. Data are from GLORYS12V2 for SST, mixed-layer depth, and velocities and from ERA5 for Q; anomalies are relative to the 1993–2013 climatology. Abbreviations: ERA5, European Centre for Medium-Range Weather Forecasts Reanalysis 5; GLORYS12V2, Global Ocean Reanalysis and Simulation 12 version 2; MHW, marine heatwave; SST, sea surface temperature.

can also inhibit MHWs by bringing cool water to the surface (DeCastro et al. 2014, Gentemann et al. 2017, Fewings & Brown 2019).

The net air–sea heat fluxes (Q) are the sum of the net shortwave (Q_{SW}) and longwave (Q_{LW}) radiative components minus the fraction of shortwave radiation that escapes out the bottom of the mixed layer [$Q_{SW(-h)}$], as well as the net latent (Q_{lat}) and sensible (Q_{sens}) turbulent heat fluxes (positive into the ocean) (Cronin et al. 2019). With the exception of shortwave radiation, which has a depth structure, these heat fluxes are distributed through the whole mixed layer, and so their effect on temperature tendency is inversely related to the mixed-layer depth (h). MHWs are often associated with anomalous air–sea heat fluxes, which can include abnormally high Q_{SW}, as a result of less cloud cover and greater insolation, or Q_{sens} when the surface air is warm. Often, both scenarios occur during an atmospheric high-pressure system and coincide with reduced wind speeds that suppress vertical mixing, thereby reducing h. Meanwhile, unusually low latent heat loss from the ocean (negative Q_{lat} anomalies), as a result of weak winds, may also contribute to temperature increases. These processes, which may act independently or simultaneously, are responsible for air–sea heat flux–type MHWs (**Figure 3*e*,*f***), such as the 2003 Mediterranean Sea MHW (Sparnocchia et al. 2006, Olita et al. 2007) (**Figure 4*b*–*n***).

Serial autocorrelation: the correlation of a time series with a delayed version of itself

The remaining terms in Equation 1 are associated with mixing due to horizontal diffusive flux, mixing due to vertical turbulent flux at the base of the mixed layer, and entrainment of waters into the mixed layer due to temporal or spatial variations in mixed-layer depth. These processes are often assumed to account for a smaller proportion of mixed-layer temperature changes associated with MHWs, and so are often neglected or considered part of a residual term.

4.2. Statistical Understanding

The statistical properties of a daily temperature time series form the basis of MHW properties, such as their frequency, duration, and intensity. We can decompose the time series of temperature as

$$T_t = T_t^{\mathrm{tr}} + T_t^{\mathrm{S}} + T_t^{\mathrm{NS}}, \qquad 2.$$

where T_t is the SST at time t, T_t^{tr} is the change related to the long-term (secular) trend, T_t^{S} is the seasonal climatological mean (identically repeating each year), and T_t^{NS} is the nonseasonal component of the SST (the anomalies, with the secular trend removed). If MHWs are defined as SST values above a seasonally varying threshold (e.g., Hobday et al. 2016), and assuming that there is no long-term trend in SST, then MHW SSTs are dependent on the nonseasonal component's properties.

Frankignoul & Hasselmann (1977) developed a stochastic climate model to represent the temperature of a one-dimensional surface mixed layer forced by noisy surface heat fluxes. This model elucidates the relationships between MHW properties and the statistical characteristics of SST. Considering the nonseasonal component T_t^{NS} to have zero mean, variance σ^2, and a nonnegligible serial autocorrelation (i.e., the memory timescale τ), the nonseasonal component can be modeled as an order-1 autoregressive (AR1) process (see also Deser et al. 2010), so that the temperature time series is red noise:

$$T_{t+1}^{\mathrm{NS}} = aT_t^{\mathrm{NS}} + \epsilon_t, \qquad 3.$$

where a is the autoregressive parameter ($0 \leq a \leq 1$), and ϵ_t is a white noise process that is assumed here to be normally distributed with zero mean and variance σ_ϵ^2. The memory timescale of the AR1 process τ increases with a, given by $\tau = -1/\ln a$, and the variance of T_t^{NS} is a function of both a and σ_ϵ^2, given by $\sigma^2 = \sigma_\epsilon^2/(1 - a^2)$. Given values of a and σ_ϵ^2 and realizations of ϵ_t, simulations of T_t^{NS} and (after assuming a sinusoidal form for T_t^{S}) T_t may be generated (**Figure 5*a*–*c***).

Memory timescales are related to the ocean's slow integration of relatively fast atmospheric forcing (e.g., atmospheric weather on timescales of one to two weeks) via surface heat fluxes, near-surface currents, and mixing processes, and temperatures relax to climatological values via damping caused by turbulent energy and longwave radiative fluxes (Deser et al. 2010, Di Lorenzo & Ohman 2013). The variance of this process is related to energetics of the atmospheric forcing and

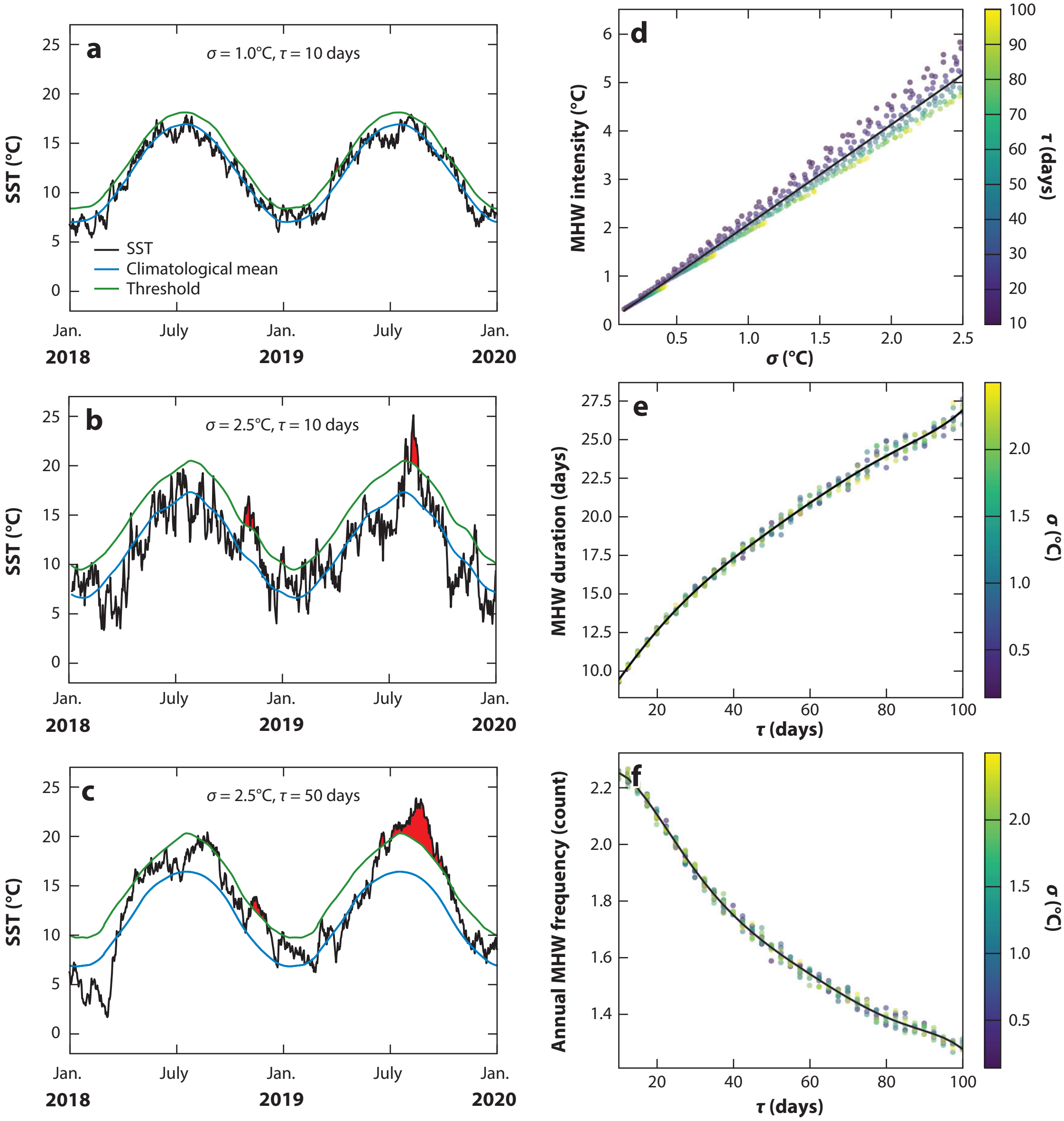


Figure 5

The effect of SST statistical properties on MHW characteristics. (*a–c*) Simulated SST time series assuming a sinusoidal seasonal climatology and a nonseasonal component given by an AR1 process with memory timescale τ and noise variance $\sigma_\epsilon^2 = (1 - a^2)\sigma^2$. Shaded areas indicate MHWs according to the Hobday et al. (2016) definition. (*d–f*) MHW properties as a function of SST standard deviation σ and memory timescale τ. The plots show the annual maximum MHW intensity (panel *d*), annual mean MHW duration (panel *e*), and annual count of MHW events (panel *f*). An ensemble of 100 SST time series were simulated for each σ_ϵ and τ value over the ranges 0.01–2.00°C and 10–100 days, respectively. Abbreviations: AR1, order-1 autoregressive; MHW, marine heatwave; SST, sea surface temperature.

the local ocean dynamics (e.g., the generation of eddies via instability growth). MHWs occurring in time series with larger τ (**Figure 5*c***) are typically longer than for those from time series with smaller τ (**Figure 5*a*,*b***). In addition, MHWs are more intense for larger σ^2 (**Figure 5*b*,*c***) than for smaller σ^2 (**Figure 5*a***). Performing simulations of an ensemble of 40-year SST time series for a range of realistic values of σ^2 and τ and calculating the ensemble-mean annual MHW properties shows that these properties are strongly dependent on underlying SST properties. Specifically, annual maximum MHW intensity increases with SST variance (**Figure 5*d***), annual mean MHW duration increases with SST memory timescale (**Figure 5*e***), and annual MHW count (frequency) decreases with SST memory timescale (**Figure 5*f***).

Stationarity: the condition that the statistical properties of a time series (e.g., mean and variance) do not change over time

The conclusions provided above assume that the SST statistics are stationary, i.e., that the mean and variance of SST do not change over time. In a warming ocean, we know that this is unlikely to be true, particularly for the mean SST (Oliver 2019). Therefore, we expect trends in the mean SST (effectively a nonzero T_t^{tr}) and SST variance to affect MHW properties. Nonstationarity in SST statistics leads directly to trends in MHW frequency, duration, and intensity (Oliver et al. 2018a, Oliver 2019). This aspect is an important consideration that must be taken into account when defining baseline periods for studies on the effects of climate change on MHWs (see also Sections 5.3, 5.4, and 6.1).

5. MEAN STATE, VARIABILITY, AND LONG-TERM TRENDS IN MARINE HEATWAVES

5.1. Global Distribution

Remotely sensed SSTs indicate that MHW frequencies range from approximately one to three events per year on average (Oliver et al. 2018a). In the eastern tropical Pacific, however, El Niño–Southern Oscillation (ENSO) events manifest as individual, long-lasting MHWs (Holbrook et al. 2020a). Hot spots of high MHW intensity (**Figure 6*b***) occur in regions of large SST variability (**Figure 6*e***), including the five western boundary current extension regions (Chen et al. 2014, Oliver et al. 2017), the central and eastern equatorial Pacific Ocean (Echevin et al. 2018), and eastern boundary current regions (Rouault et al. 2007). Typical MHW durations (**Figure 6*c***) are longest in the eastern tropical Pacific, a region dominated by ENSO SST variability with an average duration of up to 60 days (Holbrook et al. 2020a), and shortest over other tropical regions, typically 5–10 days. In the extratropics, MHW durations are more uniformly 10–15 days, with the northeast and southeast Pacific Ocean being exceptions (up to 30-day mean durations; Di Lorenzo & Mantua 2016).

The observed spatial pattern of MHW properties is dependent on the physical processes controlling temperature variability across the globe (see Section 4.1). Unstable boundary currents and mesoscale eddies cause MHWs through anomalous temperature advection in those regions, and anomalous air–sea heat flux is responsible for setting MHW properties in regions susceptible to atmospheric forcing. The observed patterns of SST and MHW statistics follow the expected statistical relationships (see Section 4.2). Spatial correlations show that MHW intensity is strongly correlated with SST variance ($r = 0.95$) and MHW duration is strongly related to SST memory timescale ($r = 0.68$).

5.2. Variability

MHWs are modulated by local and remote processes acting across a large range of spatial and temporal scales (see figure 2 in Holbrook et al. 2019). The strength of many of these local processes, including surface heat fluxes and vertical mixing, are a function of the overlying atmospheric synoptic conditions (winds, cloud cover, and humidity). These conditions may in

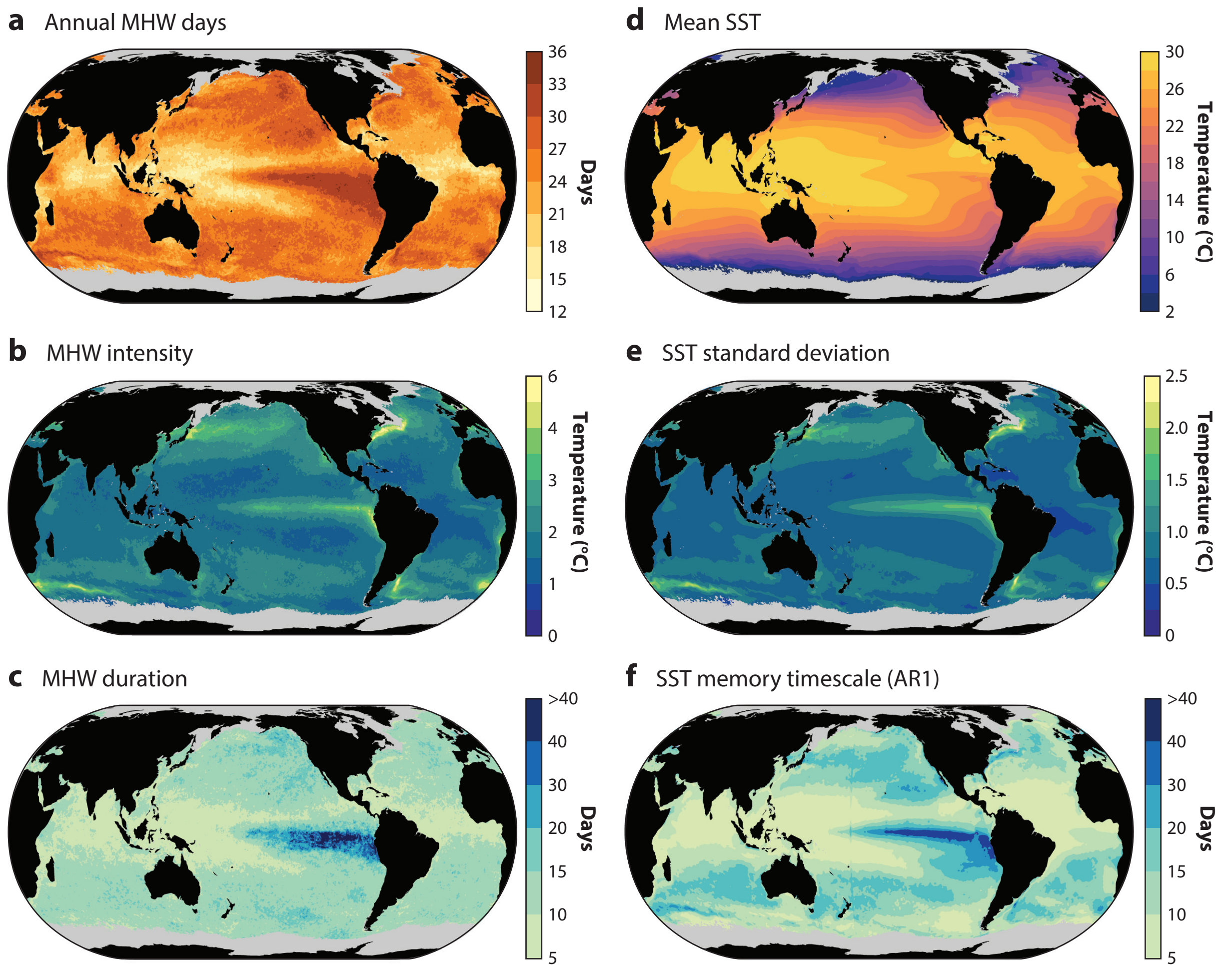


Figure 6

Statistical properties of (*a–c*) MHWs and (*d–f*) SST. The plots shown are the (*a*) annual count of MHW days, (*b*) annual maximum MHW intensity, (*c*) annual mean MHW duration, (*d*) annual mean SST, (*e*) standard deviation of the nonseasonal component of SST, and (*f*) memory timescale of the nonseasonal component of SST (Section 4.2). The nonseasonal component of SST was calculated by subtracting the seasonal climatology and long-term linear trend. The plots were created using NOAA OI SST V2.0 data for 1982–2019, with a baseline period of 1982–2011. Abbreviations: MHW, marine heatwave; NOAA OI SST V2.0, National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature version 2.0; SST, sea surface temperature.

turn vary with changes in the general circulation (e.g., the Walker circulation) or planetary waves generated remotely (e.g., associated with ENSO or the Madden–Julian Oscillation). Such remotely forced variations can cause oceanic disturbances that propagate large distances (via Rossby and Kelvin waves), affecting local ocean advection of temperature with long predictability timescales (Holbrook et al. 2019, 2020b).

ENSO is the dominant mode of interannual climate variability across the globe (e.g., McPhaden et al. 2006). It is also a leading cause of MHW occurrences globally (Oliver et al. 2018a), with key influences and impacts in the Indo-Pacific (Holbrook et al. 2019, 2020a) and more distant links to the Atlantic and Southern Oceans (Holbrook et al. 2019). Coupled air–sea interactions in the tropical Pacific are related to large shifts in SST and directly affect MHW characteristics in the central and eastern tropical Pacific. ENSO teleconnections via atmospheric and oceanic pathways have been an important factor in triggering major MHWs in subtropical to midlatitude regions of the northeast Pacific (e.g., Doi et al. 2015; Di Lorenzo & Mantua 2016; Jacox et al. 2017, 2019), in the central South Pacific (Lee et al. 2010), and in the eastern Indian Ocean off Australia's west coast (Doi et al. 2013, Feng et al. 2013, Benthuysen et al. 2014, Marshall et al. 2015). Such ENSO teleconnections can be amplified by local air–sea feedback processes (e.g., Marshall et al. 2015, Myers et al. 2018) or work in concert with stochastic local weather conditions.

Anthropogenic forcing: forcing acting on the Earth's climate system that is caused by human activities (e.g., greenhouse gas emissions, aerosol emissions, and land use changes)

Natural variability: spatiotemporal variations in climate that are caused by natural forcing (e.g., solar, volcanic, and orbital forcing) acting on the Earth's climate system

Other climate modes also modulate the occurrence rate of MHWs either locally where the mode operates or in remote regions via teleconnections (Holbrook et al. 2019). Significant relationships exist among indices of the Indian Ocean Dipole (the Dipole Mode Index), ENSO (the El Niño Modoki and Niño3.4 indices; see figures 3*b* and 4 in Holbrook et al. 2019), and MHW occurrences and likelihoods across the tropical Indo-Pacific region. These modes exhibit a degree of predictive skill, suggesting that it may be possible to make MHW probabilistic forecasts (Holbrook et al. 2020b) using knowledge of ENSO flavors (e.g., Capotondi & Sardeshmukh 2015, Capotondi et al. 2015), the Indian Ocean Dipole (e.g., Zhao et al. 2019), and the Madden–Julian Oscillation (Zhang et al. 2017, Lim et al. 2018).

5.3. Long-Term Trends

Given the dependence of MHW characteristics on the underlying SST properties, along with a warming ocean, significant changes in MHW characteristics have been identified over the historical record. Notably, increases in both the mean SST and the variability of SST can lead to increases in warm temperature extremes (Field et al. 2012). Much of the global ocean has seen mean SST warming over the satellite record, and several such hot spots have also seen increases in SST variability, with implications for changes in MHWs (**Figure 7**).

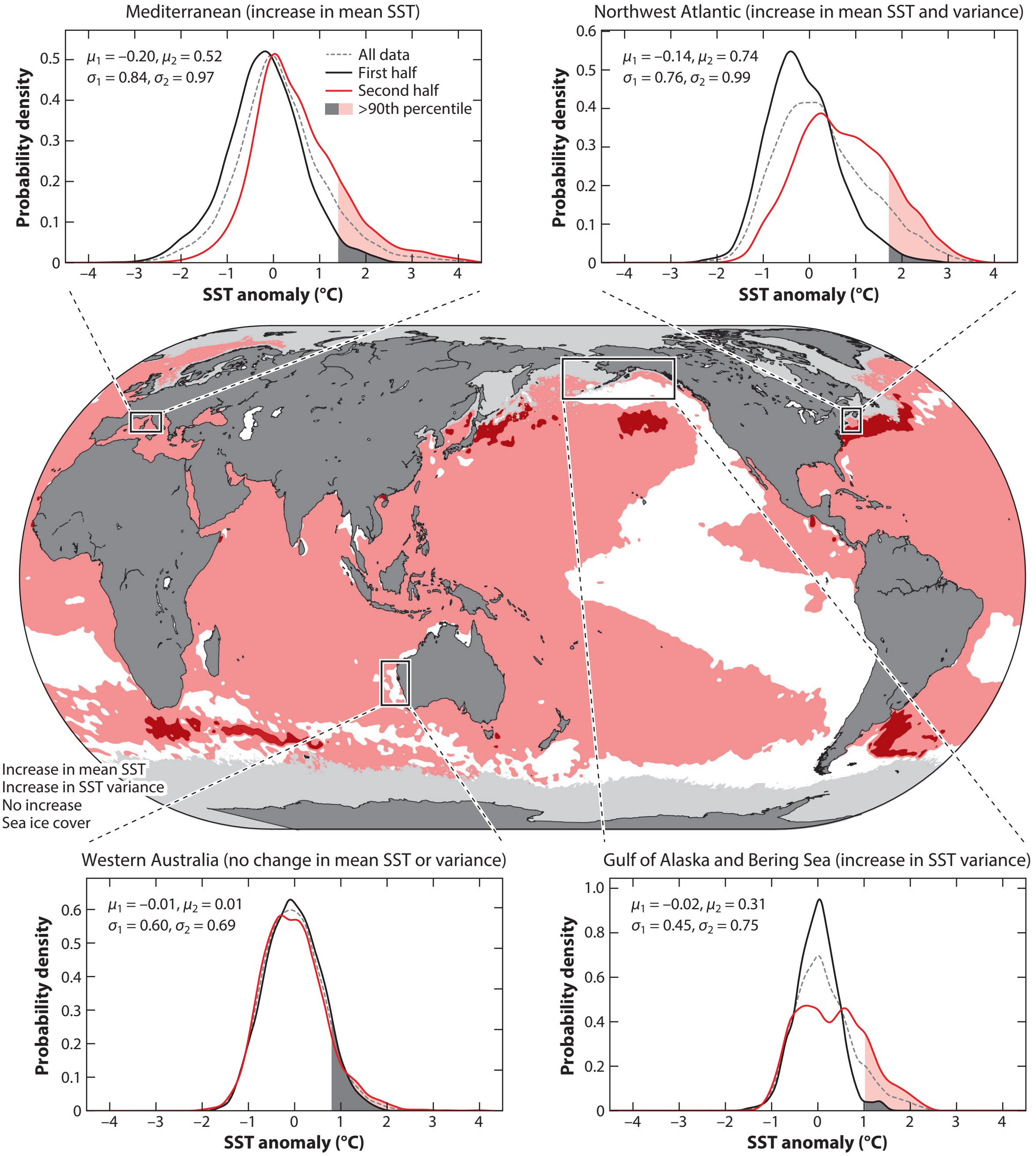
The days of extremely high SST have become more common over 38% of the world's coastline (Lima & Wethey 2012). As a global average, the frequency, intensity, duration, and spatial extent of MHWs have increased substantially over the satellite record (Frölicher et al. 2018, Oliver et al. 2018a). MHW frequency increased over 82% of the global ocean but decreased in parts of the Southern Ocean (Oliver et al. 2018a). The intensity of MHWs has increased most notably in the five midlatitude western boundary current extension regions, areas noted to be warming considerably faster than the global mean rate (Wu et al. 2012, Hu et al. 2015). The global-average duration of MHWs has nearly doubled over the satellite record, particularly over the mid- and high-latitude regions of all ocean basins (Oliver et al. 2018a).

While a few studies have assessed longer-term changes in MHWs over the presatellite records, these analyses are limited in overall spatiotemporal coverage and homogeneity by data availability (see Section 3.2). Using monthly SSTs as a proxy for MHW properties, Oliver et al. (2018a) showed that the annual count of MHW days has increased by more than 50% since the early twentieth century. Several coastal locations around the world have time series of daily or weekly SSTs (see **Table 1**), which could provide additional estimates of long-term changes in coastal MHWs.

5.4. The Role of Anthropogenic Climate Change

Long-term trends in MHW characteristics (frequency, intensity, and duration) over the instrumental record are strongly linked to anthropogenic climate change. In global climate model simulations, substantial increases in global MHW frequency, intensity, duration, and spatial extent were consistent with anthropogenic forcing (Frölicher et al. 2018), with properties exceeding the range expected by natural variability in the early-to-mid-twenty-first century (Oliver et al. 2019).

Changes in global MHW characteristics have been strongly linked to changes in the background SST (Oliver 2019); these increases are expected to continue under projected future emissions scenarios, and it is possible that much of the global ocean will reach a permanent MHW state by the late twenty-first century (Oliver et al. 2019). Most studies on the role of climate change have examined MHWs globally, but there is a need to examine regional cases. Such analyses have been



(Caption appears on following page)

Figure 7 (*Figure appears on preceding page*)

Change in SST statistics and relationship to changes in extreme temperatures. The map shows where SSTs indicate an increase in annual mean SST (*light red*) and SST variance (*dark red*) over the satellite period. White indicates no increase in either; an increase is measured by a positive linear trend in NOAA OI SST V2.0 over 1982–2017. The four surrounding panels show probability density functions of daily SST anomalies from four regions. The functions shown are for the full time series (*dashed gray lines*), the first half of the data (*solid black lines*), and the second half of the data (*solid red lines*); shaded regions indicate the area of the function above the 90th percentile of the full time series. The mean (μ, in degrees Celsius) and standard deviation (σ, in degrees Celsius) are also shown for the two time periods. Abbreviations: NOAA OI SST V2.0, National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature version 2.0; SST, sea surface temperature.

performed for a few regions, including the North Atlantic (Alexander et al. 2018) and the Mediterranean Sea (Darmaraki et al. 2019), but such analyses are encouraged for other regions as well.

Event attribution: a quantification of the role of anthropogenic versus natural climate forcing in the probability of extreme climate events, often with the use of global climate model experiments

A growing body of literature has examined how individual MHW events are attributable to global warming (see also Collins et al. 2019). These analyses draw from a method of event attribution, based on the fraction of attributable risk, that is used in atmospheric heatwave studies (Stott et al. 2004). To date, event attribution studies have been performed on the 2015–2016 Tasman Sea event (Oliver et al. 2017), the 2017–2018 Tasman Sea event (Perkins-Kirkpatrick et al. 2019), the 2016 event across northern Australian waters (Oliver et al. 2018b), the 2016 event in the Gulf of Alaska and Bering Sea (Oliver et al. 2018b, Walsh et al. 2018), the northeast Pacific Blob (Weller et al. 2015), the 2015–2016 extreme El Niño warming in the central equatorial Pacific (Newman et al. 2018), and the 2016 California Current event (Jacox et al. 2017). Some studies have extended attribution approaches to include the likelihood of ecosystem impacts, such as Great Barrier Reef coral bleaching in 2016 (Lewis & Mallela 2018). In general, anthropogenic climate change has substantially increased the likelihood of MHWs with the observed intensity and duration, although several notable MHWs remain to be attributed (Collins et al. 2019). Most studies attribute the temperature anomalies associated with the events (the intensity), but a few also independently attribute the duration of the event. Presently, there is no consistent framework for jointly attributing the totality of the event characteristics.

6. CONTEMPORARY ISSUES

6.1. Baseline Periods for Marine Heatwave Analyses

Given significant ocean warming, a major issue for MHW analyses is choosing the baseline period for calculating the climatological mean and percentile metrics. A fixed-baseline period is commonly used in climatology studies (WMO 2017, 2018) and is standard practice in atmospheric studies (Perkins et al. 2012, Perkins & Alexander 2013). Many MHW studies have chosen fixed-baseline periods (e.g., Liu et al. 2014, Benthuysen et al. 2018, Oliver et al. 2018a), while others have recommended a moving baseline (Jacox 2019). The baseline period affects how the long-term trend in mean SST is expressed through MHWs (Section 4.2), and specific research questions of interest dictate the decision to use a fixed versus moving baseline.

The effect of a fixed versus moving baseline period can be demonstrated using a time series of SST exhibiting a long-term trend. To do so, we used SST area-averaged over a region in the northeast Pacific from the Community Earth System Model (CESM) Large Ensemble Numerical Simulation (LENS) climate model (Kay et al. 2015) historical and Representative Concentration Pathway 8.5 future projection experiments, which together span 1920–2080 (**Figure 8*a***). We used two different approaches to calculate the SST climatology and anomaly time series: one using a fixed 31-year baseline period and one using a moving 31-year baseline centered on the year in question (**Figure 8*b*,*c***). We then used the exceedances above the resulting thresholds (**Figure 8*c***) to determine MHWs following the Hobday et al. (2016) method. A fixed-baseline period leads

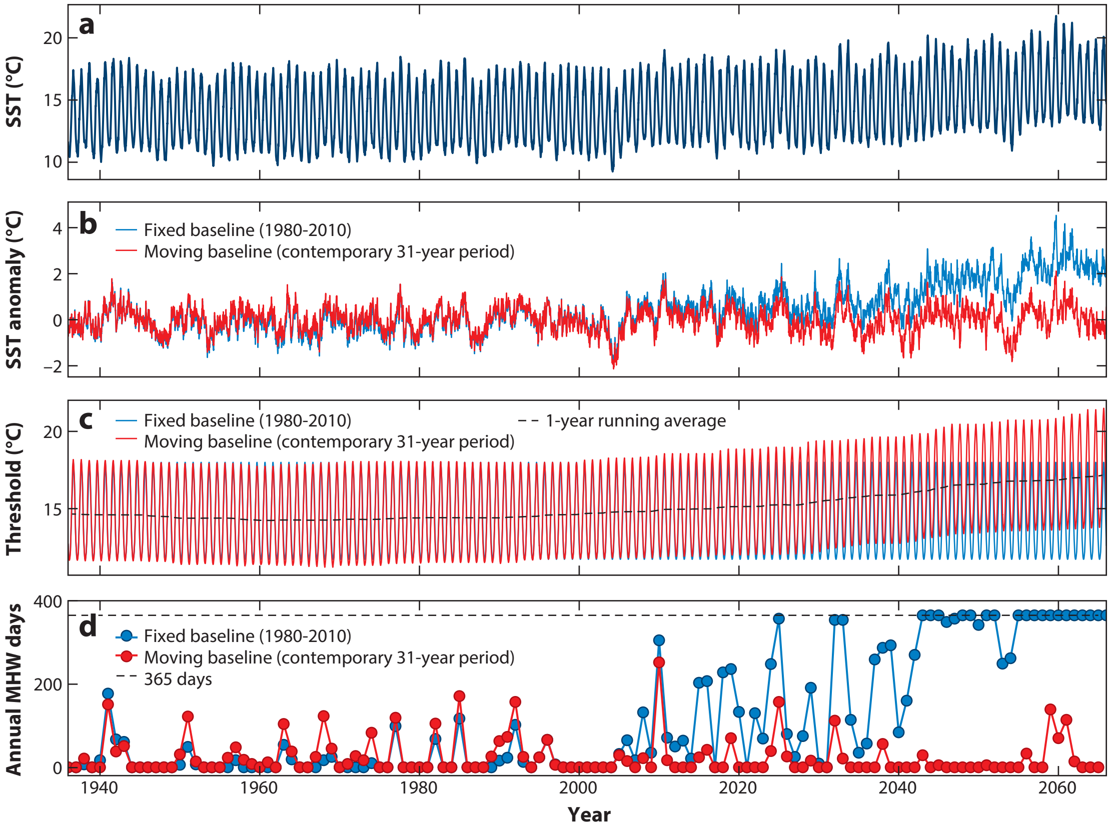


Figure 8

The effect of using a fixed baseline versus a moving baseline on the calculation of SST climatologies, anomalies, and MHWs. The plots shown are time series of (*a*) SST, (*b*) SST anomalies, (*c*) the climatological 90th-percentile threshold, and (*d*) annual MHW days; panels *b–d* were calculated using either a fixed baseline (1980–2010; *blue lines*) or a moving contemporary baseline (*red lines*). The initial time series in panel *a* is SST area-averaged over 30–57°N, 140–120°W (the Blob region), from the historical and Representative Concentration Pathway 8.5 simulations of the CESM LENS global climate model (1920–2080). Abbreviations: CESM, Community Earth System Model; LENS, Large Ensemble Numerical Simulation; MHW, marine heatwave; SST, sea surface temperature.

to a saturation of SST above the threshold, which in turn leads to a full year of MHW days (a permanent MHW state) in the later part of the twenty-first century, while a moving-baseline period leads to more stationary MHW properties over time (**Figure 8*d***). The use of a fixed-baseline period assigns all of the long-term warming to the anomalies and thus to the MHWs (i.e., in the notation of Section 4.2, the anomalies represent $T_t^{\mathrm{tr}} + T_t^{\mathrm{NS}}$ and the climatology only T_t^{S}), while the use of a moving baseline assigns all of the long-term warming to the climatology (and thus removes it from the anomalies and MHWs—i.e., the anomalies represent only T_t^{NS} and the climatology $T_t^{\mathrm{S}} + T_t^{\mathrm{tr}}$).

Both methods of calculating baseline climatologies are complementary, and the recommended choice depends on the questions asked. Much of the study of MHWs is motivated by ecological impacts, which raises the issue of each species' rate of adaptation. The rate and degree of ecosystem change under warming conditions depend on the thermal tolerance ranges and diversity of particular species (Stuart-Smith et al. 2015, Burrows et al. 2019). However, major questions remain as to whether species can acclimatize and adapt to warmer conditions and, if so, how quickly they can do so (Donelson et al. 2019, Fox et al. 2019). A fixed-baseline period is particularly useful when studying ecosystems with a slow (or no) capacity for adaptation and for illustrating overall changes, including long-term warming effects. Moving-baseline periods are most useful when considering ecosystems with a faster adaptation capacity or greater mobility (e.g., the ability to move to new habitats) and for studying physical climate characteristics with a focus on variability rather than long-term warming, as this approach primarily reflects shorter-term variability changes (changes in temperature variance and skewness). However, further research on species' and ecosystems' acclimatization and adaptation timescales are needed to inform these choices. The combination of both approaches (i.e., considering both in parallel) can be useful to disentangle the effects of long-term warming from changes in the magnitude of variability.

6.2. Communicating About Marine Heatwaves

A contemporary issue in many branches of science is effective communication. The science of understanding MHWs will be advanced with a clear communication approach to the description of events, which will aid public communication, allied research communities, and funding initiatives. As with other extreme events, including atmospheric heatwaves, tropical cyclones, and bushfires, naming and categorizing MHWs allows for straightforward communication (Hobday et al. 2018a). Importantly, naming an event based on the year and location ensures that extreme events are consistently discussed. A categorization system based on an MHW's maximum intensity allows for monitoring and communicating how its characteristics are changing in near real time.

Real-time tracking and monitoring of MHWs also offer a communication opportunity. The rapid deployment of ocean gliders during ongoing events and the dissemination of near-real-time data are expected to be of considerable interest and potential value to marine managers and the tourism, fishing, and aquaculture industries (for several examples of MHW tracking tools, see the Related Resources section at the end of this article).

There is demand for information about future weather and climate, including subseasonal to seasonal forecasts of MHWs. These forecasts are on timescales that allow proactive planning rather than reactive responses (Hobday et al. 2018b) and are based on statistical relationships and dynamical models (Holbrook et al. 2020b) (for examples, see the Related Resources section). Recent developments are enhancing understanding of the physical mechanisms that give rise to MHWs, which underpin prediction systems of MHWs (Jacox et al. 2020). Using climate mode indices may enable successful climate forecasts of likely increases or decreases in MHW days over broad geographic areas (Holbrook et al. 2019).

It is clear that MHWs, as extreme events with dramatic effects, can help scientists, policy makers, and the public build understanding about the urgency of response to long-term environmental change.

SUMMARY POINTS

1. There are a diversity of approaches for how to define marine heatwaves (MHWs), using fixed, relative, or seasonally varying thresholds, and each approach has its advantages and disadvantages. Consistent definitions and baselines facilitate comparisons and will accelerate learning about MHWs in different parts of the world.
2. Global observations of sea surface temperature by satellite and advances in data assimilative ocean models have made it feasible to monitor MHWs on a global scale in near real time.

3. The physical drivers of MHWs can be elucidated using a mixed-layer temperature budget, which relates the accumulation of surface ocean heat to physical processes, including horizontal currents and air–sea heat fluxes.
4. MHW characteristics are linked to the statistical properties of the temperature time series, with event intensity increasing with temperature variance and event duration increasing with serial autocorrelation.
5. MHWs are distributed globally and have different characteristics depending on the regionally dominant physical processes and the statistics of the underlying temperature distribution. For example, highly variable regions, such as western boundary current extensions, have high-intensity events that are caused predominantly by anomalous heat transport.
6. The historical record shows that the occurrence frequency of MHWs and their characteristics are sensitive to climate modes of variability and long-term warming, which has implications for the predictability of MHW events.
7. Anthropogenic climate change has led to substantial increases in the intensity and duration of MHWs, with several recent events explicitly attributable to anthropogenic forcing, and these trends are projected to continue throughout the twenty-first century.

FUTURE ISSUES

1. Efforts toward developing a process-based understanding of MHW mechanisms and their predictability need to inform the development of appropriate forecast systems with relevant lead times.
2. Reliable, consistent observational data sets of daily ocean temperatures, including subsurface temperatures, are needed to study observed MHWs with improved data coverage in space and time.
3. Further research is needed to develop a more robust understanding of the physical processes and climate drivers of subsurface MHWs and their links to the surface.
4. To better inform climatological baseline periods, further research is required on linking the physical and climatological aspects of MHWs with species' and ecosystems' acclimatization and adaptation timescales.
5. In the case of MHWs calculated with a fixed baseline and in the presence of long-term warming conditions, is the notion of permanent MHW conditions useful? How can ecosystem adaptation timescales be incorporated into how baselines are defined?
6. In regions where the environmental conditions have radically and abruptly shifted (e.g., in areas historically dominated by sea ice cover), there is no clear definition of MHWs.
7. Currently, global systems for SST and other data streams are in place that allow for near-real-time identification of MHWs. These systems can be adapted to ensure that when unprecedented MHWs arise, resources are available to the public and the scientific community for rapid research and dissemination of information regarding ongoing events.

DISCLOSURE STATEMENT

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Australian Bureau of Meteorology ocean temperature outlooks: **http://www.bom.gov.au/oceanography/oceantemp/sst-outlook-map.shtml**

California Current Marine Heatwave Tracker: **https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-projects-blobtracker**

Climate Prediction Center seasonal climate forecast from CFSv2: **https://www.cpc.ncep.noaa.gov/products/CFSv2/CFSv2seasonal.shtml**

Coral Reef Watch satellite monitoring and modeled outlooks: **https://coralreefwatch.noaa.gov/satellite**

Fishforecasts Marine Heatwave Monitoring: **https://fishforecasts.dtu.dk/heatwaves**
Integrated Marine Observing System OceanCurrent: **http://oceancurrent.imos.org.au**
Marine Heatwaves International Working Group Marine Heatwave Tracker: **http://www.marineheatwaves.org/tracker.html**
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