Lengthening of Warm Periods Increased the Intensity of Warm-season Marine Heatwaves Over the Past Four Decades

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1 Lengthening of warm periods increased the intensity of warm-season marine
2 heatwaves over the past four decades

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6 **Abstract**

7 Marine heatwaves (MHWs), periods of anomalously warm sea surface temperature (SST) which can
8 have significant impacts on marine ecosystems, have increased in frequency and severity over recent
9 decades. Many coastal systems (e.g. coral reefs) are particularly vulnerable to warm-season heat stress
10 when temperature can exceed organisms' thermal thresholds and lead to mass mortality. While many
11 studies have examined the change of the warm-season heat stress occurrence over time, e.g., for coral
12 reefs, there has been less analysis of the thermal structure of heat stress events. Here we examined the
13 trend in the characteristics of warm-season heat stress (referred to as warm-season MHWs) at the
14 global-scale from 1985 to 2019, using multiple metrics for each of duration, peak intensity,
15 accumulated heat stress, heating rates and level of intensity. The results showed that warm-season
16 MHWs have become more frequent, longer-lasting, featured higher peak intensity and accumulated
17 heat stress across most of the ocean over the past four decades. Furthermore, decomposition of the
18 trends in warm-season MHWs structure showed that the increased accumulated heat stress was
19 predominantly driven by the increased duration rather than the increased intensity, especially in the
20 western and central equatorial Pacific. The results contribute to improving the understanding of warm-
21 season MHWs, which may help inform the prediction of their impacts on marine ecosystems as well as
22 marine conservation and management under climate change.

23 1 Introduction

24 Along with anthropogenic climate change, global mean sea surface temperature (SST) has increased by
 25 0.11 °C per decade since the 1970s (Collins and Sutherland 2019). This ocean warming has increased the
 26 frequency and duration of the period of extreme temperatures, often referred to as Marine Heatwave
 27 (MHW; Collins and Sutherland 2019). Scientific and public attention to ocean extreme events has grown
 28 recently, as severe biological impacts have been observed, such as rapid changes in species distribution,
 29 widespread mortality, changes in ecosystem function, and loss of ecosystem services (e.g. Smale and
 30 Wernberg 2013; Hughes et al. 2018; Smale et al. 2019). For example, the 2014/2015 North Pacific MHW
 31 event caused intrusion of warm-water diatom species into the water off Northern California Current
 32 (Peterson et al. 2017), mass mortality of seabirds (Jones et al. 2018), as well as the kelp forest degradation,
 33 and the resulting collapse of the recreational and commercial abalone fisheries in northern California
 34 (Rogers-Bennett and Catton 2019). As the ocean continues to warm, MHWs are likely to become more
 35 frequent, intensive and prevalent (Collins and Sutherland 2019), threatening more broad and severe
 36 impacts on key marine ecosystems including coral reefs, seagrass meadows and mangrove forests
 37 (Hughes et al. 2018b; Arias-Ortiz et al. 2018; Sippo et al. 2018).

38 The quantitative definition of heatwaves in the ocean varies across studies depending on the
 39 particular purpose of the research. Many previous studies (e.g. Sorte et al. 2010; Marbà et al. 2015;
 40 Skirving et al. 2020) used thresholds developed based on the thermal responses of marine species and
 41 ecosystems to identify the periods of potentially fatal heat stress. For example, the extensive literature
 42 on monitoring and predicting coral bleaching, the paling of corals which can occur when exposed to heat
 43 stress, adopted a metric of accumulated heat stress based on a threshold of 1°C above the maximum
 44 climatological mean (e.g. Donner 2011; Skirving et al. 2019; Eakin et al. 2019). Rather than calibrate a
 45 method to a specific ecosystem or marine taxa, the framework proposed by Hobday et al. (2016)
 46 quantifies MHWs more generically using a thermal threshold based on the 99th percentile of SSTs in each
 47 location of each day. This generic definition approach is a method of assessing global ocean heat stress
 48 coherently and comparably. However, unlike the definition using a climatological maximum for detecting
 49 coral bleaching-level heat stress, the Hobday et al. (2016) definition identifies periods of prolonged
 50 temperature anomalies at all times of the year similarly as MHWs. Although heat stress in the cold season
 51 can negatively affect marine organisms (Morley et al. 2017), it is during the warm season that heat stress
 52 may exceed 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 warm-season heat stress, henceforth called "warm-season MHW", by detecting positive SST anomalies relative to a thermal threshold drawn from historical warm-season temperatures.

While it is well established that warm-season MHWs have become more intensive and extensive under global ocean warming (Frölicher et al. 2018; Hu 2021), there has been less research on the structure of heat stress events. Two events with the same magnitude of accumulated warm-season heat stress but with different thermal structures might 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). Thus, it is important to decompose the trend of increasing heat stress intensity via a comprehensive examination of the structure of heat stress events.

In this study, we examined changes in the thermal structure of warm-season MHWs globally over the past four decades. We developed 13 metrics that describe the thermal structure of warm-season MHWs, including duration, peak intensity, accumulated heat stress, heating rates, and frequency of different levels of intensity (Table 1). The trend in each metric from the calendar year 1985 to 2019 was computed using a global daily satellite SST dataset (CoralTemp v3.1). We then explored the global pattern of the warm-season MHW metrics and investigated whether lengthening of heat stress period or increased intensity of peak heat stress is the primary driver of the increased accumulation of heat stress.

2 Methods

2.1 Sea surface temperature dataset

We used the 0.05° x 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 was 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 order to remove abrupt changes from the switch in different data sources, a linear transition approach was applied (Skirving et al. 2020). The dataset provides a continuous record of globally

complete SSTs gridded at 0.05° (i.e. about 5km, a resolution comparable with the scale of many marine ecosystems, e.g. coral reefs; Skirving et al. 2020). The gap-free SST dataset with high spatial and temporal resolutions provides an unprecedented opportunity to develop the fine-scale metrics of warm-season MHWs and evaluate them at small regional scales worldwide. Here, the data analysis excluded 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 marine heatwave (MHW) is qualitatively defined as a prolonged period of extremely high ocean temperatures that persists for days or months (Collins and Sutherland 2019). In this study, we quantified 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 defined a heat stress year (HSY) in each grid cell starting from a month in the climatological cold season. An 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 refer to HSY as year, and label them based on the first calendar year of an HSY (i.e. HSY 1985 is the period of March 1985 to February 1986 in most Northern Hemisphere cells). The final year of the analysis is HSY 2018, which includes data from the calendar years 2018 and 2019.

We conducted all analyses twice, using two different methods to define the thermal threshold in each grid cell to detect daily HS. The first method used the Maximum Monthly Mean (MMM), a threshold widely used in coral bleaching prediction (Skirving et al. 2020). Here, the MMM in each grid cell was calculated as the maximum from a 1985-2019 monthly mean SST climatology. The second method used the 90th percentile of historical warm-season SSTs (p90) as the threshold. The p90 in each grid cell was 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 the approach for defining MHWs in Hobday et al. (2016), 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 the past warm-season SSTs in order to identify warm-season heat stress. Using either of the thermal thresholds, the daily HS was 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:

$$HS_{MMM} = MAX (SST(i, j, time) - MMM(i, j), 0)$$

$$HS_{p90} = MAX (SST(i, j, time) - p90(i, j), 0)$$

Note that unlike the NOAA Coral Reef Watch bleaching prediction method, which excludes $HS < 1^\circ\text{C}$ (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 defined a set of metrics that characterize the thermal structures of warm-season MHW (Table 1, Fig. 1). The period of heat stress was characterized by three metrics: the duration of continuous positive HS that includes peak HS (D_c), the total number of days with positive HS (D_{tot}) and the length of the period between the first and last positive HS (i.e. the warm season length, D_{ws}). The length of D_{ws} could be longer than or equivalent to the D_{tot} , and both of them are usually longer than the D_c . In addition, the conditioning or “priming” period (D_p) was computed as the number of days between the first positive HS in a year and the onset of D_c , referring to the period that might prime marine organism thermal tolerance (Hilker et al. 2016). The rate of peak HS development was described by two metrics: HR measures a heating rate starting from the date of the first positive HS, whereas HR_c measures from the start of the continuous positive HS period. The accumulation of warm-season heat stress was similarly described by metrics measuring the sum of total heat stress in a year (A_{tot}) and the sum of the heat stress throughout the continuous or D_c period (A_c). Thus, A_{tot} might be larger than A_c when some discrete HS exist in a year (e.g. the condition in Fig. 1). We also computed Degree Heating Days (DHD), an approach adapted from the Degree Heating Week (DHW) method used by the NOAA Coral Reef Watch program for real-time coral bleaching alerts (Skirving et al. 2020), to categorize levels of intensity of warm-season MHW events: Level 1 ($DHD > 0^\circ\text{C}\cdot\text{day}$), L2 ($DHD > 28^\circ\text{C}\cdot\text{day}$, equivalent to the $DHW > 4^\circ\text{C}\cdot\text{week}$ threshold used by Coral Reef Watch), L3 ($DHD > 56^\circ\text{C}\cdot\text{day}$, equivalent to the $DHW > 8^\circ\text{C}\cdot\text{week}$ threshold used by Coral Reef Watch) and L4 ($DHD > 84^\circ\text{C}\cdot\text{day}$).

Variable		Description
HotSpot (°C)	HS _{MMM}	Daily HotSpot in that grid cell, using MMM baseline
	HS _{p90}	Daily HotSpot in that grid cell, using p90 baseline
	HS _{peak}	Maximum HS value that year
Duration (day)	D _c	Duration of continuous positive HotSpot, based on the time period that includes the maximum annual HotSpot
	D _{tot}	Total number of days with positive HotSpot
	D _{ws}	Number of days between the first and last positive HotSpot (i.e. the warm season length)
	D _p	Number of days between the first positive HotSpot and onset of a continuous positive HotSpot period (i.e. D _c), referring to the “conditioning or priming period”
Accumulated heat stress (°C·day)	A _c	Accumulated sum of heat stress during the continuous positive HotSpot period, based on the time period used for D _c
	A _{tot}	Accumulated sum of all HotSpot in the given year
	DHD	Maximum 84-day (three months) continuous accumulated sum of positive HotSpot in the given year
Mean heat stress intensity (°C)	I _c	Average HotSpot value over the continuous positive HS period (computed as A _c / D _c)
Heating rate (°C·day ⁻¹)	HR	Rate of SST increase from the first HotSpot in a year to the date of HS _{peak}
	HR _c	Rate of SST increase from the start of the D _c period to the date of HS _{peak}
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

135 Table 1. The metrics measuring the warm-season MHW characteristics.

Fig. 1 A time series of theoretical SST in a year with the metrics characterizing warm-season MHW. The dashed black horizontal line represents the level of Maximum Monthly Mean (MMM) threshold

3. Results

3.1 Trends in warm-season marine heatwave characteristics

Fig. 2 Trend in warm-season MHW characteristics from 1985 to 2018. **a.** the duration of the continuous warm-season MHW (D_c , day·year⁻¹), **b.** the number of annual total HS (D_{tot} , day·year⁻¹), **c.** the number of days between the onset and end of HS in a year (i.e. warm-season length, D_{ws} , day·year⁻¹), **d.** the number of days between the first HS of a year and the start of a continuous event with annual peak HS (i.e. the priming period, D_p , day·year⁻¹). Grey dots indicate $p < 0.05$. All HS were calculated using the MMM baseline

The warm-season MHW metrics were 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 °C greater than the MMM values, with the greatest differences in north of 40°N, 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 smaller magnitudes of HS computed using the p90 threshold, and thereby leading to smaller magnitudes of warm-season MHW characteristics. The trends in the characteristics based on HS using the p90 threshold are generally lower than those computed using the MMM threshold (Fig. 2, 3; Fig. S3, S4). However, the global patterns of trend in the metrics were broadly similar (Fig. 2, 3; Fig. S3,

S4). Therefore, we present the results using the MMM threshold here, with equivalent results for the p90 threshold available in the supplementary material (Fig. S3, S4).

The duration of continuous positive HS period (D_c) significantly increased in 93% of the ocean from 1985 to 2018 at a rate of 0.2 to 3 day·year⁻¹ (Fig. 2a, S3a). The western equatorial Pacific, Bering Sea, Tasman Sea, central Indian Ocean, and parts of the western Atlantic Ocean show large positive slopes of D_c above 1.4 day·year⁻¹ that is equivalent to a 48-day increase in the duration length (i.e. D_c) in 2018 than in 1985 (Fig. 2a). The positive slopes are particularly large in parts of the Western Pacific Warm Pool (WPWP), mainly 3 day·year⁻¹ (Fig. 2a). In contrast, D_c decreased at a rate of 0.2 to 0.8 day·year⁻¹ in areas south of 50°S and in a small part of eastern tropical Pacific and Northeastern Atlantic Ocean (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 (D_{tot}) and the warm season length between the first and last HS (D_{ws}) in a year, show broadly similar spatial patterns to that of D_c , but with a greater extent of decreasing values (Fig. 2a-c). These two metrics increased across 90% and 72% of the ocean over the past 34 years, respectively (Fig. 2a-c). The largest positive slopes of D_{tot} and D_{ws} appear in the western and central tropical Pacific Ocean (i.e. around the WPWP), with values of 5 and 4 day·year⁻¹ respectively, which are larger than that of D_c (Fig. 2a-c). The decreasing trends of D_{tot} and D_{ws} in the central and eastern tropical Pacific as well as parts of the ocean south of 50°S are generally not statistically significant (Fig. 2a-c).

The combination of negative trends in D_{tot} and D_{ws} but positive trends in D_c , as occurred in parts of the central and eastern tropical Pacific, eastern Indian Ocean, and the south of 50°S, suggests that the warm-season heat stress period became more concentrated, with fewer gaps between positive HS. This is reflected in the trend in the priming period (D_p), which decreased across 60% of the ocean, (Fig. 2d). The decreasing trends of D_p were associated with increases in D_c , i.e. longer continuous HS (Fig. 2a).

Fig. 3 Trend in warm-season MHW characteristics from 1985 to 2018. **a.** the accumulation of heat stress of the continuous warm-season MHW (A_c , $^{\circ}\text{C}\cdot\text{day}\cdot\text{year}^{-1}$), **b.** the accumulation of annual total HS (A_{tot} , $^{\circ}\text{C}\cdot\text{day}\cdot\text{year}^{-1}$), **c.** the heating rate from the onset of a continuous event to annual peak HS (HR_c , $^{\circ}\text{C}\cdot\text{day}^{-1}\cdot\text{year}^{-1}$), **d.** the heating rate from the first HS of a year to annual peak HS (HR , $^{\circ}\text{C}\cdot\text{day}^{-1}\cdot\text{year}^{-1}$), **e.** annual peak HS (HS_{peak} , $^{\circ}\text{C}\cdot\text{year}^{-1}$). Grey dots indicate $p < 0.05$. All HS were calculated using the MMM baseline

The annual peak hotspot (HS_{peak}) increased in 59% of the ocean cells including the western boundary regions of the mid- and high- latitude oceans, and decreased or remained relatively unchanged across much of the tropical oceans and south of 45°S (Fig. 3e, S3e). The largest increasing trends are about 0.08 to 0.12 $^{\circ}\text{C}\cdot\text{year}^{-1}$ in some portions of the north of 40°N , translating to a 2.7°C to 4°C higher maximum annual SST in 2018 than 1985. In the regions where HS_{peak} significantly decreased, the rate of decline was comparatively low; for example, HS_{peak} decreased by 0.01 to $0.03^{\circ}\text{C}\cdot\text{year}^{-1}$ (i.e. 0.3°C to 1°C HS_{peak} increase from 1985 to 2018; Fig. 3e).

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, individually (Fig. 3a, 3b), with similar spatial patterns to those of the trends in the equivalent duration variables (i.e. D_c , D_{tot} ; Fig. 2a, 2b). For example, A_c increased significantly 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 equatorial Pacific, North Pacific, Northwestern Atlantic Ocean, Tasman Sea and the ocean of south of Africa (Fig. 3a).

Unlike the duration and accumulated heat stress metrics, the heating rate metrics, HR_c and HR , significantly decreased in 60% and 84% of the ocean, respectively, with exceptions in some western boundary current regions and area poleward of 40°, particularly the Labrador Sea and Bering Sea (Fig. 3c, 3d). For example, the heating rate measured from the first day of the continuous positive HS (HR_c) significantly decreased at a rate of 0 to 0.013 °C·day⁻¹ per year in 83% of the ocean. The large negative trends of HR_c in the tropical and subtropical regions correspond with positive trends in duration (Fig. 2a) and small or no trends in HS_{peak} (Fig. 3a, S5a). The trend in heating rate measured from the date of first HS (HR) showed similar global patterns but lower magnitudes, primarily due to higher magnitudes of increase in the corresponding duration, D_{tot} (Fig. 3b, S5b).

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 in the shifts on the distribution of metrics values from the first half of the time periods (1985-2001) to the second half of the time period (2002-2018; Fig. S7, S8). Large values of D_c , A_{tot} and HS_{peak} was 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 °C·day) were less common (Fig. S7a-c, S8a, S8b, S8e). Conversely, the distribution of D_p , HR_c , and HR shifted to lower values in the second half of time period, corresponding to their globally dominant declining trends.

3.2 Decomposition of changes in accumulated warm-season heat stress

Fig. 4 Coefficients for a) duration (D_c) and b) annual peak HS (HS_{peak}) from a multiple linear regression for the accumulated heat stress during the period of continuous positive HS (A_c), using the MMM baseline for heat stress.

Grey dots indicate $p < 0.05$

Multiple linear regression indicated that the change in duration (D_c), rather than the change in annual maximum HS (HS_{peak}), was a larger contributor to the change in accumulated heat stress (A_c) from year 1985 to 2018 across most of the ocean (Fig. 4). The coefficients for D_c are significantly larger (i.e. $p < 0.05$ and $r^2 > 0.8$) than that for HS_{peak} over the central and eastern equatorial Pacific, as well as parts of the mid- and high- latitude oceans (Fig. 4). The greater contribution of duration to the increasing trend in the accumulated heat stress in most of the ocean is also demonstrated by the smaller magnitudes of the trend in the mean intensity of the accumulated heat stress (I_c) compared to that of the trend in D_c (Fig. S6). Since A_c is the product of the mean intensity (I_c) and duration (D_c), this is a more direct way to decompose the accumulated heat stress into duration and magnitude. The global pattern of the I_c trend was similar to that of HS_{peak} , with negative trends dominant in the tropics and high latitudes of the Southern Hemisphere and positive trends more common in the mid-latitudes (Fig. 3a, S6).

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

Fig. 5 Change in the frequency of years with warm-season MHW event at a) Level 1 or above ($\text{DHD} > 0 \text{ } ^\circ\text{C}\cdot\text{day}$), b) Level 2 or above ($\text{DHD} > 28 \text{ } ^\circ\text{C}\cdot\text{day}$), c) Level 3 or above ($\text{DHD} > 56 \text{ } ^\circ\text{C}\cdot\text{day}$), and d) Level 4 or above ($\text{DHD} > 84 \text{ } ^\circ\text{C}\cdot\text{day}$) in the latter 16-year period (year 1986-2001) than the earlier 16-year period (year 2003-2018)

The increase in the frequency of warm-season MHW events was larger and covered a greater extent of the ocean for the higher-level events in the latter half of the time period (Fig. 5). For example, Level 2 or above ($\text{DHD} > 28 \text{ } ^\circ\text{C}\cdot\text{day}$, equivalent to a NOAA Bleaching Alert) and Level 3 or above ($\text{DHD} > 56 \text{ } ^\circ\text{C}\cdot\text{day}$, equivalent to a NOAA Severe Bleaching Alert) 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 largest increases of frequency occurred in the region extending eastward from the western tropical Pacific. 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 $0 < \text{DHD} \leq 28 \text{ } ^\circ\text{C}\cdot\text{day}$) were more limited.

4. Discussion and conclusions

Our results show that warm-season MHWs have become more frequent, longer-lasting, featured higher peak intensity and higher accumulated heat stress 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. The periods of anomalously warm days (D_c , D_{tot} and D_{ws}) have lasted longer in above 80% of the ocean, with particularly large increases in the western tropical Pacific Ocean, the Southern Indian Ocean and the western tropical Atlantic. The accumulated heat stress, both for the continuous metric (A_c) and the warm season metric (A_{tot}), increased over 87% of the ocean, with particularly large increases over some portions of the western tropical Pacific and the mid- to high- latitudes. Unlike the periods of warm days (D_c , D_{tot} and D_{ws}) and the corresponding accumulated heat stress (A_c , A_{tot}) with the globally prevalent increasing trends, annual peak HS (HS_{peak}) decreased in large areas of the ocean, especially in the tropics and high latitudes of the Southern Hemisphere.

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 continuous warm-season heat stress across most of the ocean. The feature was also detected in Skirving et al. (2019), however, only for pixels containing warmwater coral reefs. It suggests that the predominant impact of recent ocean warming on the warm season is an increase in the number of days and length of the season with SST in excess of the climatological summer maximum. 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 (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 (Newell 1979; Clement et al. 2005). The combination of small 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 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 theoretically restrain the maximum SST, including the feedback effects of evaporation and wind (Newell 1979; Wallace 1992), clouds (Ramanathan and Collins 1991) as well as ocean dynamics (i.e. advective and vertical heat transport; Sun and Liu 1996). Although the significant global ocean warming drove the increase in peak SST intensity, these processes might mitigate its increasing rate, resulting in a disproportionate increase in duration relative to the intensity of heat stress, as noted for coral reefs in Skirving et al. (2019).

Like the western tropical Pacific and other parts of the equatorial ocean, the high-latitude ocean (i.e. south of 40°S) that similarly experiences small seasonality of SST also showed large increases in the periods of warm days and the corresponding large increases in accumulated heat stress. The low seasonality means that SST is close to the warm-season climatological maximum throughout the year, such that small SST trends can lead to a sharp increase in the occurrences and duration of heat stress.

The results are nevertheless clear that the significantly increased accumulation of warm-season MHW heat stress was predominantly driven by the prolonged duration of heat stress than the increased heat stress intensity across most of the ocean. This change in thermal structure may affect marine organisms differently depending on the historical SST variations and the magnitude of accumulated heat stress. The disproportionate increase in duration relative to the change in peak HS might make marine organisms less vulnerable than anticipated by the accumulated heat stress value. For example, a prolonged moderate heat stress event as occurred in parts of the west-central equatorial Pacific from 2014 through 2016 might not lead to coral bleaching or mortality. Coral bleaching did not occur from 2014 through 2016 in the Gilbert Islands of Kiribati's surrounding coral reefs, while the SSTs were above the bleaching-level thermal threshold over more than a year (Cannon et al. in review). However, there is also a potential high thermal threat from the significant accumulation of prolonged periods of

heat stress to marine organisms experienced small SST variabilities, as the heat stress sensitivity appeared negatively related to natural SST variations (McClanahan and Maina 2003; Donner 2011). Although the processes supporting ocean thermostat feature might mitigate the magnitude and extent of heat stress intensity in the WPWP, the significant accumulated heat stress under future ocean warming combined with low thermal resistance related to low SST variabilities might put marine organisms in severe risks. 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 be critically important to the responses of marine organisms to heat stress, such as the timing and extent of coral bleaching (McLachlan et al. 2020; Martell and Zimmerman 2021). A decrease in the heating rate could mitigate the effect of the increase in accumulated heat stress on marine organisms by allowing more time for acclimation. The negative trends in heating rates in some portions of the tropical and subtropical regions imply some increased potential for short-term acclimation in warm-water corals, depending on the importance of the decreasing conditioning period. Conversely, the positive trends in the high latitudes, particularly the Northern hemisphere, might be under higher risks from more acute heating rates. The physiological benefit of the increase (or decrease) in heating rate could be exacerbated (or offset) by the observed decline in the conditioning or priming period.

All the warm-season MHW metrics were computed based on daily heat stress (HS) relative to two thermal thresholds (i.e. MMM and p90). The global patterns of warm-season MHW metrics are similar but have lower magnitudes, if computed using the p90 threshold compared to those calculated using the MMM threshold. It suggests that the trends in these warm-season MHW characteristics are generally robust against the different choices of a thermal threshold. Note that the values of our thresholds are larger compared to some findings in 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 high-level ocean warming of recent years. The use of high-level thresholds results in less frequent and lower magnitudes of heat stress.

The use of multiple data sources in generating the CoralTemp (v3.1) SST dataset might create inconsistencies that potentially affect our results. The dataset bias correction reference 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 when data sources switch, 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, mainly because of the regional variations of the frequency of ship collected in-situ data from ICOADS that are blended for generating the SST dataset. The higher data density from 2002 forward due to the availability of the Geo-Polar SST data could produce some inconsistencies that might imply errors when comparing the MHW metrics between the latter 17-year period (2002-2018) and the earlier 17-year period (1985-2001) in some regions.

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 showed the signals of the interannual and decadal natural climate variabilities, such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO), in the trend of changes in the warm-season MHW characteristics (e.g. Oliver et al. 2018; Holbrook et al. 2019). While some in-situ SST datasets (e.g. HadISST) extend the SST data record back on centennial timescale, the lower temporal resolutions are not appropriate for calculating metrics like heating rate and duration.

Continued observational and modelling research examining the response of marine ecosystems with foundational species that are vulnerable to heat stress (e.g. corals, kelp and seagrasses) to different heat stress structures (e.g. the trends in warm-season MHW characteristics we demonstrated) is necessary to identify the areas where might face more or less severe threat from climate change (McLachlan et al. 2020). For example, the small trends in the period of warm days and accumulated

heat stress, combined with the declining trends in peak HS and heating rates, marine ecosystems in the central equatorial Pacific could be under less threat than other tropical areas. The potential impacts of these trends in the central equatorial Pacific together with comparatively high historical SST variabilities might have provided a more favourable condition for marine species, particularly those less-mobile organisms (e.g. corals, kelp), to acclimate to climate change.

Under the likely continuing global ocean warming through this century (Collins and Sutherland 2019), the trends in these warm-season MHW characteristics might persist or even become stronger. Improved understanding of the structure 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 inform marine conservation, marine management and climate change adaptation policies.

380 **Declaration**

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387 Conflicts of interest/Competing interests

388 Not Applicable

389 Availability of data and material

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

392 Code availability

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

395 Authors' contributions

396 Both authors contributed to the study conception and design. Xinru Li conducted Data collection,
397 curation, analysis and visualization and written the original draft. Simon D. Donner provided critical
398 comments and editing on the draft. Both authors read and approved the final manuscript.

399 Ethics approval

400 Not applicable

401 Consent to participate

402 Both authors consent to participate.

403 Consent for publication

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

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