

Supplementary Information for:

The ocean losing its breath under the heatwaves

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Supplementary Note 1. LMF analysis after detrending the data

LMF analysis after detrending the data is conducted serving as a sensitivity analysis within our study. Supplementary Fig. 22 illustrates the observation-based correlation coefficient between temperature and oxygen concentration anomalies (the anomalies are calculated relative to the mean seasonal cycle), along with the LMF of CLH events, for the nine ocean basins. The circles represent the values before detrending, while triangles signify the values after detrending.

It can be seen that the correlations reduced in most of the ocean basins after detrending, as indicated by the transition from circles to triangles (Supplementary Fig. 22a). Despite this decrease, all correlations after detrending remain negative, except for the East Pacific, and exhibit statistically significant results at the 99% confidence level. Concerning the LMFs, we observed a decline in their values across most ocean basins, with the most significant decrease evident in the North Pacific Ocean. Contrarily, the North Atlantic and West Indian Oceans display a slight increase in LMF after detrending. All of the ocean basins, except for East Pacific Ocean, have LMF values larger than 1.0 for the detrended time series.

Supplementary Fig. 23 displays the LMFs in model simulations before and after detrending temperature and oxygen concentration time series, along with their differences. Compared with the results from original data, an overall decrease in LMF is evident across the global ocean after detrending, with the most significant decline found in the North Atlantic and Pacific Ocean (Supplementary Fig. 23c). Regions with LMF values less than 1.0 expand in the equatorial oceans. However, the spatial patterns of LMFs in the detrended time series closely resemble those before detrending, with the majority of regions exhibiting LMF values larger than 1.0 (Supplementary Fig. 23b).

Supplementary Note 2. Contribution of frequency and duration changes to the increase of annual CLH days

The annual CLH days (hereafter abbreviated as ACD) is determined by the frequency of CLH event and the annual averaged duration: $ACD = fre \times dur$. Therefore, the changes of the annual CLH days could be written as:

$$\Delta ACD = fre \times \Delta dur + dur \times \Delta fre + \Delta fre \times \Delta dur \quad (1)$$

The first term on the right side of the equation denotes the impact of changes in duration, the second term is the contribution of frequency change and the third is the combination effect of the two changes. Based on this equation, we firstly analyzed how frequency and duration changes contribute to modifications of global averaged annual CLH days (Supplementary Fig. 24). It is evident that both frequency and duration contribute positively to the rise in annual CLH days on a global scale, but what particularly noteworthy is that this increase is predominantly attributable to the rise in frequency.

At the regional scale, differences emerge with varying in locations (Supplementary Fig. 25). The contribution of duration prolongation is most significant in East Indian Ocean near the Australia, as well as some Pacific regions. Increase of frequency contributes most to the annual CLH days increase in the North Pacific Ocean, West Indian Ocean and Southern Ocean surrounding the Africa. Simultaneously, the increase of annual CLH days in North Atlantic Ocean are dominated by the combination effect of an increase in event frequency in conjunction with a prolongation of event duration. These findings reveal distinct variations in the response of CLH event to climate change across the ocean regions.

Supplementary Note 3. Consistency between the results from EEMD-based method in our study and the shifting baseline approach

There are several methods for separating relatively short-lived and transient changes from long-term signals, such as detrending the data using linear or polynomial splines, subtracting the ensemble means, and applying low-pass filtering. Here, we compare the characteristics of marine heatwaves derived from the shifting baseline approach, which uses a shifting window for extreme event definition, with those derived from the EEMD-based method. For the shifting baseline approach, the baseline period is set as the most recent 30-year period to the year under study (e.g., period 1985–2015 is used as a reference for analyzing heatwaves in the year 2000).

As for the EEMD-based method, the EEMD (Ensemble empirical mode decomposition) is firstly applied to separate the “long-term warming signal” and “relatively short-lived and intense changes in ocean temperature”. Then the marine heatwaves are detected in the processed timeseries (Supplementary Fig. 7). Note that the baseline is calculated over the full range of years in the supplied timeseries. Moreover, the principles underlying the EEMD are elucidated in Wu et al. (2009)¹ and Huang et al. (2017)².

Supplementary Fig. 26 presents an overall view of annual total days of marine heatwave derived from the two methods, the shifting baseline approach and EEMD-based method, respectively. The temporal variations in globally-averaged annual total days based on shifting baseline approach (the blue line in Supplementary Fig. 26a) exhibit a remarkable degree of consistency with those obtained through the

EEMD-based method (red line), with a correlation coefficient of 0.91, which is statistically significant at the 99% level. The most significant disparities are found in the late 1970s, yet they remain below 13 days, a threshold we think typically deemed acceptable. Furthermore, we compare the spatial distributions of the annual total days obtained from the two different methods. The characteristics of annual total days from shifting baseline approach corresponds well with those from EEMD-based method (Supplementary Fig. 26b-g). Even for the late 1970s, a period when most significant disparities existed, our analysis reveals a high spatial consistency in the annual number of heatwave days as derived from both methods, with a Pearson pattern correlation of 0.81.

We also evaluate the differences of shifting baseline and EEMD-based method in detecting low-oxygen extreme events. The results are shown in Supplementary Fig. 27, which are similar with those in marine heatwave.

The spatial distributions of extreme event shown in the figures above reveal that not only the shifting baseline but also the EEMD-based method can provide the important information about connections with ocean oscillation modes such as ENSO. For example, a clear ENSO-related pattern is found in Supplementary Fig. 26 d, g (also observable in Supplementary Fig. 27 d, g). It therefore provides robust evidence for the reliability of our findings shown in Fig. 4b and 4c in the manuscript, which describe the relationship between extreme event and climate variability.

It should be particularly noted that the shifting baseline approach, which uses a shifting window for extreme event definition, exhibits certain limitations inherent to

its methodology³. On the one hand, a moving baseline does not necessarily remove the influences of rising mean temperature, and the long-term warming signal is still included in the 30-year baseline period. On the other hand, the definition of shifting baseline imposes a limitation on the length of the time series for extreme events. Specifically, the data is missing for the initial 15 years as well as the final 15 years of the time series, as illustrated by the blue line in Supplementary Fig. 26a. The EEMD-based method allows us to overcome the inherent limitations of shifting baseline approach while preserving its core tenets (i.e., separating the relatively short and transient changes from long-term signals).

As illustrated in Fig. 4b, the EEMD-based method has already been employed in our manuscript. This figure presents a global map indicating variations in the annual total of extreme event days attributed to the relatively short-lived and transient changes of temperature and oxygen concentration.

Supplementary Note 4. Descriptions of nine climate indices

Below, we provide descriptions of these climate mode indices along with their corresponding calculation methods.

1. Niño-3.4 index is indicative of the state of ENSO⁴. It is calculated based on the area averaged sea surface temperature from 5°S-5°N and 170-120°W.

2. EMI (ENSO Modoki Index) measures the strength of El Niño Modoki, which is based on the difference between sea surface temperature in the central equatorial Pacific and the averaged eastern and western Pacific⁵.

3. DMI (Dipole Mode Index) measures the strength of the Indian Ocean Dipole (IOD), which is based on anomalous sea surface temperature difference between the western equatorial Indian Ocean (50-70° E and 10°S-10°N) and the south-eastern equatorial Indian Ocean (90-110°E and 10°S-0°N)⁶.

4. NAO (North Atlantic Oscillation) index describes a north-south dipole in atmospheric pressure anomalies between the subtropical high-pressure system near the Azores and the subpolar low-pressure system near Iceland⁷. The index is based on a rotated principal component analysis of monthly standardized 500-mb height anomalies in the North Atlantic poleward of 20°N.

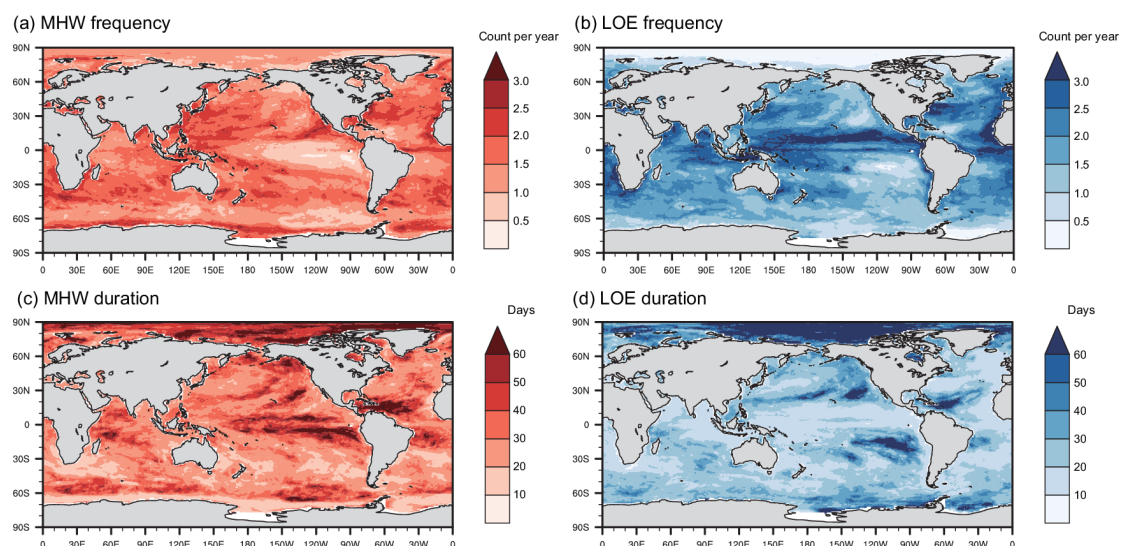
5. PDO (Pacific Decadal Oscillation) index describes climate pattern characterized by the alternation between warm and cool phases of sea surface temperatures in the North Pacific Ocean⁸. The index is defined as the leading principal component of North Pacific monthly sea surface temperature variability poleward of 20°N.

146 6. TPI (Tripole index) is used to indicate the state of the IPO (Interdecadal Pacific
147 Oscillation), and is based on the difference between sea surface temperature
148 anomalies averaged over the central equatorial Pacific and the average of sea surface
149 temperature anomalies in the northwest and southwest Pacific⁹.

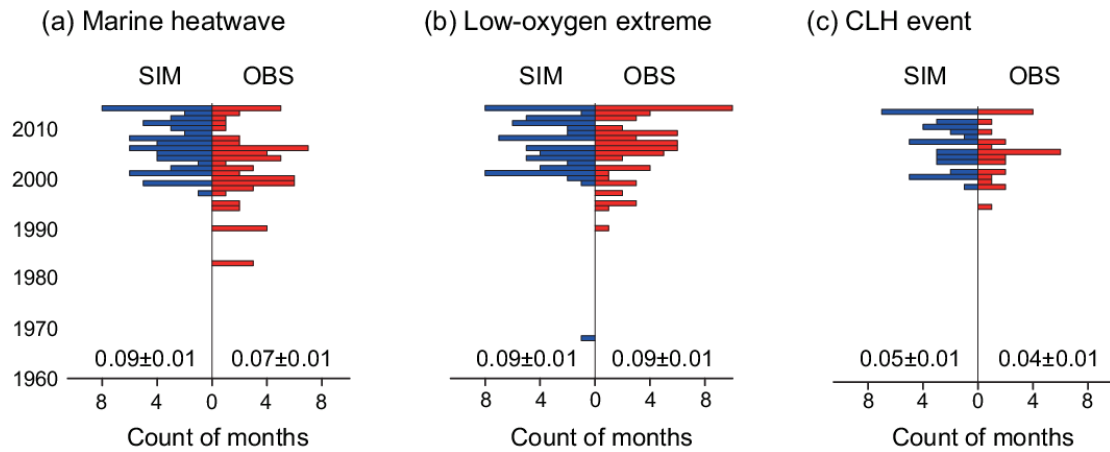
150 7. Atlantic Niño index (Abbreviated as ATLN1) describes warm and cold water
151 events in the tropical Atlantic¹⁰. It is based on the sea surface temperature anomalies
152 in the tropical eastern South Atlantic (17–7°S and 8–15°E).

153 8. SAM (Southern Annular Mode) index describes low frequency variability of the
154 Southern Hemisphere extratropics. The index is defined as the difference of zonal
155 mean sea level pressure between 40°S and 65°S¹¹.

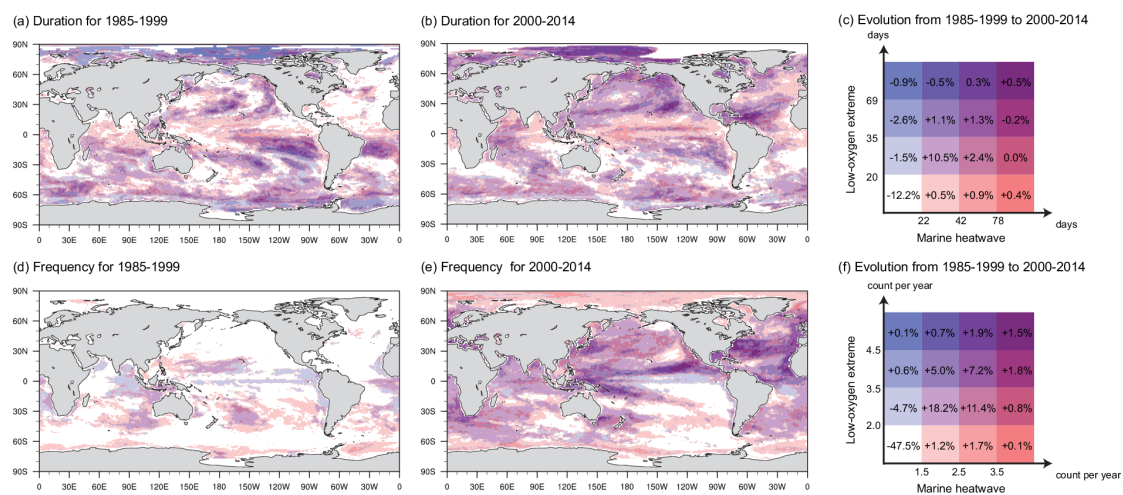
156 9. NPGO (North Pacific Gyre Oscillation) index represents the low-frequency
157 variability of sea surface height anomalies in the North Pacific¹². It is based on the
158 second mode of sea surface height variability in the northeast Pacific.



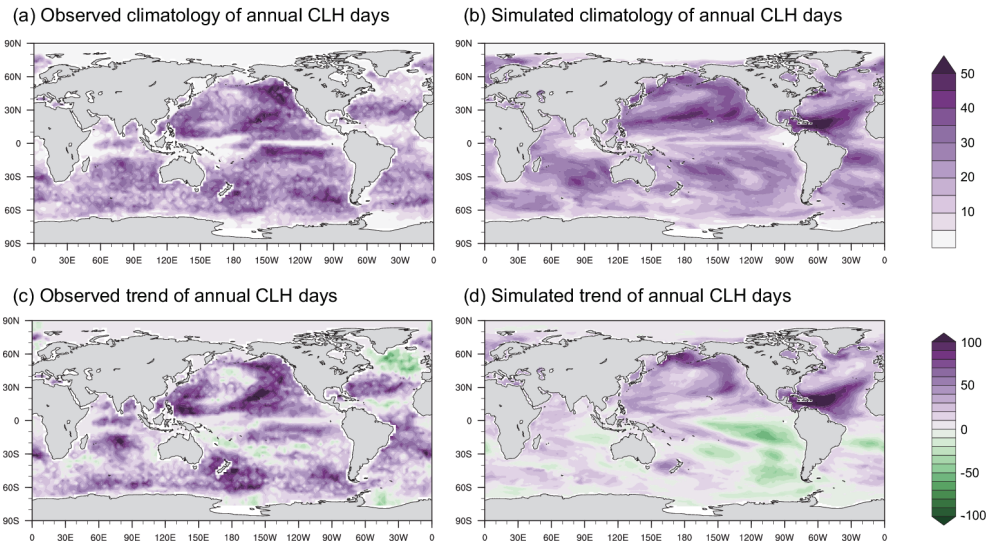
Supplementary Figure 1. The spatial distributions of marine heatwave (a, c) and low-oxygen extreme event (b, d) averaged from 1985 to 2014 based on model simulations. Here we focus on extreme events within the uppermost ocean layer (0-10 meters). Both the two panels exhibit outcomes derived from model simulations.



Supplementary Figure 2. Number of months with extreme events. **a**, marine heatwave. **b**, low-oxygen extreme. **c**, compound low-oxygen extreme and heatwave event. Results derived from model simulations are colored in blue and the WOD observations colored in red. The linear trend (units: month per year) is shown in the bottom. Note that the simulation data is regridded to monthly mean values here for sake of comparisons.

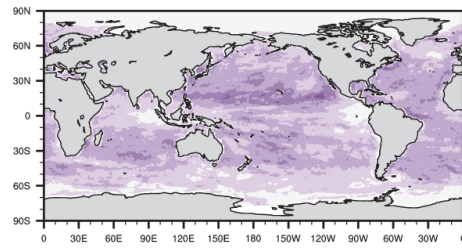


174 **Supplementary Figure 3.** Joint distributions of the two types of extreme event and
 175 their evolutions. This figure is similar with Fig. 1, but for duration (a-c) and frequency
 176 (d-f). The duration and frequency of each extreme event type is classified into four
 177 levels. Panel c and f present the changes in percentage of marine regions affected by
 178 extreme events from 1985-1999 to 2000-2014.

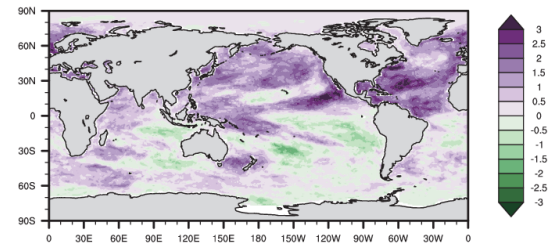


Supplementary Figure 4. The characteristics of annual CLH days in observations (a, c, unit: days) and simulations (b, d, unit: days per 15 year). In this figure, the observed CLH event is based on OISST and GOBAI-O2 datasets and its original unit is “month per year”. For sake of comparisons with the model results, here we convert this unit to “days per year” by assuming a factor of 30 days per month. Note that panel b is the same as Fig. 2a in the main text

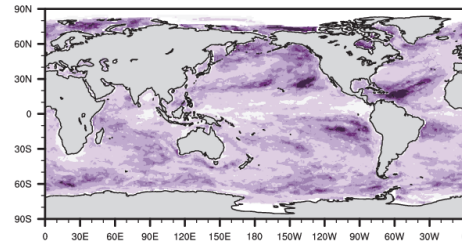
(a) Frequency 1895-2014 averaged



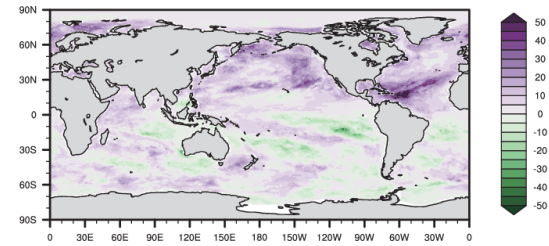
(b) Changes of frequency (2000-2014 minus 1985-1999)



(c) Duration 1895-2014 averaged

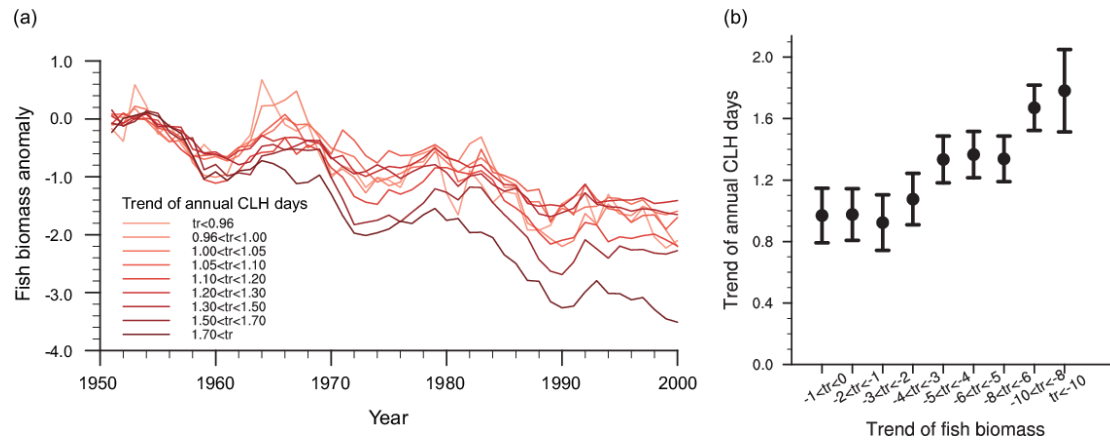


(d) Changes of duration (2000-2014 minus 1985-1999)



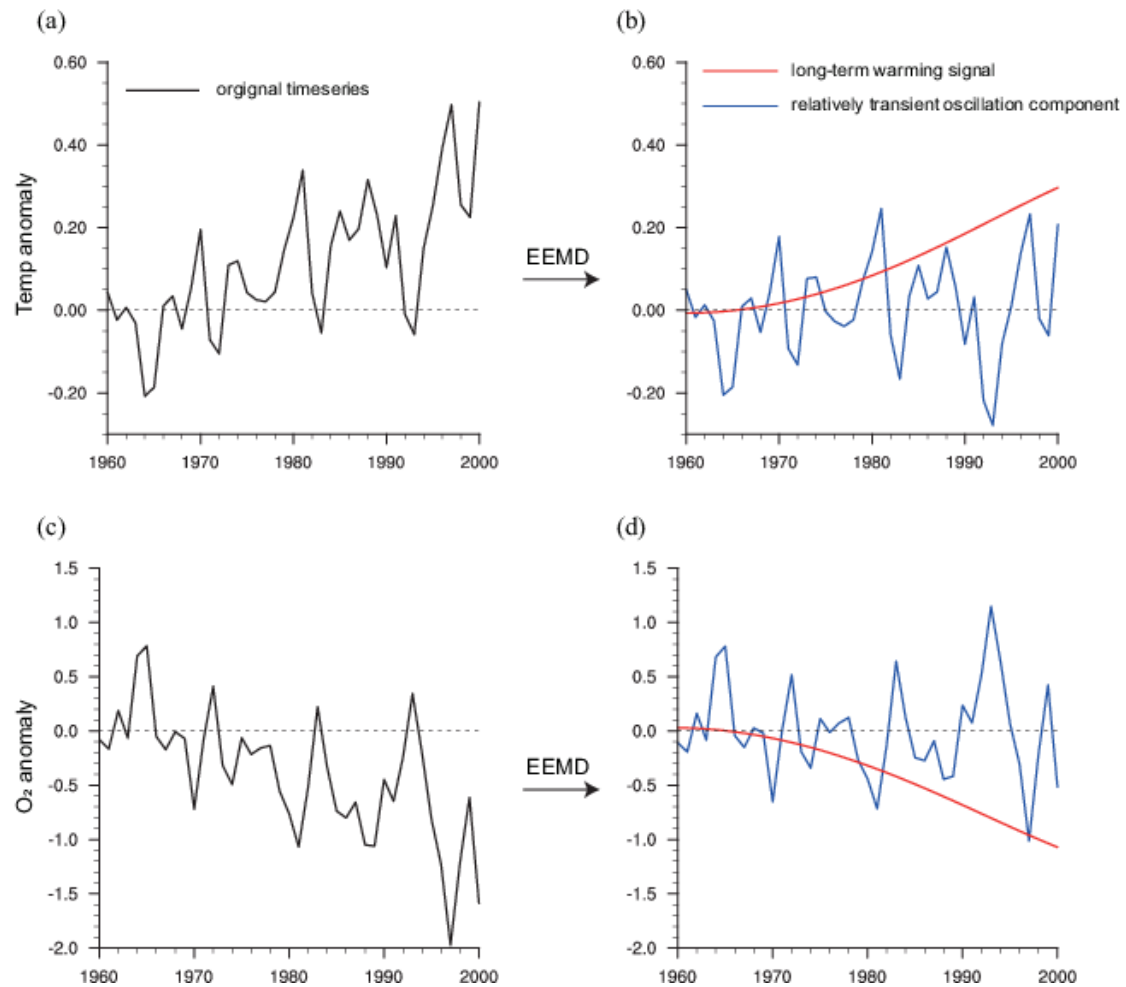
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187 **Supplementary Figure 5.** Characteristics of CLH events in the historical periods. **a-b**,
188 spatial distribution of frequency and its changes (units: count per year). **c-d**, spatial
189 distribution of duration and its changes (units: days). All of the panels exhibit
190 outcomes derived from model simulations. these results are derived from model
191 simulations.

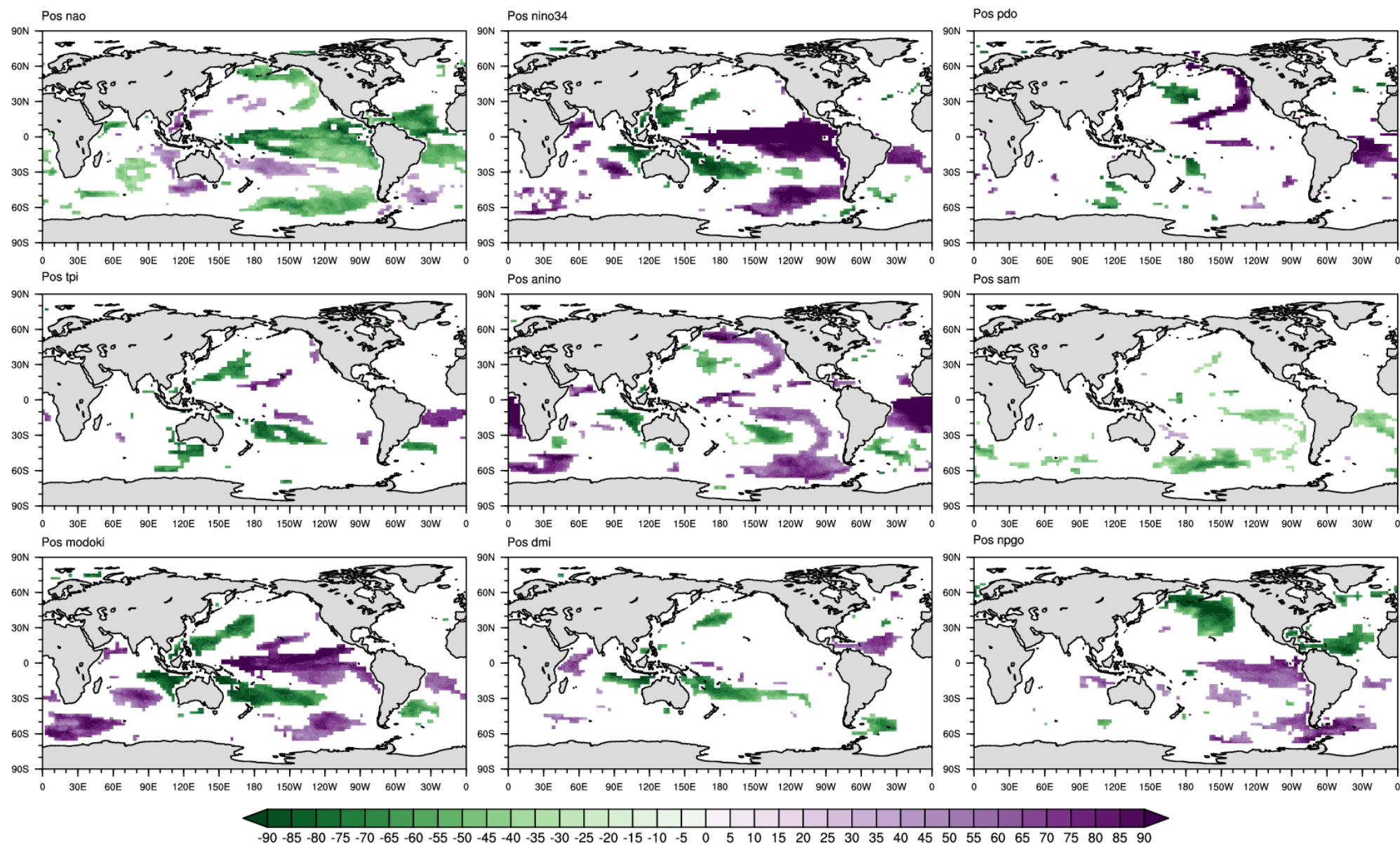


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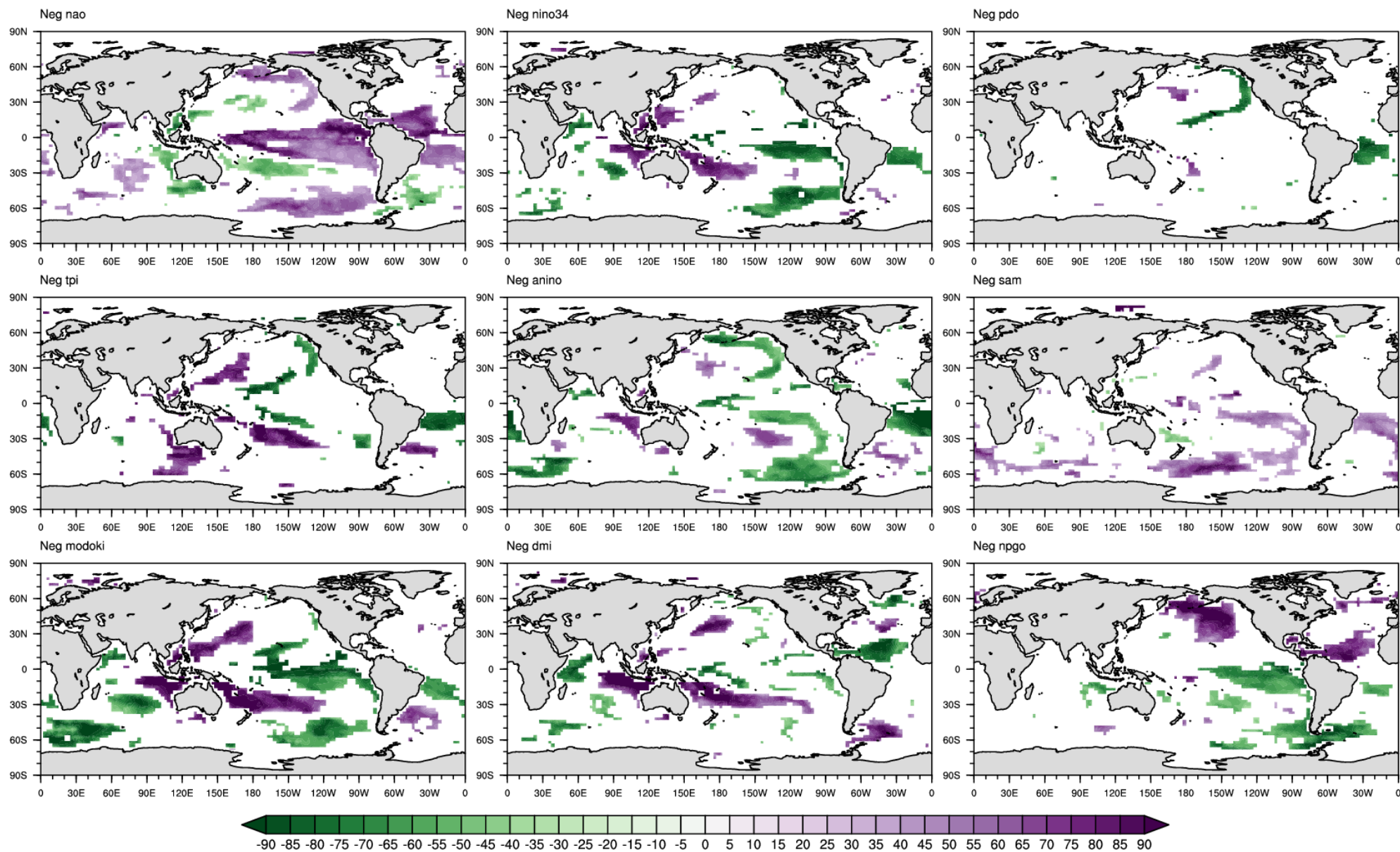
193 **Supplementary Figure 6.** The time series of fish biomass anomaly in regions with
 194 different trend of CLH days (a) and the relationship between trend of fish biomass
 195 (per 15 year) and trend of CLH days (b). The error bars in (b) represents standard
 196 error of the regression.



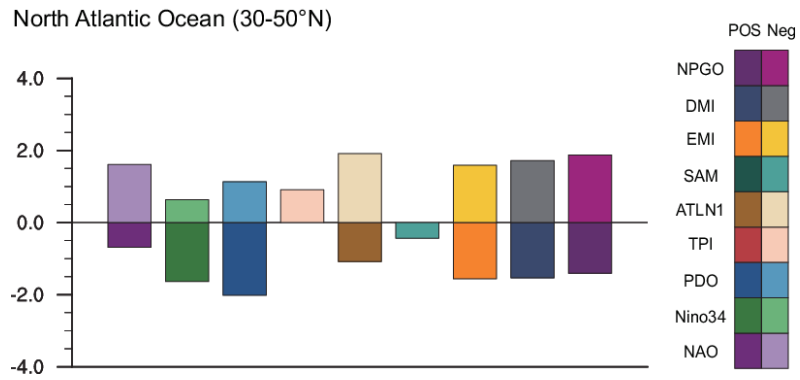
Supplementary Figure 7. The EEMD decomposed global temperature (a,b unit: °C) and oxygen concentration (c,d unit: mmol m⁻³) anomaly. The time series in (a) and (c) is the global averaged time series of temperature and oxygen concentration anomaly, respectively. Results in (b) and (d) shows long-term signal (red lines) and relatively short-lived and transient oscillation component (blue lines) decomposed by EEMD method.



Supplementary Figure 8. Percentage change in annual CLH event days in mode positive phase. Nine climate indices are selected in this study (see “Method”) and the baseline is median percentage of annual CLH event days.

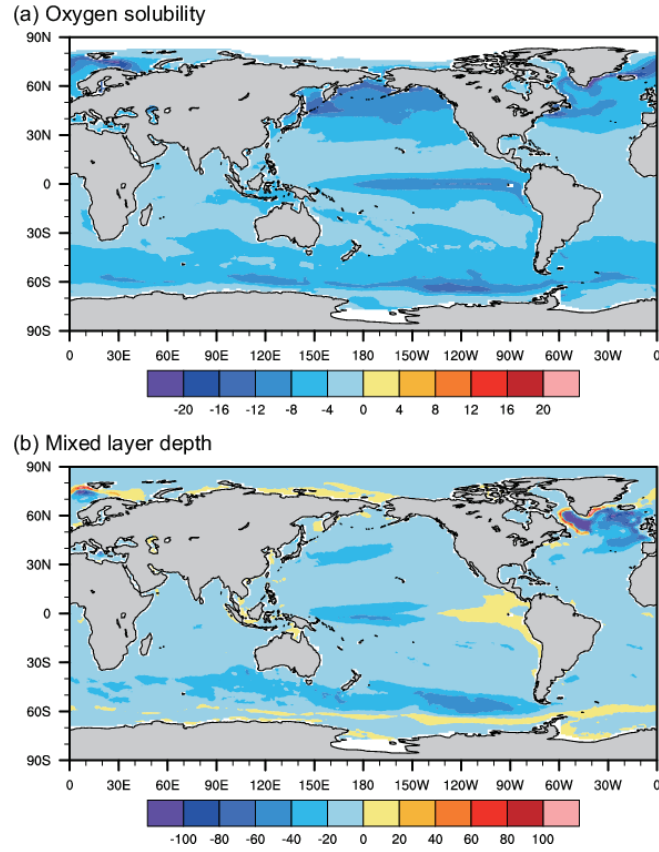


Supplementary Figure 9. Same as Supplementary Fig. 8, but for the mode negative phase.



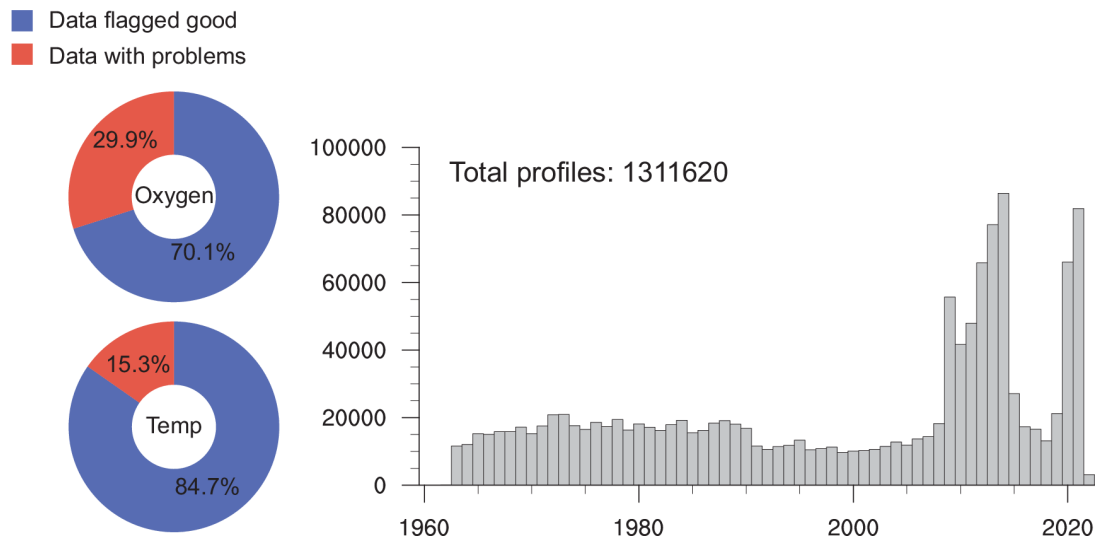
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210 **Supplementary Figure 10.** Percentage change in CLH event occurrences linked to
 211 climate mode phase. Values above (below) this bar indicate the climate mode phase
 212 enhances (suppresses) the likelihood of CLH event occurrences compared to the
 213 median percentage over the full period irrespective of the phase of the modes.



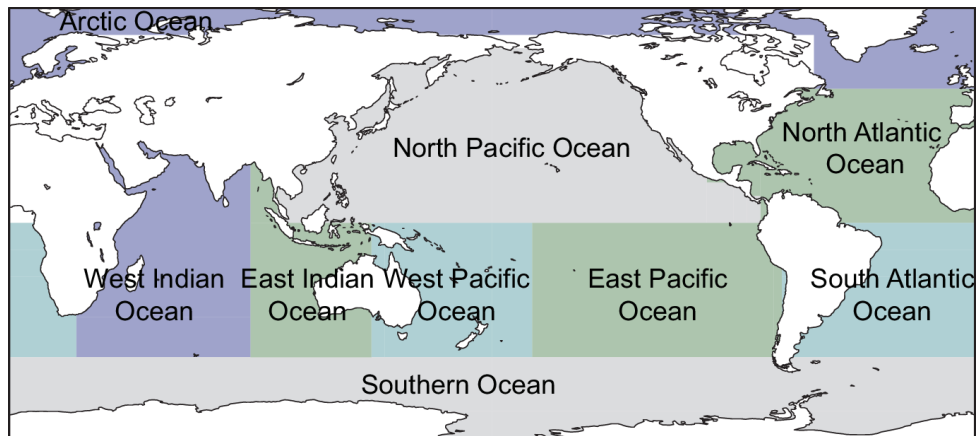
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215 **Supplementary Figure 11.** The anomaly of oxygen solubility (a, unit: mmol/m³) and
 216 mixed layer depth (b, unit: m) during CLH events. Anomalies are obtained by
 217 subtracting the mean value from the value of these variables during the CLH event
 218 across each grid, for example, $MLD_{anomaly} = MLD_{CLH} - MLD_{average}$. The seasonal
 219 variation cycle is removed before the calculation, and results presented in this figure
 220 are derived from model simulations.



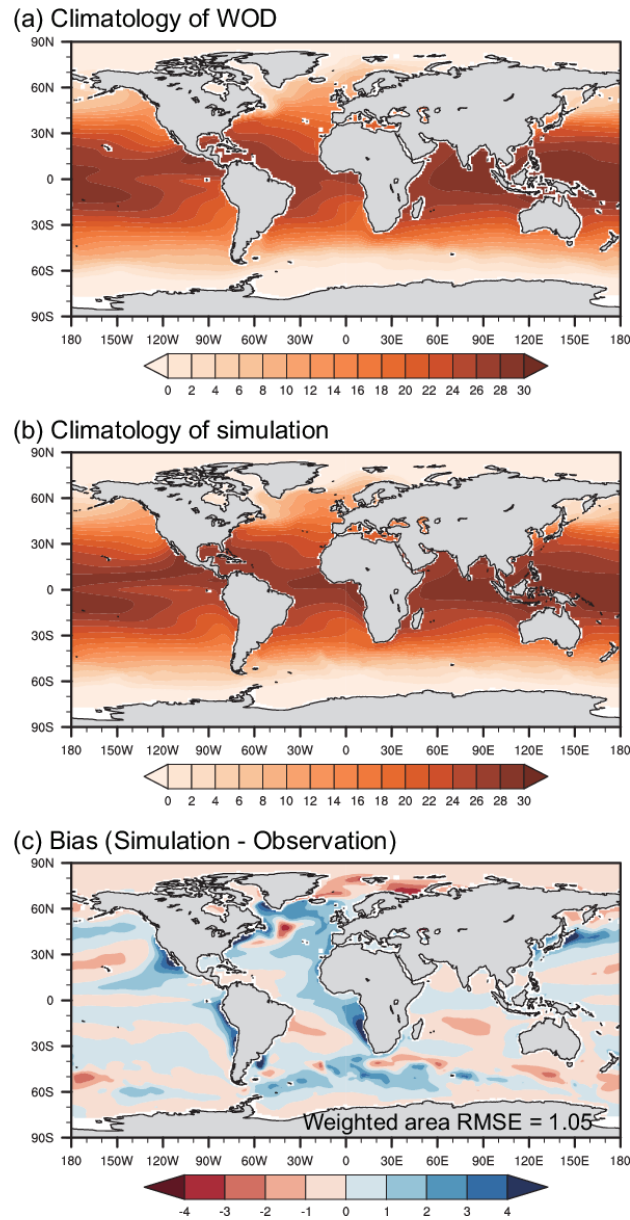
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222 **Supplementary Figure 12.** The observed profiles derived from World Ocean
 223 Database. Note that each profile contains both temperature and oxygen concentration
 224 data. Only profiles flagged good are used in this study.



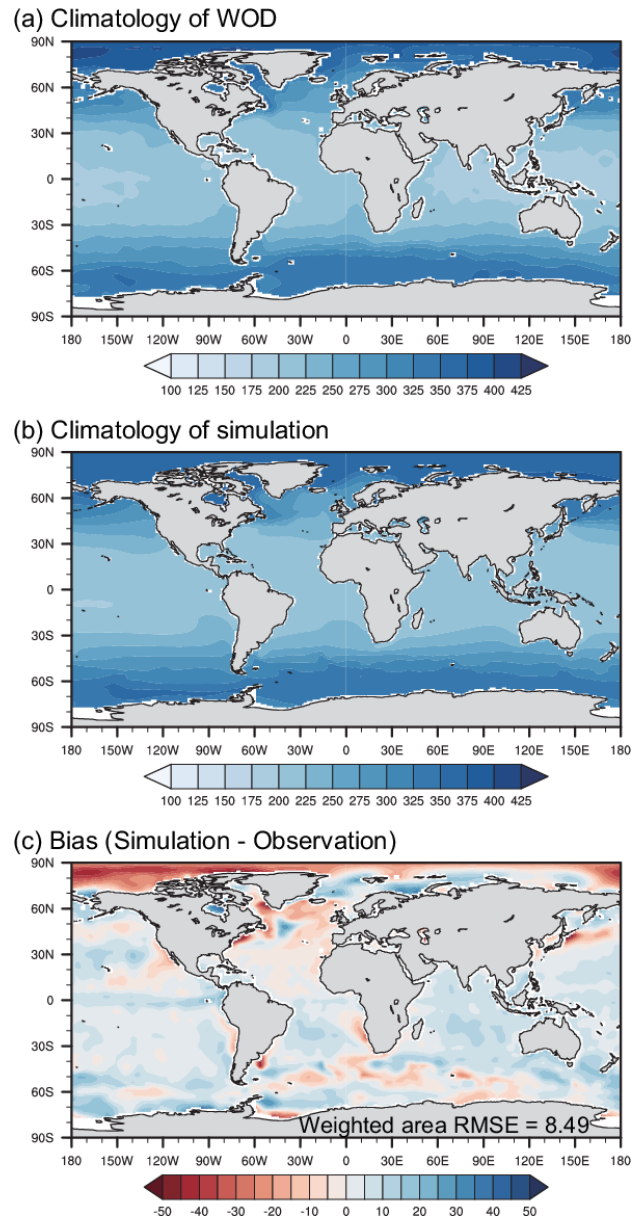
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226 **Supplementary Figure 13.** The boundaries of nine ocean basins in our study.



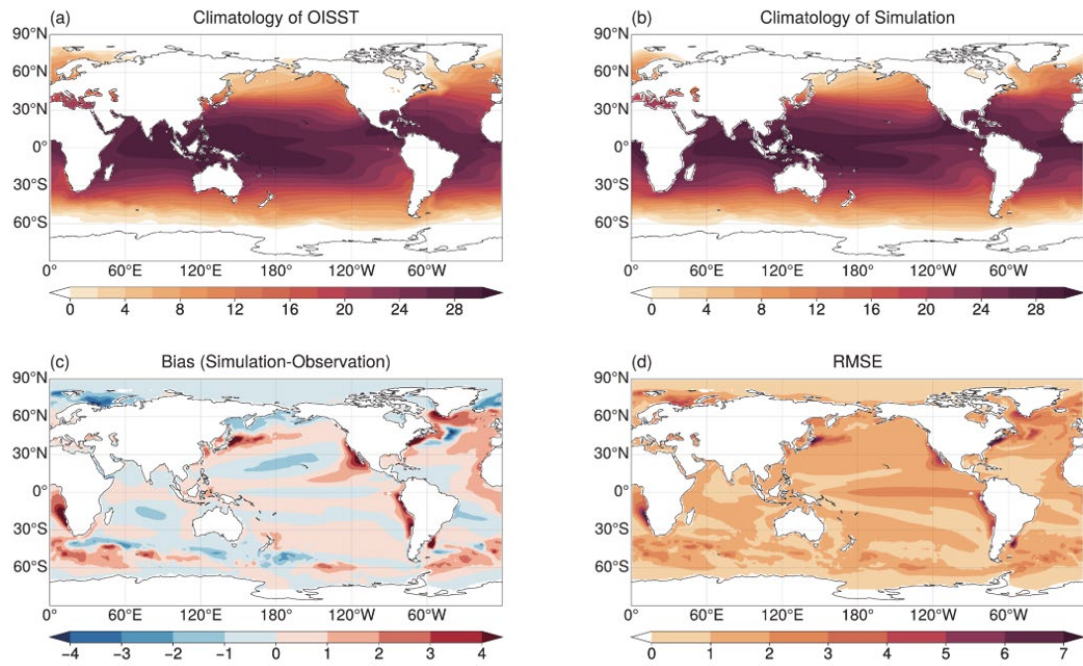
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228 **Supplementary Figure 14.** Seawater temperature in the climatic mean state derived
 229 from WOD observations (a), simulations (b) and the disparities between the two (c).
 230 Unit:°C.

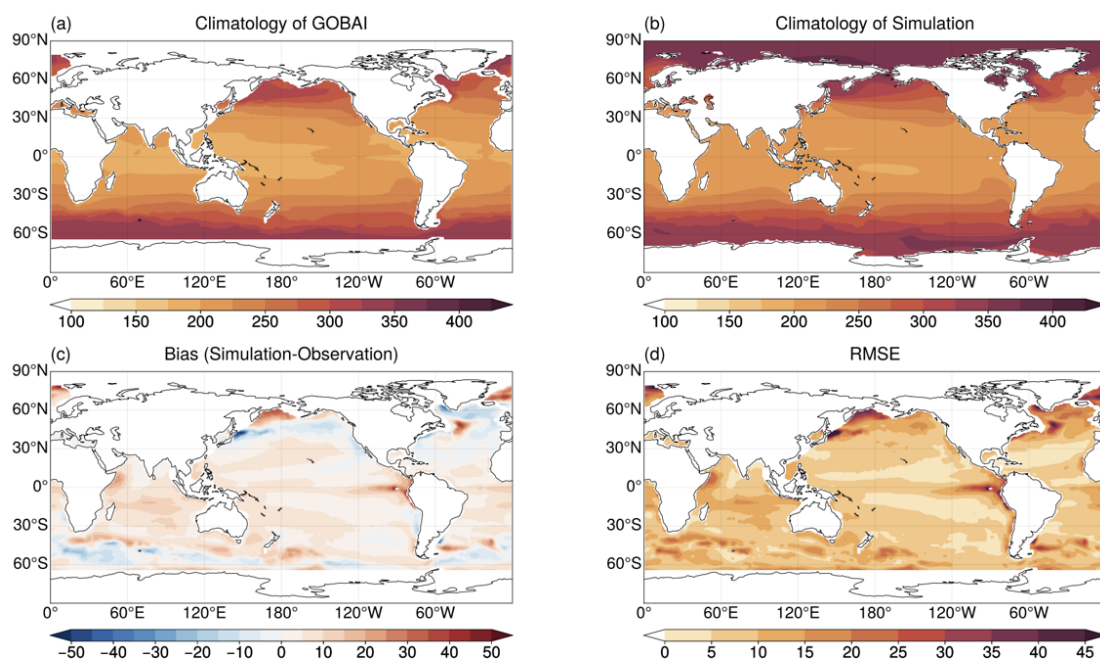


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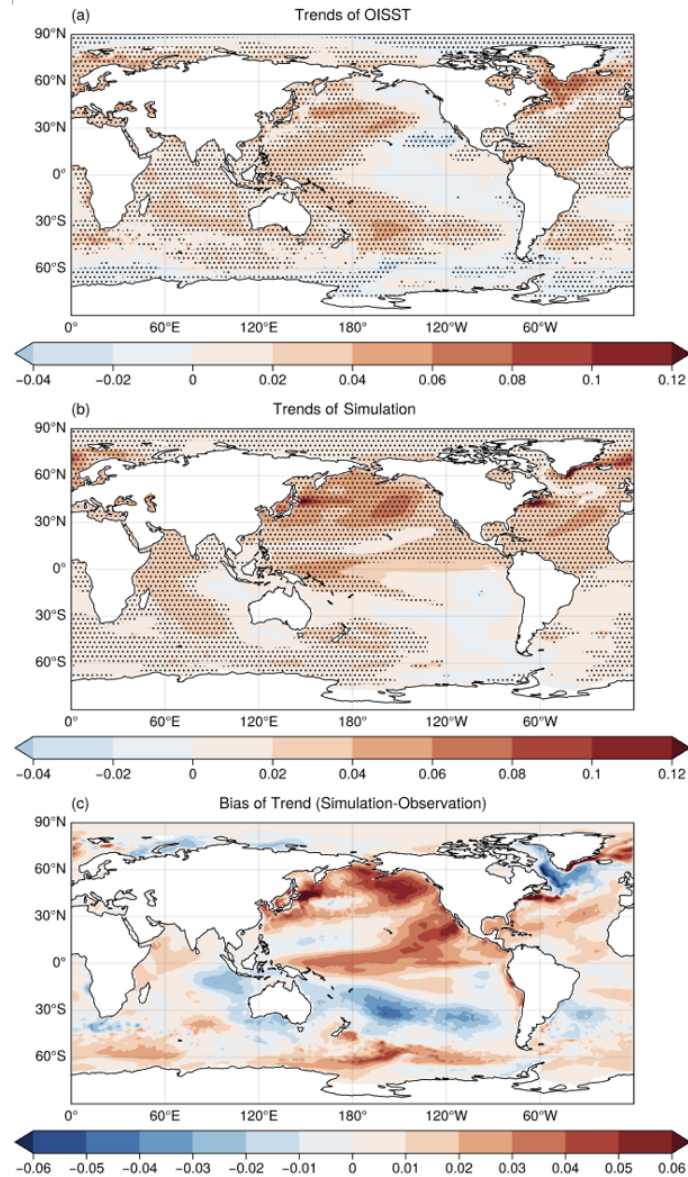
232 **Supplementary Figure 15.** Same as Supplementary Fig. 14, but for the dissolved
 233 oxygen concentration. Unit: mmol m^{-3} .



Supplementary Figure 16. Comparison of observed OISST (a) and simulated (b) seawater temperature in the climatic mean state and their bias (c) and root mean square error (d). Unit: °C.

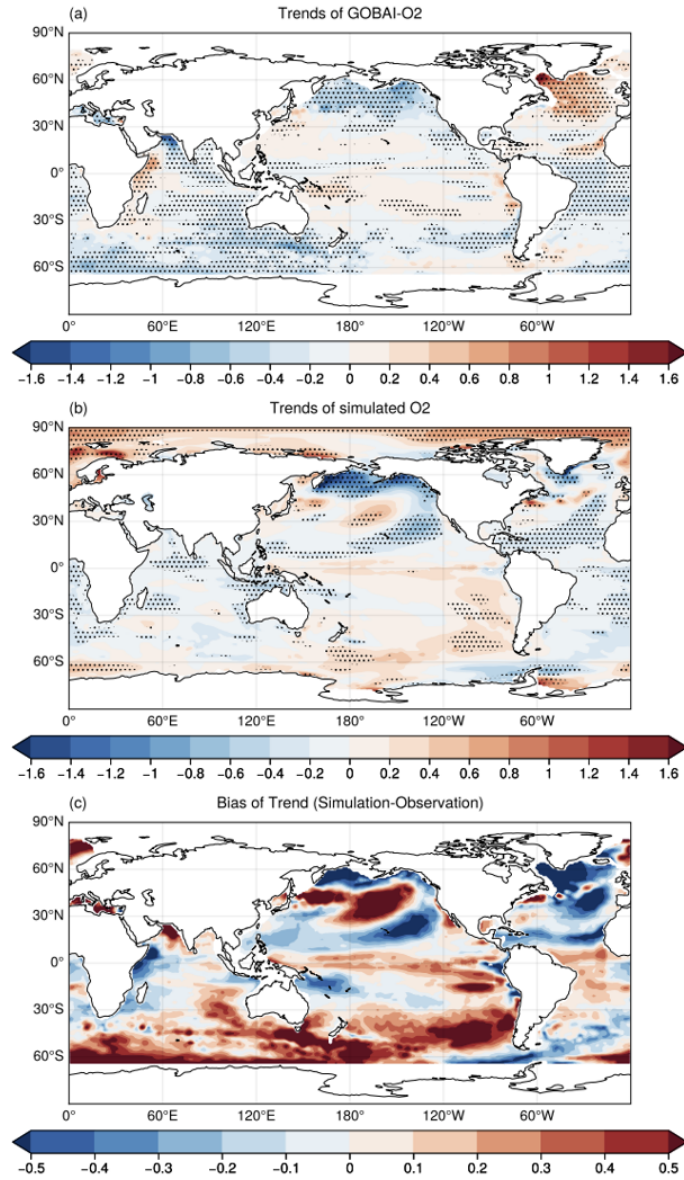


Supplementary Figure 17. Comparison of observed GOBAI-O2 (a) and simulated (b) oxygen concentration in the climatic mean state and their bias (c) and root mean square error (d). Unit: mmol m^{-3} .



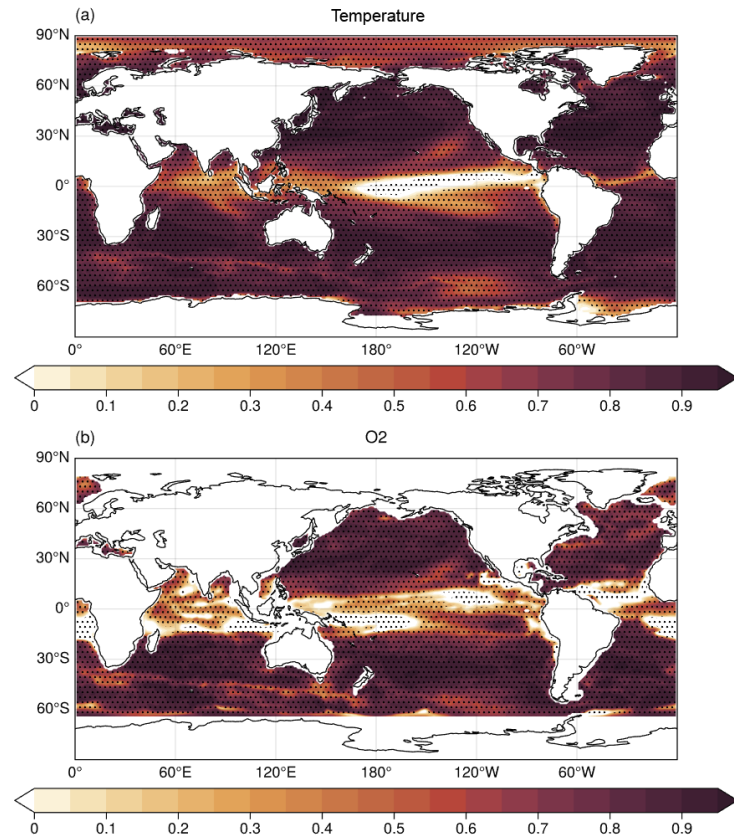
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243 **Supplementary Figure 18.** Comparison of observed (a) and simulated (b) seawater
 244 temperature in the trend and their bias (c). The dots represent trend significant at 99%
 245 level.



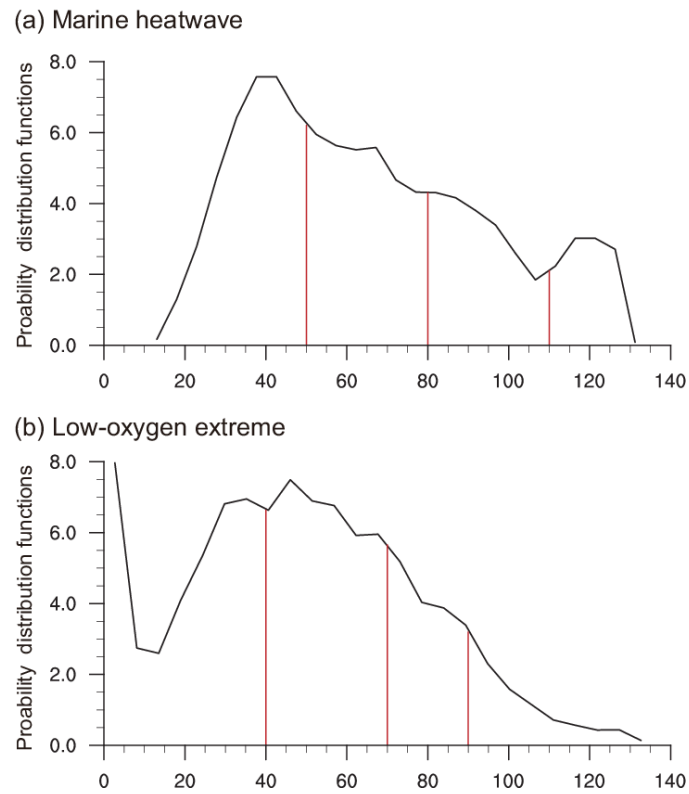
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247 **Supplementary Figure 19.** Same as Supplementary Fig. 18, but for the dissolved
 248 oxygen concentration.



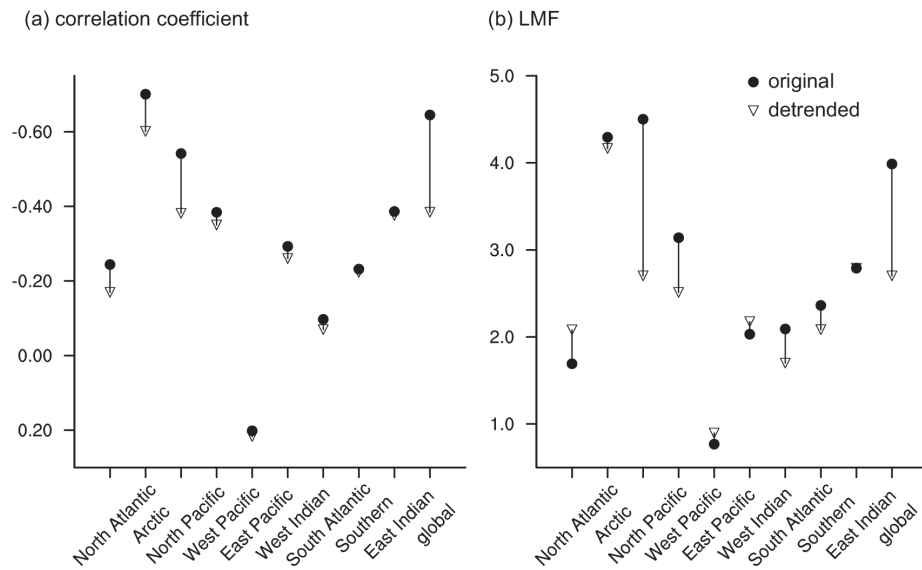
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250 **Supplementary Figure 20.** The temporal correlation coefficient between observed
 251 and simulated seawater temperature (a) and dissolved oxygen concentration (b) for
 252 the surface ocean (0-10m). The coefficient is calculated throughout their overlapping
 253 periods, which span from 1982 to 2014 for temperature and from 2004 to 2014 for
 254 dissolved oxygen. The dots represent significant at 99% level.

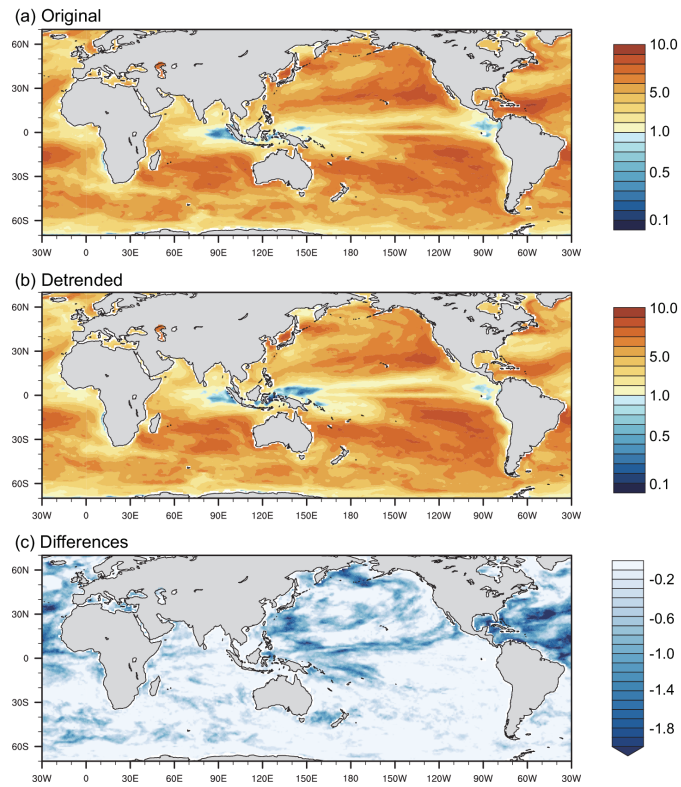


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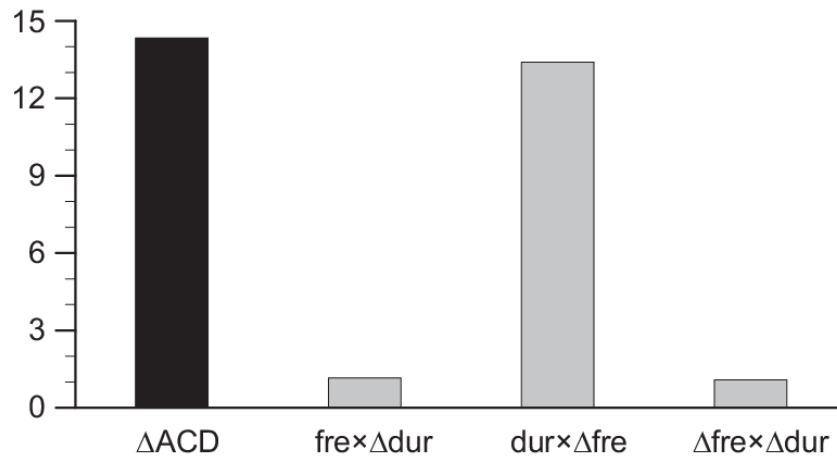
256 **Supplementary Figure 21.** The probability distribution functions of marine heatwave
 257 (a) and low-oxygen extreme event (b). The thresholds of classification are represented
 258 by the vertical lines.



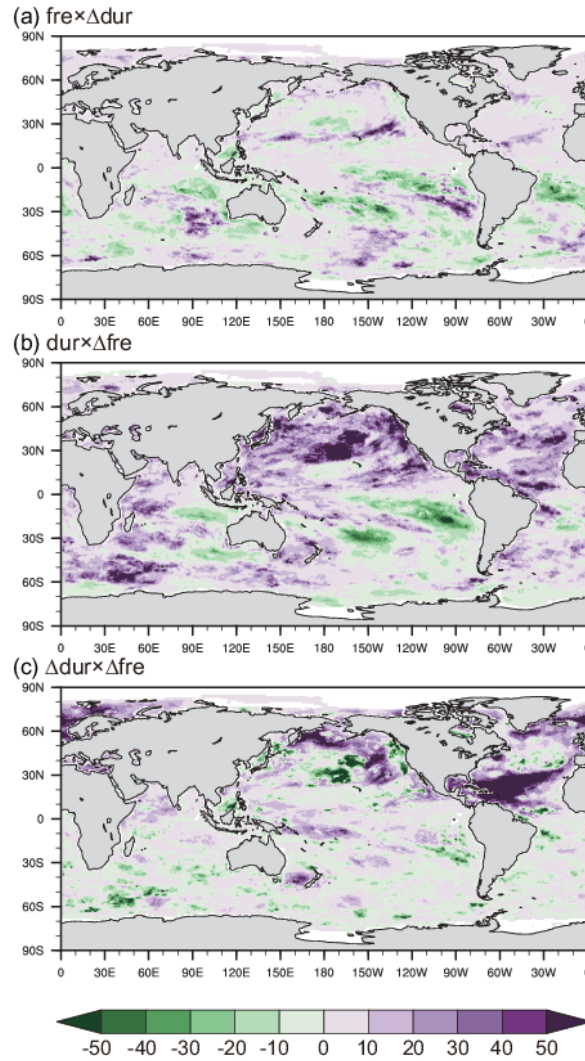
Supplementary Figure 22. The correlation coefficient between temperate and oxygen concentration anomalies (a) and LMF of CLH events (b) before (circles) and after detrending (triangles).



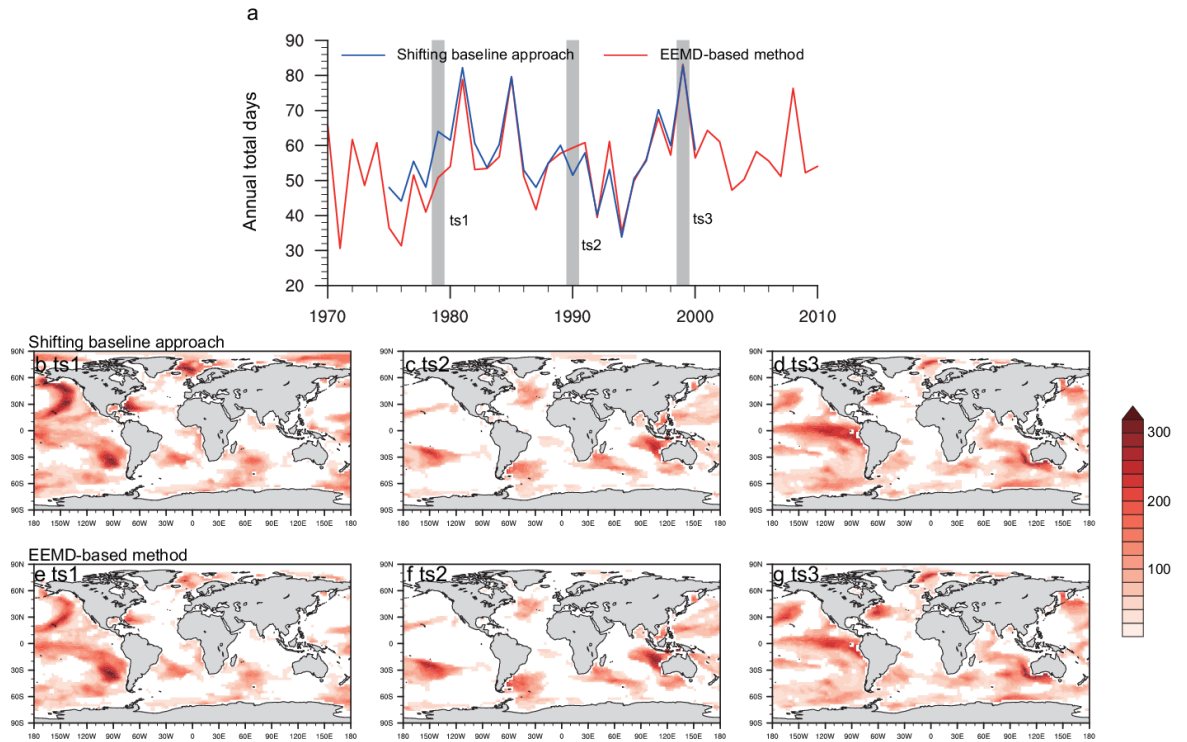
Supplementary Figure 23. The spatial distributions of LMF before (a) and after detrending (b). Their differences are illustrated in (c)



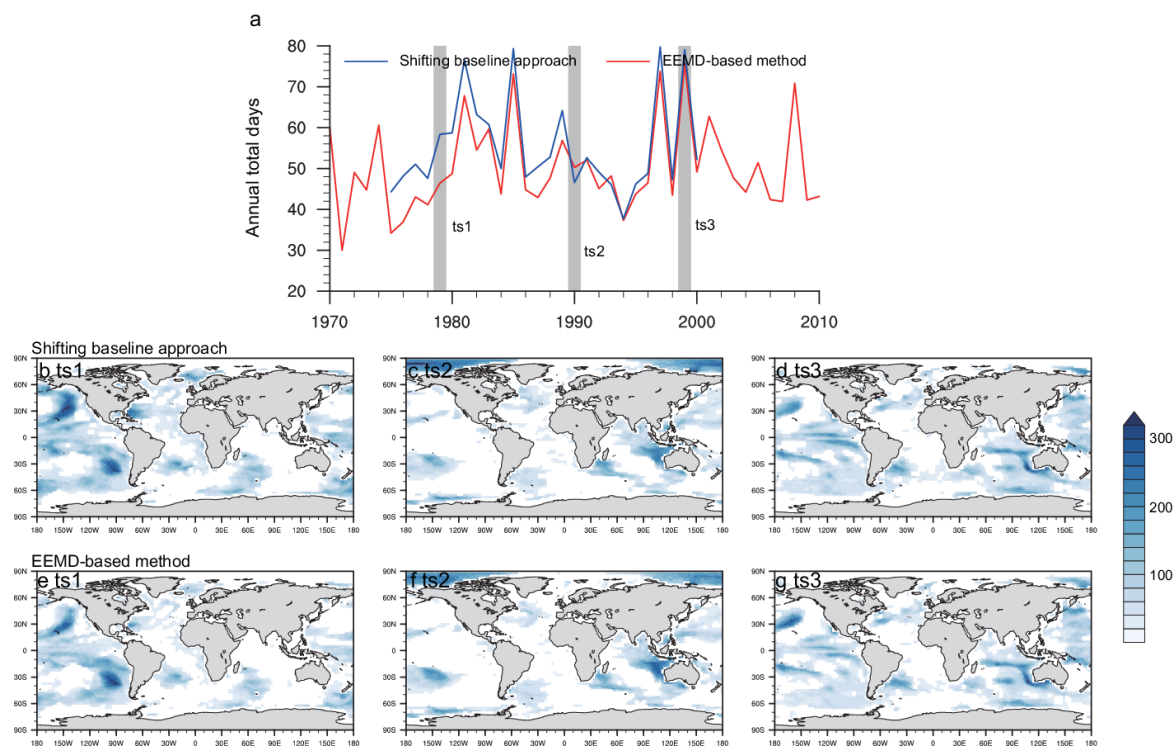
Supplementary Figure 24. The contribution of frequency and duration changes to increase of annual CLH days from period 1985-1999 to 2000-2014. The change in annual CLH days (ΔACD) is calculated as the difference between the average ACD from 2000 to 2014 and that from 1985 to 1999, similarly for Δfre (change in frequency) and Δdur (change in duration). Unit: days.



Supplementary Figure 25. The contribution of duration changes (a), frequency changes (b) and combination effect of the two changes (c) to modification of annual CLH days from period 1985-1999 to 2000-2014. Unit: days.



Supplementary Figure 26. Annual total days of marine heatwave derived from shifting baseline approach and EEMD-based method. a, global averaged annual total days in shifting baseline approach (blue) and EEMD-based method (red). b-d, the spatial distribution of annual total days in three time slices (ts1, ts2 and ts3 respectively, shown as the grey region in a) obtained by shifting baseline approach. e-g, same as b-d, but for the EEMD-based method.



Supplementary Figure 27. Same as Supplementary Fig. 26, but for the low-oxygen extreme events.

Supplementary References

1. Wu, Z. & Huang, N. E. Ensemble Empirical Mode Decomposition: a noise-assisted data analysis method. *Advances in Adaptive Data Analysis* **01**, 1–41 (2009).
2. Huang, J., Xie, Y., Guan, X., Li, D. & Ji, F. The dynamics of the warming hiatus over the Northern Hemisphere. *Climate Dynamics* **48**, 429–446 (2017).
3. Liu, X. *et al.* The role of seasonality in the spread of COVID-19 pandemic. *Environmental Research* **195**, 110874 (2021).
4. Rayner, N. A. *et al.* Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres* **108**, (2003).
5. Ashok, K., Behera, S. K., Rao, S. A., Weng, H. & Yamagata, T. El Niño Modoki and its possible teleconnection. *Journal of Geophysical Research: Oceans* **112**, 1–27 (2007).
6. Saji, N. H. & Yamagata, T. Possible impacts of Indian Ocean Dipole mode events on global climate. *Climate Research* **25**, 151–169 (2003).
7. Hurrell, J. W. Decadal trends in the North Atlantic oscillation: Regional temperatures and precipitation. *Science* **269**, 676–679 (1995).
8. Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M. & Francis, R. C. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bulletin of the American Meteorological Society* **78**, 1069–1079 (1997).
9. Henley, B. J. *et al.* A Tripole Index for the Interdecadal Pacific Oscillation. *Climate Dynamics* **45**, 3077–3090 (2015).

- 308 10. Lutz, K., Rathmann, J. & Jacobeit, J. Classification of warm and cold water
309 events in the eastern tropical Atlantic Ocean. *Atmospheric Science Letters* **14**, 102–
310 106 (2013).
- 311 11. Gong, D. & Wang, S. Definition of Antarctic oscillation index. *Geophysical*
312 *Research Letters* **26**, 459–462 (1999).
- 313 12. Di Lorenzo, E. *et al.* North Pacific Gyre Oscillation links ocean climate and
314 ecosystem change. *Geophysical Research Letters* **35**, 2–7 (2008).