Analysis of compound marine heatwave and low-chlorophyll extremes across the Indo-Pacific Ocean

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1. Purposes

This project aimed to investigate the multi-scale spatiotemporal variability (climatology, seasonality and linear trends) and potential drivers (large-scale modes of climate variability) of compound marine heatwave and low-chlorophyll (MHW-LChl) extreme events in the Indo-Pacific Ocean.

2. Data and methods

To identify and characterize compound MHW-LChl events, we employ satellite-derived sea surface temperature (SST) from the National Oceanic and Atmospheric Administration (NOAA) Daily Optimum Interpolation Sea Surface Temperature (OISST) at 0.25° resolution. For chlorophyll concentration (Chl), the daily data were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) global biogeochemical multi-year reanalysis. The analysis period for all the above datasets is 1993–2020, and anomalies of all variables were calculated relative to the corresponding mean seasonal cycle.

Following the studies of Le Grix et al. (2021) and Hobday et al. (2016), we define MHWs as abnormal high-temperature extremes where the daily SST anomaly exceeds its 90th percentile threshold. For consistency, LChl events are defined as days when the surface Chl anomaly falls below its 10th percentile threshold. Intuitively, compound MHW and LChl extremes are defined as when both marine heatwaves and low-chlorophyll extremes co-occur in time and space (Figure 1). For each compound event, we calculate a series of metrics to quantify variations in its characteristics, such as the total days, duration, and intensity (Table 1).

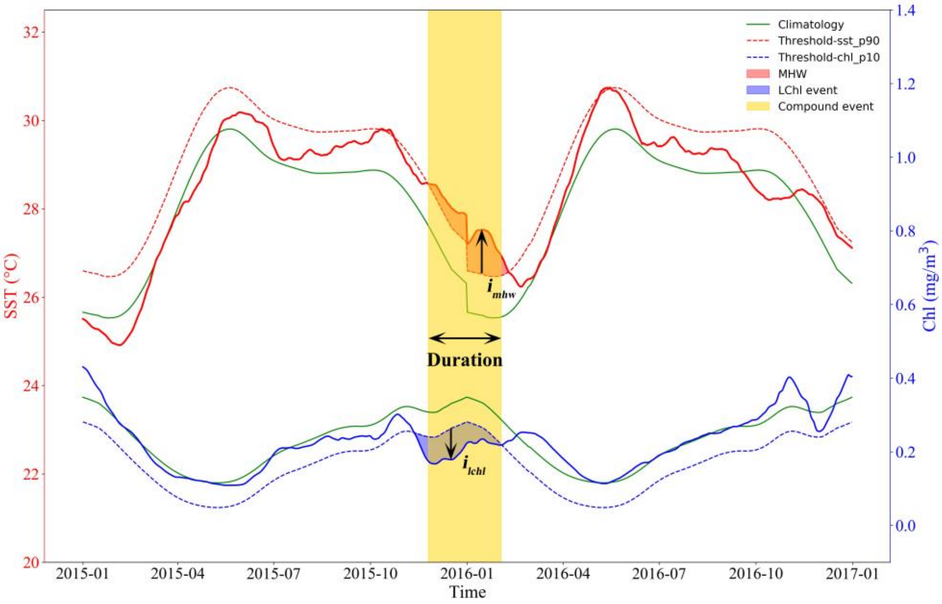

Figure 1. Schematic diagram illustrating the definition of MHWs, LChl events, and compound MHW-LChl extreme events.

Table 1. Definitions of metrics to characterise compound MHW-LChl extremes.

Name	Definition	Unit
Climatology	The climatological mean, calculated using daily SST and Chl as well as smoothed by applying a 30-day moving average for 1993–2020 (28 years)	°C & mg/m^3
Threshold	The seasonally varying value that defines a compound event (e.g., the 90th percentile of SST anomaly and the 10th percentile of Chl anomaly based on the climatology period, which are denoted as sst_p90 and chl_p10, respectively)	°C & mg/m^3
Total days	The total number of compound event days, which daily SST anomaly above sst_p90 and Chl anomaly below chl_p10	days (d)
Duration	The number of days the compound event lasted without interruption (note that two consecutive events with an interval of ≤ 1 day are combined, but the non-compound intermediate day is not counted in the duration)	days (d)
Intensity	i_{mhw}: The difference between the average SST anomaly over all MHW days of an event and its sst_p90 (i.e., mean intensity of MHWs)	°C
	i_{lchl}: The difference between the average Chl anomaly over the duration of a LChl event and its chl_p10 (i.e., mean intensity of LChl events)	mg/m^3
	i_{com}: The product of standardized SST anomalies and standardized Chl anomalies, a unitless intensity index of compound events	unitless

3. Results

3.1 Climatological characteristics of compound MHW-LChl extremes

The climatology of the annual total days, duration, and intensity of compound MHW-LChl extremes has a heterogeneous distribution across the Indo-Pacific Ocean for 1993–2020 (Figure 2). The frequency of MHW-LChl extremes exceeds 1% over 60% of the ocean area (see stippling areas; Figure 2a). It displays that the co-occurrence of MHWs and LChl events more often than expected if variations in SST and Chl anomalies were independent. The mean annual total days of compound MHW-LChl events is 5.17

d, ranging from 0.1 to 17.8 d. Higher-value areas are in the south of the western South China Sea (WSCS) (> 8.4 d) and southwestern Indonesian Seas (IS) (> 9.4 d), and lower-value in the northeastern East China Sea (ECS) (< 3.4 d) and central Philippine Sea (PS) (< 1.4 d). Combining the results of correlation analysis (Figure 2d), it can be concluded that there is a significant negative correlation between the MHW-LChl occurrences (Figure 2a) and the correlation coefficient of SST and Chl anomalies. That is, hotspots of compound MHW-LChl extremes correspond to regions where SST and Chl anomalies are strongly negatively correlated, and vice versa.

The spatial pattern of the average duration of compound MHW-LChl extremes broadly resembles the total days but with slight differences (Figure 2b). Long MHW-LChl events (> 7.0 d) concentrate in the east of Taiwan Island, the central-southern WSCS, and northwestern New Guinea. Short MHW-LChl events (< 3.0 d) are observed in the PS, where the total MHW-LChl days are also low. Conversely, the spatial distribution of intensity is rather heterogeneous (Figure 2c). The mean intensity of compound MHW-LChl extremes ranges from 0.21 to 5.75. Areas with high intensity (> 2.2) mainly include the midwest of the Japan Sea, the Kuroshio Current, north and south of the WSCS, Java Sea, southeastern Java Island, and west of New Guinea Island. Overall, the southern WSCS, southeastern Java Island and northwestern New Guinea in the IS tend to register the highest total days (> 8.4 d), longest-lasting (> 6.5 d), and strongest intensity (> 2.4).

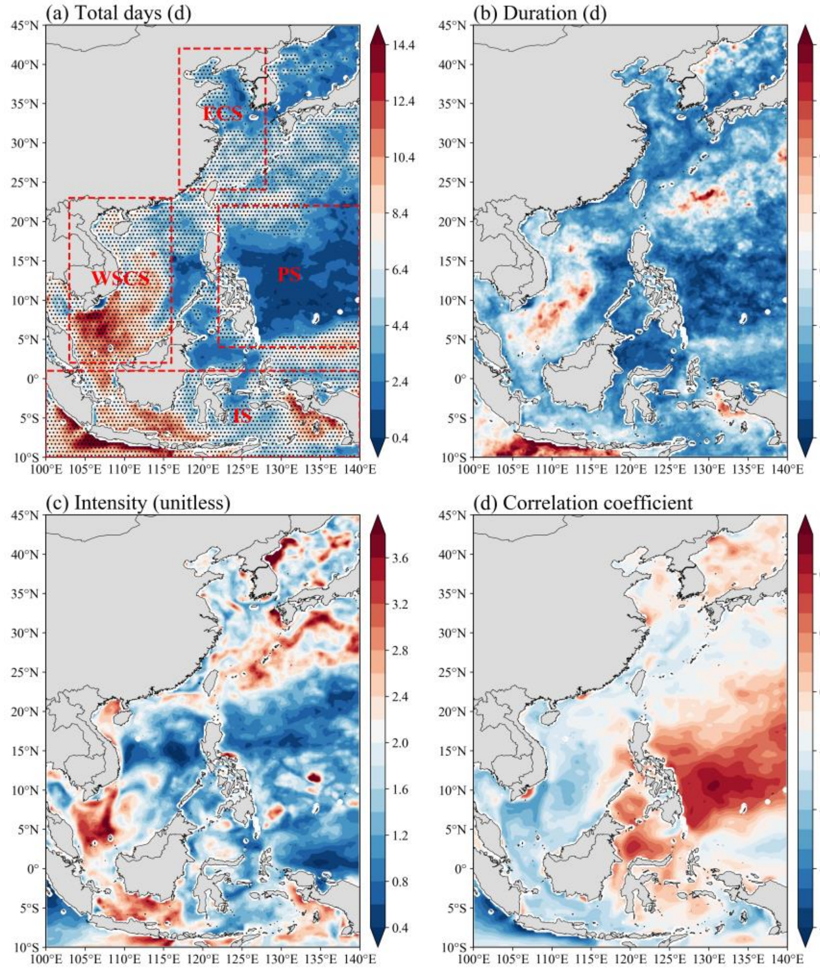

Figure 2. The annual average compound MHW-LChl events during 1993–2020: (a) total days, (b) duration, and (c) intensity. (d) Linear correlation coefficient of SST and surface Chl anomalies.

3.2 Long-term spatiotemporal trends in compound MHW-LChl extremes

Figure 3 displays the spatial distribution of the estimated trends of compound MHW-LChl extremes during 1993–2020. The patterns of the three MHW-LChl event properties show high similarity. For total days, the highest significant trends (> 2.2 d/decade) are mainly found along the Kuroshio Current, Beibu Gulf, and the south of Java Sea, especially in the southern WSCS with a linear trend above 4.2 d/decade ($p < 0.05$; Figure 3a). In these regions, the MHW-LChl duration and intensity show a linear increase of 0.8–2.2 d/decade and 0.2–0.8, respectively ($p < 0.05$; Figures 3b, c).

In the whole study region, the mean MHW-LChl days and duration exhibit rapidly increasing trends of 1.52 d/decade and 0.72 d/decade, respectively ($p < 0.01$; Figures 4a, f). The total days display a relatively larger trend of 3.30 d/decade ($p < 0.05$; Figures 4a–e) only in the WSCS. For intensity, MHWs, LChl events, and compound MHW-LChl extremes all remain a relatively stable weak trend throughout the study period ($p < 0.1$; Figures 4k–o), but PS experiences a significant decreasing trend ($p < 0.05$; Figure 4n). Taking a univariate perspective, the total days and duration of MHWs display extremely significant positive trends ($p < 0.01$) in most parts of the study region. However, LChl events generally show no statistically significant negative trends. Thus, we conclude that the long-term trends of most compound MHW-LChl extremes are supposed to be caused by changes in MHWs instead of LChl events.

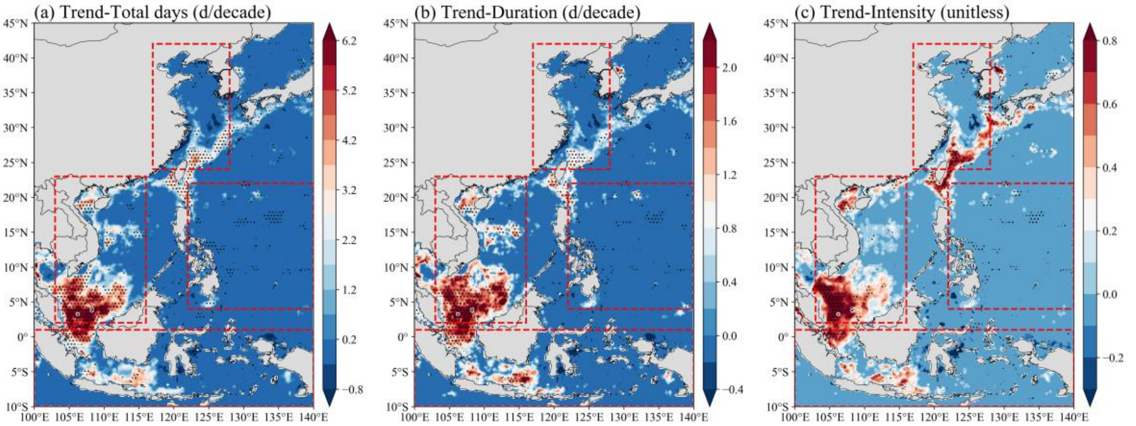

Figure 3. The linear trend of compound MHW-LChl extremes over the 1993–2020 period: (a) total days, (b) duration, and (c) intensity. Stippling indicates areas where the trends are significant at a 0.05 level.

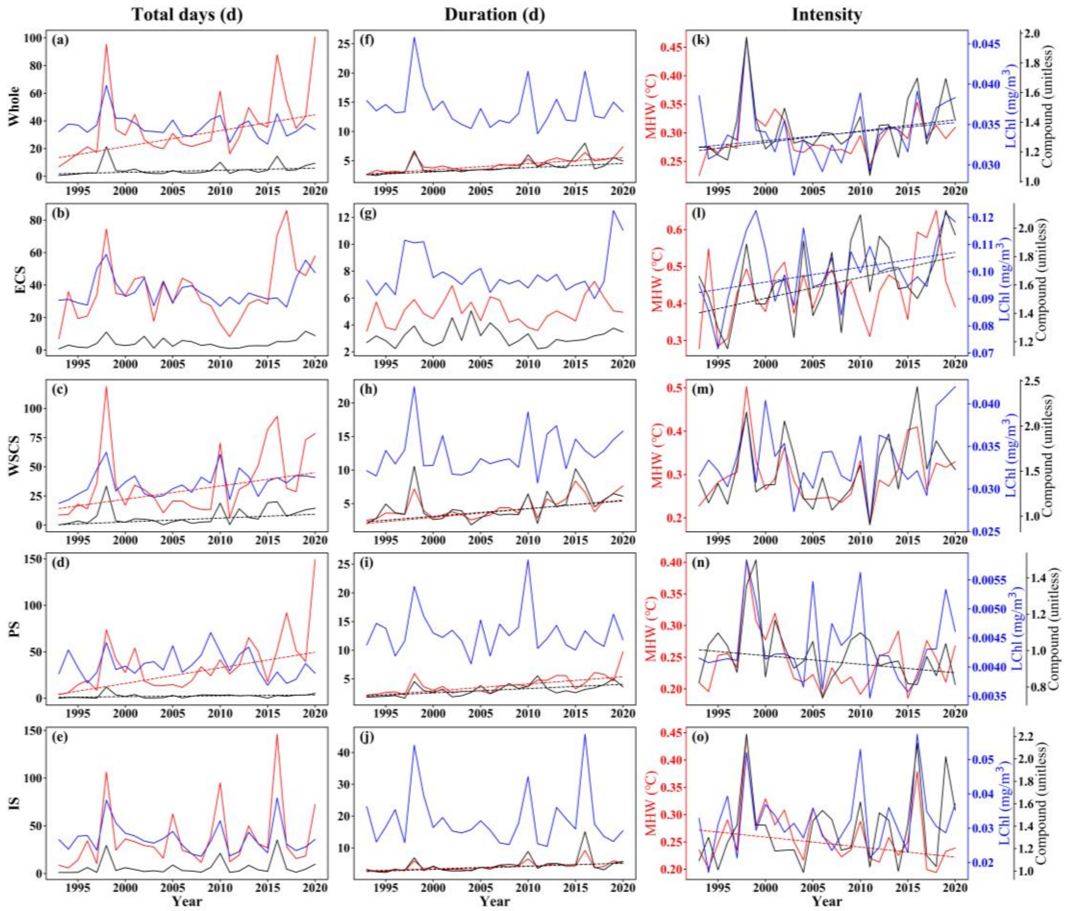

Figure 4. The annual time series of regionally-averaged (a–e) total days, (f–j) duration, and (k–o) intensity of MHWs (red lines), LChl events (blue lines), and compound MHW-LChl extremes (black lines) during 1993–2020.

3.3 Relationship between MHW-LChl extremes and climate modes

To further understand the influence of large-scale modes of inter-annual to decadal climate variability on compound MHW-LChl events in the study region, we perform correlation and composite analysis between the total days of compound events and five different climate modes, such as ENSO, DMI, NAO, AO, and PDO.

Figure 5 illustrates the large regional differences in the correlation distribution of total MHW-LChl days during these climate modes in 1993–2020. Most MHW-LChl occurrences are significantly related to ENSO compared to other climate indices (Figure 5a), implying its critical role in compound extremes over the Indo-Pacific. Specifically, the positive phase of ENSO can contribute to enhancing total MHW-LChl days along the Kuroshio and most parts of the Java Sea, especially in the southern WSCS ($r > 0.35$). In contrast, the negative phase of ENSO is closely correlated with increased MHW-LChl days in the northern New Guinea Island and southern Java Island.

The correlation pattern between total MHW-LChl days and DMI (Figure 5b) broadly resembles that of ENSO. However, during the positive phase of DMI, MHW-LChl events in the WSCS are less affected by it than by ENSO; during the negative phase of DMI, along the southern Sumatra-Java Island in IS are observed more MHW-LChl days (> 7.5 d) than in the negative ENSO phase. Different from both positive ENSO and DMI phases, the positive phases of NAO and AO are the relatively dominant phases that enhance MHW-LChl days in the ECS, even if they have a slightly weak significant correlation coefficient (Figures 5c,d).

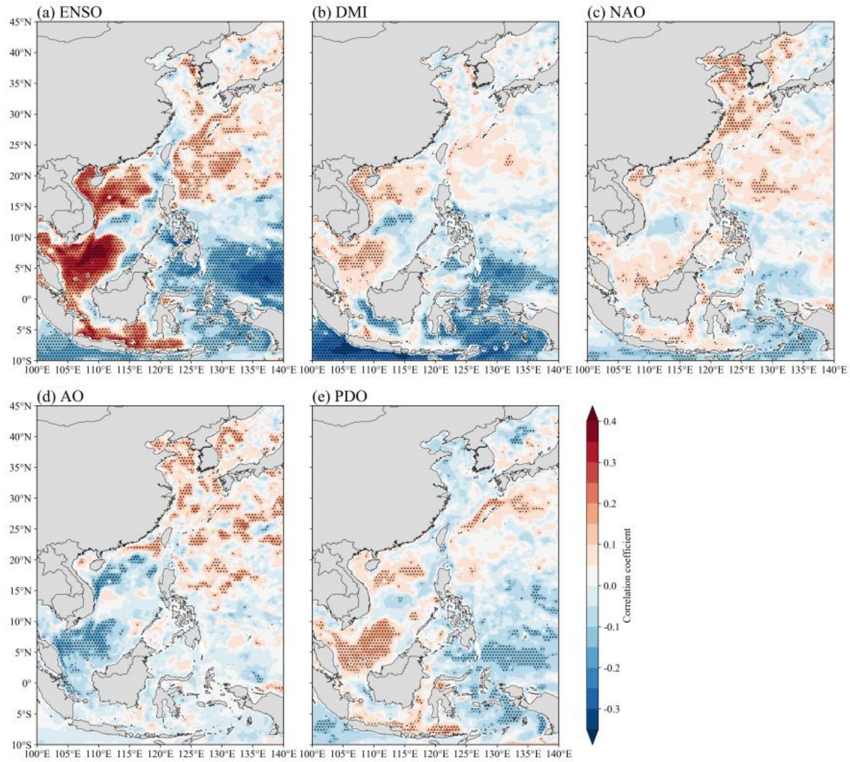

Figure 5. Spatial patterns of the correlation coefficients between the MHW-LChl total days field and (a) ENSO index, (b) DMI, (c) NAO index, (d) AO index, and (e) PDO index from 1993 to 2020. The dotted areas indicate statistically significant at the 95% confidence level.

4. Conclusions

(1) The climatological spatial distribution of compound MHW-LChl extremes in total days, duration, and intensity exhibits heterogeneous distributions.

(2) There are statistically significant increasing trends in MHW-LChl events for all properties on both seasonal and inter-annual timescales coinciding with El Niño years.

(3) Spatial distribution: MHW-LChl distribution mainly follows the distribution of LChl events; Time series: Most of the long-term trends in MHW-LChl can be explained by MHWs.

(4) The total MHW-LChl days are strongly modulated by large-scale climate modes such as ENSO and DMI.

5. Perspectives in future

In the future, we should carry out more process-oriented research to determine the precise physical and biogeochemical processes underlying the various spatiotemporal patterns of compound MHW-LChl extreme events.