Lengthening of warm periods increased the intensity of warm-season marine heatwaves over the past 4 decades

Xinru Li1 · Simon D. Donner1

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Abstract
Marine heatwaves (MHWs), periods of anomalously warm sea surface temperature (SST) which can have significant impacts on marine ecosystems, have increased in frequency and severity over recent decades. Many coastal systems (e.g., coral reefs) are particularly vulnerable to warm-season heat stress when temperature can exceed organisms’ thermal thresholds and lead to mass mortality. While many studies have examined the change of the warm-season heat stress occurrence over time, e.g., for coral reefs, there has been less analysis of the thermal properties of heat stress events. Here we examine the trend in the characteristics of warm-season heat stress (referred to as warm-season MHWs) at the global-scale from 1985 to 2019, using multiple metrics for each of duration, peak intensity, accumulated heat stress and heating rates. The results show that warm-season MHWs have become more frequent, longer-lasting, featured higher peak intensity and accumulated heat stress across most of the ocean over the past 4 decades. Furthermore, decomposition of the trends in warm-season MHW properties shows that the increased accumulated heat stress was predominantly driven by the increased duration rather than the increased intensity. The results contribute to improving the understanding of warm-season MHWs, which may help inform the prediction of their impacts on marine ecosystems as well as marine conservation and management under climate change.

Keywords Climate change · Marine heatwave · Sea surface temperature · Ocean thermostat · Coral reefs

1 Introduction

As a result of anthropogenic climate change, global mean sea surface temperature (SST) has increased by 0.11 °C per decade since the 1970s (Rhein et al. 2013). This ocean warming has increased the frequency and duration of extreme temperature events, often referred to as MHW (Frölicher et al. 2018; Oliver et al. 2018). Scientific and public attention to ocean extreme events has grown recently, as severe biological impacts have been observed, such as rapid changes in species distribution, widespread mortality, changes in ecosystem function, and loss of ecosystem services (e.g., Smale and Wernberg 2013; Hughes et al. 2018a, b; Smale et al. 2019; Yang et al. 2019; Cheung and Frölicher 2020). For example, the 2014/2015 North Pacific MHW event caused intrusion of warm-water diatom species into the water of Northern California Current (Peterson et al. 2017), mass mortality of seabirds (Jones et al. 2018), as well as kelp forest degradation and the resulting collapse of the recreational and commercial abalone fisheries in northern California (Rogers-Bennett and Catton 2019). As the ocean continues to warm, MHWs are likely to become more frequent, intensive and prevalent (Frölicher et al. 2018; Oliver et al. 2018; Hu 2021), threatening to cause more broad and severe impacts on key marine ecosystems including coral reefs, kelp forests, seagrass meadows and mangrove forests (e.g., Hughes et al. 2018b; Arias-Ortiz et al. 2018; Sippo et al. 2018).

The quantitative definition of heatwaves in the ocean varies across studies depending on the particular purpose of the research. Many previous studies (e.g., Sorte et al. 2010; Marbà et al. 2015; Skirving et al. 2020) used thresholds developed based on the thermal responses of marine species and ecosystems to identify the periods of potentially fatal heat stress. For example, the extensive literature on monitoring and predicting coral bleaching, the paling of corals which can occur when exposed to heat stress, adopted a metric of accumulated heat stress based on a threshold of 1 °C above the maximum climatological mean over...
12 weeks (e.g., Donner 2011; Skirving et al. 2019; Eakin et al. 2019). Rather than calibrate a method to a specific ecosystem or marine taxa, the framework proposed by Hobday et al. (2016) quantifies MHWs more generically using a thermal threshold based on the 90th percentile of SSTs at each location for each day. This generic definition approach is a method of assessing global ocean heat stress coherently and comparably. However, unlike the definition using a climatological maximum for detecting coral bleaching-level heat stress, the Hobday et al. (2016) definition identifies periods of prolonged temperature anomalies at all times of the year similarly as MHWs. Although heat stress in the cold season can negatively affect marine organisms (Morley et al. 2017), it is during the warm season that heat stress may exceed the thermal tolerance of marine organisms, leading to mass mortality (e.g., corals; Eakin et al. 2010). Therefore, there is value in specifically examining changes in heat stress that only occur in the period of a year when temperature can exceed the climatological maximum, henceforth called “warm-season MHW”.

While it is well established that warm-season MHWs have become more intensive and extensive under global ocean warming (Frölicher et al. 2018; Oliver et al. 2018; Hu 2021), there has been less research on the various thermal properties of MHWs. The focus of most MHW research is on accumulated heat stress (e.g., Degree Heating Weeks, as in Skirving et al., 2020), which combines the magnitude and duration of heat stress into one metric. However, two events with the same accumulated heat stress but with different thermal properties (e.g., duration, peak intensity and heating rate) can affect marine organisms differently (McClanahan et al. 2019). For example, a long period of moderate heat stress (e.g., four weeks of 1 °C anomaly) may imply less severe biological impacts than a numerically equivalent short period of high SST anomalies (e.g., one week of 4 °C anomalies). To understand the potential effects of the more frequent and severe MHWs on marine ecosystems, it is important to decompose the trend of increasing heat stress intensity by examining the duration, magnitude and other characteristics of MHWs.

In this study, we examine changes in the thermal properties of warm-season MHWs globally over the past 4 decades. We develop a series of metrics that describe the thermal properties of warm-season MHWs, including duration, intensity, accumulated heat stress and heating rates (Table 1). The trend in each metric from 1985 to 2019 was computed

| Table 1 The metrics measuring the warm-season MHW characteristics |
|----------------------|----------------------------------------------------------------------------------|
| **Variable**         | **Description**                                                                 |
| HotSpot (°C)         |                                                                                  |
| HS<sub>MM</sub>      | Daily HotSpot in that grid cell, using MMM baseline                            |
| HS<sub>p90</sub>     | Daily HotSpot in that grid cell, using p90 baseline                             |
| HS<sub>peak</sub>    | Maximum HS value that year                                                       |
| Duration (day)       |                                                                                  |
| D<sub>c</sub>        | Duration of continuous positive HotSpot, based on the period that includes the maximum annual HotSpot |
| D<sub>tot</sub>      | Total number of days with positive HotSpot                                       |
| D<sub>ws</sub>       | Number of days between the first and last positive HotSpot (i.e., the warm season length) |
| D<sub>p</sub>        | Number of days between the first positive HotSpot and onset of a continuous positive HotSpot period (i.e., D<sub>c</sub>, referring to the “conditioning or priming period”) |
| Accumulated heat stress (°C·day) |                                                                      |
| A<sub>c</sub>        | Accumulated sum of heat stress during the continuous positive HotSpot period, based on the time period used for D<sub>c</sub> |
| A<sub>tot</sub>      | Accumulated sum of all HotSpot that year                                         |
| DHD                  | Maximum 84-day (i.e., three months) continuous accumulated sum of positive HotSpot in a year |
| Mean heat stress intensity (°C) |                                                                                   |
| I<sub>c</sub>        | Average HotSpot value over the continuous positive HS period (computed as A<sub>c</sub> / D<sub>c</sub>) |
| Heating rate (°C·day<sup>-1</sup>) |                                                                                   |
| HR                   | Rate of SST increase from the first HotSpot in a year to the date of HS<sub>peak</sub> |
| HR<sub>c</sub>       | Rate of SST increase from the start of the D<sub>c</sub> period to the date of HS<sub>peak</sub> |
| Heat stress level    |                                                                                  |
| Level 1              | Degree Heating Day (DHD) > 0 °C·day                                              |
| Level 2              | DHD > 28 °C·day                                                                  |
| Level 3              | DHD > 56 °C·day                                                                  |
| Level 4              | DHD > 84 °C·day                                                                  |
using a global daily satellite SST dataset (CoralTemp v3.1). The results show that the duration of warm-season MHW increased across most of the ocean, whereas the peak intensity and heating rates decreased in parts of the tropics and subtropics, and in the high latitudes in the Southern Hemisphere. Furthermore, the increase in duration, rather than the magnitude of heat stress, was the predominant driver of the increase in warm-season MHW intensity over time.

2 Methods

2.1 Sea surface temperature dataset

We use the 0.05° × 0.05° latitude–longitude global daily SST dataset CoralTemp v3.1, from the National Oceanic and Atmospheric Association (NOAA) Coral Reef Watch (CRW) program (Skirving et al. 2020), to explore the dynamics of warm-season MHW characteristics from the calendar year 1985 to 2019. The dataset is derived by the combination of the Operational SST and Sea Ice Analysis (OSTIA) reanalysis (Jan. 1985-Nov. 2002), the NOAA National Environmental Satellite, Data, and Information Service’s (NESDIS) Geo-Polar-orbiting Blended Night-only SST reanalysis (Nov. 2002-Oct. 2016) and the Near Real Time (NRT) Geo-Polar SST (Oct. 2016-Dec. 2019; Skirving et al. 2020). In this dataset, a linear transition approach is applied to remove abrupt changes from the switch in different data sources (Skirving et al. 2020). The dataset provides a continuous record of globally complete SSTs gridded at 0.05° (i.e. about 5 km, a resolution comparable with the scale of many marine ecosystems, e.g. coral reefs, Skirving et al. 2020). This gap-free dataset with high spatial and temporal resolution is ideal for analyzing the thermal properties of MHWs, which requires daily scale data. Here, the data analysis excludes the regions poleward of 60°N and that of 60°S to avoid the influence of sea ice in calculating trend in warm-season MHW characteristics.

2.2 Definition of warm-season marine heatwave

A MHW is qualitatively defined as a prolonged period of extremely high ocean temperatures that persists for days to months (Collins and Sutherland 2019). In this study, we define a warm-season MHW as a period of positive anomalies of daily SSTs or HotSpots (HS) relative to a thermal threshold based on climatological warm-season SST. Given that the warm season in parts of the ocean overlaps across two calendar years, we define a heat stress year (HSY) in each grid cell starting from a month in the climatological cold season. A HSY extends from March to February in most of the Northern Hemisphere and from September to August in most of the Southern Hemisphere (Fig. S1). For clarity, we henceforth label each HSY based on the calendar year that the HSY begins; for example, HSY 1985 in most of the Northern Hemisphere refers to the period from March 1985 to February 1986. The final year of the analysis is HSY 2018, which includes data from the calendar years 2018 and 2019.

We conduct all analyses twice, using two different methods to define the thermal threshold in each grid cell for detecting daily HS. The first method uses the Maximum Monthly Mean (MMM), a threshold widely used in coral bleaching prediction (Skirving et al. 2020). Here, the MMM in each grid cell is calculated as the maximum from a 1985–2019 monthly mean SST climatology. The second method uses the 90th percentile of historical warm-season SSTs (p90) as the threshold. The p90 in each grid cell is calculated as the 90th percentile of the 90 highest daily SSTs (i.e., three months) from each year over the 1985–2019 period. This threshold is based on Hobday et al. (2016) method for defining MHWs, except that rather than defining a different SST threshold for each day of the year, a single SST threshold is defined per cell based on past warm-season SSTs. In both methods, the daily HS is calculated as the positive-only anomaly between the daily SST and the respective threshold, where ‘i’ refers to individual latitude, ‘j’ refers to individual longitude:

\[ HS_{\text{MMM}} = \max (\text{SST}(i,j,time)) - \text{MMM}(i,j,0) \]

\[ HS_{p90} = \max (\text{SST}(i,j,time)) - p90(i,j,0) \]

Note that unlike the NOAA Coral Reef Watch bleaching prediction method, which excludes HS < 1 °C (Liu et al. 2014), all positive HS are included in warm-season heat stress calculations in this study.

2.3 Warm-season marine heatwave metrics

We define a set of metrics that characterize the properties of warm-season MHWs (Table 1). For duration, we test three different metrics: the duration of continuous positive HS that includes the maximum HS value (Dc), the total number of days with positive HS (Dtot) and the length of the period between the first and last positive HS (i.e., the warm season length, Dw). The length of Dw could be longer than or equivalent to the Dtot and both are usually longer than the Dc. In addition, the conditioning or “priming” period (Dp) is computed as the number of days between the first positive HS in a year and the onset of Dc. Such a period of sub-lethal heat stress can prime marine organisms for exposure to later heat stress (Hilker et al. 2016).

The heating rate, or rate of SST increase during a warm-season, is described by two different metrics: HR measures the rate of SST increase starting from the date...
of the first positive HS, whereas HRc measures the rate of SST increase from the start of the continuous positive HS period. The accumulated warm-season heat stress is similarly described by metrics measuring the sum of total heat stress in a year (Atot) and the sum of the heat stress throughout the continuous Dc period (Ac). Thus, Atot might be larger than Ac when some discrete HS exist in a year (e.g., the condition in Fig. 1). We also compute the maximum Degree Heating Days (DHD) value for each year, a daily version of the DHW method used by the NOAA Coral Reef Watch program for real-time coral bleaching alerts (Skirving et al. 2020). The annual DHD value is used to categorize levels of intensity of warm-season MHW events: Level 1 (DHD > 0 ºC·day), L2 (DHD > 28 ºC·day, equivalent to the DHW > 4 ºC·week threshold used by Coral Reef Watch), L3 (DHD > 56 ºC·day, equivalent to the DHW > 8 ºC·week threshold used by Coral Reef Watch) and L4 (DHD > 84 ºC·day).

We use Matlab2018b for all analysis. Trends in each metric in each grid cell are computed using standard linear regression following the ‘fitlm’ function. We use multiple linear regression (‘regress’ function) to evaluate the contribution of changes in peak intensity (HSpeak) and changes in duration (Dc) to the changes in accumulated heat stress over time (Ac) in each grid cell:

\[ A_c = a \cdot D_c + b \cdot H_{peak} + c \]

We use ratio of the coefficients (a:b) to identify the relative contribution of changes in Dc and HSpeak to the trend in accumulated heat stress. All statistical relationships with p < 0.05 are displayed as grey dots in the coefficients map (e.g., Figs. 4; S11).

### 3 Results

#### 3.1 Trends in warm-season marine heatwave characteristics

The warm-season MHW metrics are computed twice, using two sets of HS relative to the thermal thresholds of MMM and p90, respectively. The p90 values are 0.2 to 3 ºC greater than the MMM values, with the greatest differences in north of 40ºN, in the central and eastern tropical Pacific Ocean, and in the ocean south of Africa and near South America (Fig. S2). The higher p90 values result in lower magnitudes of HS and the warm-season MHW metrics. The trends in the metrics are therefore generally lower using the p90 thresholds than using the MMM threshold, however the global patterns of those trends are broadly similar (Figs. 2, 3; S3, S4). Therefore, we present the results using the MMM threshold here, with equivalent results for the p90 threshold available in the supplementary material (Figs. S3, S4).

The duration of continuous positive HS period (Dc) significantly increased in 93% of the ocean from 1985 to 2018 at a rate of 0.2 to 3 day·year⁻¹ (Figs. 2a, S3a). The slope of Dc is > 1.4 day·year⁻¹ in the western equatorial Pacific, Bering Sea, Tasman Sea, and parts of the western Atlantic, which is equivalent to a 48-day increase in the average duration of the warm-season heat stress from 1985 through 2018 (Fig. 2a). The positive slopes are particularly large in parts of the Western Pacific Warm Pool (WPWP), where values exceed 3 day·year⁻¹ (Fig. 2a). In contrast, Dc decreased at a rate of 0.2 to 0.8 day·year⁻¹ in areas south of 50ºS and parts of the eastern tropical Pacific and Northeastern Atlantic. (Fig. 2a). Most of the negative slopes are not statistically significant, except poleward of South America (Fig. 2a).

The trends in the number of total days with HS (Dtot) and the number of days between the first and last HS (Dws) show broadly similar spatial patterns to that of Dc, but with fewer grid cells (90% and 72% respectively) featuring positive trends (Fig. 2a–c). The largest positive slopes of Dtot and Dws appear in and around the WPWP and in the latitudinal band of 40ºS to 50ºS, with values larger than that of Dc (Fig. 2a–c). As with Dc, the negative slopes are generally not statistically significant (Fig. 2a–c).

The combination of negative trends in Dtot and Dws but positive trends in Dc, as occurred in parts of the central and eastern tropical Pacific, eastern Indian Ocean, and the south of 50ºS, suggests that the warm-season heat stress period there became more concentrated, with fewer gaps between positive HS. This is reflected in the map of trends in the priming period (Dp), which decreased across 60% of the ocean (Fig. 2d). The decreasing trends of Dp are associated with increases in Dc, i.e. longer period of continuous heat stress (Fig. 2a).
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The accumulation of heat stress over the continuous positive HS period \( (A_c) \) and the year \( (A_{tot}) \) increased across 91% and 88% of the ocean from 1985 to 2018, respectively (Fig. 3a, b), with similar spatial patterns to those of the trends in the equivalent duration variables (Fig. 2a, b). For example, \( A_c \) significantly increased at a rate of 0.3 to 1.2 °C·day·year\(^{-1}\) in 66% of the ocean, with the highest trends in the western tropical Pacific, North Pacific, Northwest Atlantic, and Tasman Sea (Fig. 3a).

The annual maximum or peak hotspot \( (H_{peak}) \) increased in 59% of the ocean cells including the western boundary regions of the mid- and high- latitudes, and decreased or remained relatively unchanged across much of the tropical oceans and south of 45°S (Figs. 3e, S4e). The largest positive trends (0.08 to 0.12 °C·year\(^{-1}\)) occurred in north of 40°N, and equate to a 2.7 °C to 4 °C increase in maximum annual SST from 1985 to 2018. In the regions where trend of \( H_{peak} \) was negative, the rate of decrease was comparatively low; for example, \( H_{peak} \) decreased by 0.01 to 0.03 °C·year\(^{-1}\) (Fig. 3e), equivalent to a 0.3 °C to 1 °C decrease in \( H_{peak} \) from 1985 to 2018.

The pattern of trends in duration (i.e. \( D_c, D_{tot}, D_{ws}, D_p \)), cumulative heat stress (i.e. \( A_c, A_{tot} \)) and peak intensity (\( H_{peak} \)), with high positive values in the western Pacific, Northeast Pacific, Northwest Atlantic and around the latitudinal band of 40°S to 50°S, correspond with the predominant pattern of inter-decadal SST variability. The first and second leading empirical orthogonal function (EOF) patterns of SST anomalies in Pacific Ocean reflect the features of the negative and positive phases of the Pacific Decadal Oscillation (PDO), indicating more positive SST anomalies in the western Pacific and Northeast Pacific, respectively.
The spatial pattern in decadal-scale SST variability combined with the ocean warming trend lead to the increase in duration and magnitude of heat stress in the western and Northeast Pacific, contributing to the larger increasing trends in $D_{c}$, $D_{\text{tot}}$, $D_{ws}$, $D_{p}$, $A_{c}$, $A_{\text{tot}}$ and $H_{\text{Speak}}$. Conversely, the decadal-scale variability contributed to decreasing trends in these metrics in the central and eastern Pacific (Fig. S5). The predominant pattern of SST anomalies in the Atlantic reflects the positive phase of North Atlantic Oscillation (NAO), which contributes to the higher trends in the metrics in the Northwest Atlantic (Fig. S6).

The limited seasonality in the equatorial ocean and the mid- to high- latitudes of the Southern Hemisphere means that relatively low SST trends lead to disproportionate increases in the occurrence, duration and accumulated heat stress, as SST is close to the warm-season...
climatological maximum throughout the year. This explains the large positive trends in duration ($D_c$, $D_{tot}$, $D_{ws}$, $D_p$) and cumulative heat stress ($A_c$, $A_{tot}$) in the mid- to high- latitudes of the Southern Hemisphere. Conversely, the limited seasonality combined with the phasing of Pacific decadal variability contributed to the decreasing or insignificant positive trends in these metrics in the central and eastern tropical Pacific. The decreasing trends are larger for the warm season length ($D_{ws}$) and the priming period ($D_p$) than those for $D_c$ and $D_{tot}$, because the definition of $D_{ws}$ and $D_p$ is more sensitive to the timing of heat stress.

Unlike the duration and accumulated heat stress metrics, the heating rate metrics, HR and $HR_c$, significantly decreased in 60% and 84% of the ocean, respectively, with exceptions in some western boundary current regions and poleward of 40°, particularly the Labrador and Bering Seas (Fig. 3c, d). The large negative trends of $HR_c$ in the tropical and subtropical regions correspond with large positive trends in duration (Fig. 2a) and decreasing trends in $HS_{peak}$ (Figs. 3a, S8a). The trend in heating rate measured from the date of first HS (HR) show similar global patterns but lower magnitudes, primarily due to higher magnitudes of increase in the corresponding duration, $D_{tot}$ (Figs. 3b, S8b).

The increasing trend in several warm-season MHW metrics across most of the ocean (i.e. $D_c$, $D_{tot}$, $HS_{peak}$, $A_c$ and $A_{tot}$) is further illustrated by the shifts in the distribution of their values from the first half (1985–2001) to the second half of the time period (2002–2018; Figs. S9, S10). Large values of $D_c$, $A_{tot}$ and $HS_{peak}$ are more common in the second half of the time period, while the occurrence of the short durations (i.e. $D_c$, $D_{tot}$, $D_{ws}$ < 40 days) and small magnitudes of $HS_{peak}$ (< 1 °C), $A_c$ and $A_{tot}$ (< 10 ºC·day) were less common (Figs. S9a-c, S10a, S10b, S10e). Conversely, the distribution of $D_p$, $HR_c$, and HR shifted to lower values in the second half period, corresponding with more common declining trends.

### 3.2 Decomposition of changes in accumulated warm-season heat stress

Multiple linear regression indicates that the change in duration ($D_c$), rather than the change in annual maximum HS ($HS_{peak}$), is a greater contributor to the change in accumulated heat stress ($A_c$) from year 1985 to 2018 across 84% of the ocean (Fig. 4). The coefficients for $D_c$ are significantly higher (i.e. $p < 0.05$ and $r^2 > 0.8$) than those for $HS_{peak}$ (e.g., the median difference of 0.13), especially over the central and eastern equatorial Pacific, as well as parts of the mid- and high- latitudes (Fig. 4). Similar results are found using the p90 baseline, with higher coefficients for $D_c$ across 74% of the ocean, particularly in the mid- to high- latitudes (Fig. S11). The spatial pattern of Pacific decadal variability is less apparent in the coefficients for $D_c$ using the p90 baseline, due to regional differences in the p90 and MMM baselines (Fig. S2). The greater contribution of duration to the increasing trend in the accumulated heat stress over most of the ocean is also demonstrated by the smaller magnitudes of the trend in the mean intensity of accumulated heat stress ($I_c$) compared to that of the trend in duration ($D_c$) (Fig. S12). Since $A_c$ is the product of the mean intensity ($I_c$) and duration ($D_c$),
this is a more direct way of decomposing the accumulated heat stress into duration and magnitude. The global pattern of the \( I_c \) trend is similar to that of \( H_{\text{peak}} \), with negative trends dominant in the tropics and the high-latitudes of the Southern Hemisphere, and positive trends more common in the mid-latitudes (Figs. 3a, S12).

### 3.3 Changes in the frequency of different levels of warm-season marine heatwaves

The frequency of warm-season MHW events increased across most of the ocean, with larger increases in the mid- and high-latitudes in the latter half of the time period (Fig. 5). For example, Level 2 or above (DHD > 28 °C·day) was equivalent to the NOAA Bleaching Alert Level 1) and Level 3 or above (DHD > 56 °C·day, equivalent to the NOAA Severe Bleaching Alert Level 2) heat stress events became more common across 87% and 93% of the ocean, respectively. The increases in the frequency of Level 2 or above events and Level 3 or above events are at least 30% and 52%, respectively (Fig. 5). The smaller change in the frequency and extent of Level 1 or above events, relative to that of Levels 2 to 4 and above, indicate that warm-season heat stress became more intense over time (i.e., increases in the frequency and extent of higher-level events), but changes in the frequency of any heat stress (i.e., Level 1 events, or \( 0 < \text{DHD} \leq 28 \) °C·day) were more limited. Many of the high-level MHW events in the North Pacific and in the latitudinal band of 30°S to 50°S that occurred in the latter period were absent in the earlier period (Fig. 5b, c, d). The first and second modes of SST variability in Pacific and Indian Ocean as well as the first mode in North Atlantic during the latter half of the time periods showed more positive SST anomalies (Figs. S5, S6, S7). This reflects the more frequent high-level MHW events in the latter period, including the 2013–2015 Northeast Pacific MHW known as ‘the blob’ (Amaya et al. 2020), and the 2015–2016 Tasman Sea MHW (Oliver et al. 2017).

![Fig. 5 Change in the frequency of years with warm-season MHW event at a Level 1 or above (DHD > 0 °C·day), b Level 2 or above (DHD > 28 °C·day), c Level 3 or above (DHD > 56 °C·day), and d Level 4 or above (DHD > 84 °C·day) in the latter 16-year period (year 2003-2018) than the earlier 16-year period (year 1986-2001)](image)
4 Discussion and conclusions

In this study, we develop a series of temperature metrics to examine the changes in the thermal properties of warm-season MHWs over time. Analysis of trends in a series of MHW metrics finds that the duration, rather than the magnitude of heat stress, is the primary driver of the increase in intensity of warm-season MHW events from 1985 through 2019. In this section, we discuss the trends in the different MHW characteristics, the physical drivers of those trends, followed by the ecological consequences with a focus on the effects of longer duration MHWs and the loss of priming or pre-conditioning events.

Our results show that warm-season MHWs have become more frequent, longer-lasting, and higher intensity since 1985, which are broadly consistent with the findings of previous studies (Frölicher et al. 2018; Skirving et al. 2019). The frequency of warm-season MHW events has increased across most of the ocean, with largest increases in the frequency of high intensity events mostly in the mid- and high-latitudes. The periods of anomalously warm days (D_c, D_tot, and D_ws) have lasted longer across more than 80% of the ocean, with particularly large increases in the western tropical Pacific, the Southern Indian and the western tropical Atlantic due in part to the phasing of decadal-scale variability. The accumulated heat stress, measured using either the continuous metric (A_c) and the warm season metric (A_w), increased over 87% of the ocean, with large increases over some portions of the western tropical Pacific and the mid- to high-latitude regions. Conversely, annual peak heat stress (HS_peak) decreased in large areas of the ocean, especially in the tropics and high latitudes of the Southern Hemisphere.

The spatial distributions of the significant trends in the metrics and the increases in event frequency show signals of the large-scale modes of natural climate variability (e.g., PDO and NAO). Their coincident synoptic processes, such as the reduced heat loss or anomalous heat advection due to anomalous surface level air pressure and corresponding wind anomalies, contribute to more frequent heat stress in the western Pacific, Northeast Pacific and the ocean southeast of Australia (Holbrook et al. 2019; Sen Gupta et al. 2020). Many of the significant positive trends occurred in the western boundary current and extension regions (also seen in Oliver et al. 2017), such as eastern Australia current extension and Agulhas current extension, which is likely related to anomalous heat advection and reduced upwelling of cold water and air-sea heat flux due to weaker winds (Holbrook et al. 2019; Sen Gupta et al. 2020).

The trends in the warm-season MHW metrics have similar patterns but have lower magnitudes if computed using the p90 threshold, rather than the MMM threshold. The threshold values are also higher here compared to some previous studies (e.g. Oliver et al. 2018; Oliver 2019; Skirving et al. 2019), because of using the entire 1985–2019 time period to define the threshold, a time period that involves the anomalous ocean warmth of recent years. Higher threshold values result in less frequent and lower magnitudes of heat stress. Although the trends in warm season MHW properties are generally robust against the choice of thresholds, the signal of decadal-scale variability in the Pacific was stronger in the analysis using the MMM threshold, which was > 1 °C lower in the central and eastern equatorial Pacific and parts of the North Pacific (Fig. S2). The p90 method appears more robust against the decadal-scale SST variability. The MMM approach, however, might be more representative of marine ecosystems’ experience during a specific baseline period (e.g., the DHW method employed by NOAA Coral Reef Watch). This difference points to the importance of the choice of baseline in defining regional differences in warm-season heat stress.

Regardless of the baseline chosen, the results show that increased duration of anomalously warm SSTs (e.g., D_c), not a change in maximum SST (e.g., HS_peak), was the primary driver of increased accumulation of warm-season heat stress across most of the ocean. The feature was also detected in Skirving et al. (2019), based only warmwater coral reef pixels. This suggests that the lengthening of summer-like conditions and the consequent shortening of winter-like conditions was the dominant contributor to the increase in the accumulated heat stress intensity at the global scale. One consequence of this trend is the shrinking of the conditioning or priming period (D_p), the time between the first HS and the onset of continuous heat stress period (D_c), in large areas of the ocean. The more frequent and concentrated SST anomalies reduced gaps between positive HS such that what might have been multiple different short heat stress periods in the 1980s became a smaller number of warm periods with longer length in 2010s. The loss of such conditioning or priming periods may be a threat to coral reefs and other coastal ecosystems, for which periods of sub-lethal stress can serve as a protective mechanism against subsequent heat stress (Ainsworth et al. 2016).

The large positive trends in the periods of warm days (i.e. D_c, D_tot, and D_ws) and small or even decreasing trends in peak HS (HS_peak) in the western tropical Pacific Ocean suggest a possible thermostat phenomenon. Previous studies have suggested a feedback process may limit increases in peak SST over the warmest part of open ocean, i.e. the Western Pacific Warm Pool where SST is above 28 °C year-round (Clement et al. 2005; Luo et al. 2017). The combination of limited seasonality in SST, coupled atmosphere–ocean oscillations, and ocean warming driven by vast heat transport through large air-sea heat flux and ocean downwelling may sharply increase the chance of exceeding a climatological thermal threshold, leading to significantly increased duration
of heat stress. For example, the combination of ocean warming, weak El Niño development in 2014 and the subsequent canonical 2015–2016 El Niño, led to locations in the central and western equatorial Pacific experiencing coral bleaching-level heat stress for more than 12 consecutive months (Eakin et al. 2019). However, the increase in heat stress intensity seems to be suppressed compared to duration. Previous studies proposed different processes that influence the gradient in tropical Pacific SST warming, including strengthened zonal winds feedback effects (Heede et al. 2020), cloud feedbacks (Li et al. 2016) as well as ocean dynamics (Luo et al. 2017). Although global ocean warming drove the increase in peak SST intensity, these processes might mitigate its increasing rate in parts of the tropical ocean, resulting in a disproportionate increase in duration relative to the intensity of heat stress, as noted for coral reefs in Skirving et al. (2019).

This disproportionate increase in duration relative to the magnitude of heat stress might improve the forecast for some marine ecosystems. A prolonged moderate heat stress event might not lead to the same severity of coral bleaching or mortality as a more acute event. For example, coral bleaching did not occur from 2014 through 2016 in the equatorial Gilbert Islands of Kiribati, even though the SSTs were above the bleaching-level thermal threshold over more than a year (Cannon et al. 2021). Prolonged periods of moderate heat stress could, however, still be a threat to marine ecosystems accustomed to limited SST variability (McClanahan and Maina 2003; Donner 2011). Although thermostat processes might mitigate some of the increase in heat stress intensity in the WPWP, the historical exposure to a small SST range may limit organisms’ low thermal resistance. Kleypas et al. (2008) found that the extent of coral bleaching was lower in the WPWP where the SSTs warmed less than the surroundings between 1950 and 2005. Here, we found that the averaged SST and the accumulated heat stress in the WPWP became larger than the surrounding tropical regions along with more ocean warming in recent years, despite the vastly disproportionate increase in duration relative to the peak and mean intensity of heat stress. The response of coral reefs, mangroves, and other ecosystems in the region to the ongoing significant accumulation of moderate heat stress needs further examination.

Another consequence of the disproportionate increase in heat stress duration relative to maximum and mean HS is a decline in heating rate. Previous studies showed that the rate of heat stress development might influence the responses of marine organisms to heat stress (McLachlan et al. 2020; Martell and Zimmerman 2021). A decrease in heating rate could mitigate some of the effect of the increase in accumulated heat stress on marine organisms by allowing more time for acclimation. The negative trends in heating rate in some portions of the tropical and subtropical regions imply some increased potential for short-term acclimation in warm-water corals. Conversely, the positive trends in the high latitudes, particularly the Northern Hemisphere, suggest ecosystems might face higher risks from more acute heating rates. The physiological benefit of these increases (or decreases) in heating rate could be exacerbated (or offset) by the observed decline in the conditioning or priming period.

It should be noted that the use of multiple data sources in generating the CoralTemp (v3.1) SST dataset might create inconsistencies that potentially affect these results. The dataset bias correction, derived using NRT OSTIA, is consistent with those used in the input data sources (i.e., OSTIA reanalysis SST and NESDIS Geo-Polar SST products). Although the consistency of the bias correction data and the use of a linear transition approach in combining data sources reduce the biases caused by the switch in data sources in the CoralTemp dataset, the differences in data densities among different data sources result in spatial and temporal inconsistencies. Compared with the open ocean and the area around Europe/Africa, the rest of the ocean has less dense SST data before 2002, primarily because of regional variations in the frequency of ship collected in-situ data from ICOADS. The data density increases after 2002, due to the availability of the Geo-Polar SST data.

The analysis of trends in warm-season MHW characteristics might be improved with the availability of longer high-resolution SST data records. Although CoralTemp (v3.1) allows us to explore the warm-season MHW characteristics on fine temporal and spatial scales, the length of the data record (35 calendar years) limits the ability to attribute detected changes in MHW characteristics to anthropogenic forcing vs. internal climate variability. Previous studies also showed the signals of the inter-annual and decadal natural climate variability, such as ENSO, PDO and NAO, in the trend of changes in the warm-season MHW characteristics (e.g., Oliver et al. 2018; Holbrook et al. 2019). While some global-scale SST datasets (e.g., HadISST) extend the SST data record back on centennial timescale, the lower temporal resolutions in such datasets are not appropriate for calculating metrics like heating rate and duration.

Further research on the response of marine ecosystems with foundational species sensitive to heat stress (e.g., corals, kelp and seagrasses) to the different thermal properties of warm-season MHWs is necessary to identify areas that are more or less threatened by climate change (McLachlan et al. 2020). For example, the declining trends in peak HS and heating rate suggest that marine ecosystems in the central equatorial Pacific could be under less threat than would be apparent from considering only accumulated heat stress (e.g., DHWs). The trends in MHW properties, together with comparatively high historical SST variability, might create favourable conditions for foundational marine species like corals to acclimate to climate change.
Under continued global ocean warming (Collins and Sutherland 2019), the trends in these warm-season MHW characteristics might persist or even become stronger. Improved understanding of the properties of the warm-season heat stress and its driving mechanisms are critically important to projecting the impact of ocean warming on marine ecosystems and to better informing both marine conservation and climate change adaptation policies.

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Author contributions Both authors contributed to the study conception and design. XL conducted Data collection, curation, analysis and visualization and written the original draft. SDD provided critical comments and editing on the draft. Both authors read and approved the final manuscript.

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Availability of data and material The NOAA Coral Reef Watch CoralTemp Version 3.1 Daily Global 5 km SST dataset used in this study is publicly available at https://coralreefwatch.noaa.gov/product/5km/index_5km_sst.php.

Code availability The codes that compute the warm-season marine heatwave metrics and their trends and produce the figures in the paper are available from the corresponding author upon request.

Declarations

Conflict of interest Not applicable.

Ethical approval Not applicable.

Consent to participate Both authors consent to participate.

Consent for publication Both authors would like the manuscript to be considered for publication in Climate Dynamics.

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