Significant reduction of potential exposure to extreme marine heatwaves by achieving carbon neutrality

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April 16, 2024

Abstract

Marine heatwave (MHW), a prolonged period of anomalously warm seawater, has a catastrophic repercussion on marine ecosystems. With global warming, MHWs have become increasingly frequent, intense, and prolonged. To avoid irreversible damages from such extreme events, net-zero carbon emissions by the 2050s, called carbon neutrality, were proposed. Here, we evaluate the impact of carbon neutrality on MHWs in the late 21st century using multi-model projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) Shared Socioeconomic Pathway (SSP)1-1.9 and SSP3-7.0 scenarios. It is found that if the current regional rivalry over carbon emissions continues (i.e., SSP3-7.0), the MHWs in the late 21st century will become stronger and longer than historical ones, especially in the western boundary current and equatorial current regions. Approximately 68% of the global ocean will be exposed to permanent MHWs, regionally 93% in the Indian Ocean, 76% in the Pacific Ocean, 68% in the Atlantic Ocean, 65% in the Coastal Ocean, and 48% in the Southern Ocean. Such MHWs can be significantly reduced by achieving carbon neutrality (i.e., SSP1-1.9). In particular, the spatial proportion of the ocean exposed to permanent MHWs can be reduced to as low as 0.02 to 0.07%, depending on the regions. This result underscores the critical importance of ongoing efforts to achieve net-zero carbon emissions to reduce the potential ecological risks induced by extreme MHWs.

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January 2024

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Highlights (Limit 140 characters)

- Marine heatwaves will be stronger and longer-lasting in a warming climate
- Current warming rate will expose 68% of the oceans to permanent marine heatwaves
- Exposure to permanent marine heatwaves will be greatly reduced by carbon neutrality

Abstract

Marine heatwave (MHW), a prolonged period of anomalously warm seawater, has a catastrophic repercussion on marine ecosystems. With global warming, MHWs have become increasingly frequent, intense, and prolonged. To avoid irreversible damages from such extreme events, net-zero carbon emissions by the 2050s, called carbon neutrality, were proposed. Here, we evaluate the impact of carbon neutrality on MHWs in the late 21st century using multi-model projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) Shared Socioeconomic Pathway (SSP)1-1.9 and SSP3-7.0 scenarios. It is found that if the current regional rivalry over carbon emissions continues (i.e., SSP3-7.0), the MHWs in the late 21st century will become stronger and longer than historical ones, especially in the western boundary current and equatorial current regions. Approximately 68% of the global ocean will be exposed to permanent MHWs, regionally 93% in the Indian Ocean, 76% in the Pacific Ocean, 68% in the Atlantic Ocean, 65% in the Coastal Ocean, and 48% in the Southern Ocean. Such MHWs can be significantly reduced by achieving carbon neutrality (i.e., SSP1-1.9). In particular, the spatial proportion of the ocean exposed to permanent MHWs can be reduced to as low as 0.02 to 0.07%, depending on the regions. This result underscores the critical importance of ongoing efforts to achieve net-zero carbon emissions to reduce the potential ecological risks induced by extreme MHWs.

Plain Language Summary

Marine heatwave, a prolonged period of anomalously warm seawater, has a catastrophic effects on marine ecosystems. To avoid such extreme events, net-zero carbon emissions by the 2050s, known as carbon neutrality, has been proposed. Here, we show that achieving carbon neutrality could result in a significant reduction in the spatial proportion of the ocean exposed to permanent marine heatwaves in the late 21st century compared to current warming projections, with a potential exposure reducing from 48–93% to 0.02–0.07%, depending on the ocean regions. It is clear that achieving carbon neutrality will certainly reduce the intensity of marine heatwaves almost to current levels. This finding underscores the critical importance of ongoing efforts to achieve net-zero carbon emissions to reduce the potential ecological risks posed by extreme marine heatwaves.

1. Introduction

Marine heatwave (MHW), defined as a prolonged period of anomalously warm seawater (Hobday et al., 2016), has devastating impacts on marine ecosystems, resulting in significant ecological, social, and economic losses (Hu et al., 2021; Qiu et al., 2021; Pastor and Khodayar, 2022). Ongoing global warming is expected to lead to more frequent, intense, and longer-lasting MHWs worldwide (Oliver et al., 2019; Qiu et al., 2021; Cheng et al., 2023). This, in turn, has the potential to bring about even more irreversible transformations in marine organisms, induce more profound alterations in marine ecosystems, and trigger more far-reaching societal consequences (Frölicher et al., 2018; Pastor and Khodayar, 2022).

To avoid irreversible damages from such extreme climate events in a warming climate, the 2015 Paris Agreement proposed net-zero anthropogenic carbon emissions by 2050s, also known as carbon neutrality (UNFCCC, 2015). Its potential benefits have often been highlighted by the analysis of climate model simulations, which show that 0.5°C less warming by achieving carbon neutrality compared to 2°C warming can lead to a significant reduction in areas damaged by climate change (Park et al., 2018; King et al., 2021; Nashwan and Shahid, 2022). However, such studies have mainly been carried out in habitable land areas rather than in the ocean. The impacts of carbon neutrality on the marine environment have rarely been studied.

Ocean covers 71% of Earth's surface and contributes to over 17% of edible food production (Nijdam et al., 2012; Edwards et al., 2019). As the source to increase food production on land is limited, the ocean is becoming an increasingly important source of future food for a growing population (Edwards et al., 2019; Costello et al., 2020). In this respect, the

MHWs can have catastrophic repercussions on marine food production by disrupting the food chains and, in extreme cases, causing mass fish kills (Oliver et al., 2019; Qiu et al., 2021; Cheng et al., 2023). Therefore, a quantitative analysis of the potential impacts of carbon neutrality on the anticipated intensification of MHWs, which is likely to be exacerbated by global warming, is critical not only for establishing effective ocean climate change mitigation policies but also for our food security.

Here, we investigate the potential impacts of carbon neutrality on MHWs by examining multi-model projections from the Coupled Model Intercomparison Project 6 (CMIP6, Eyring et al., 2015). Specifically, we compare the Shared Socioeconomic Pathway (SSP)1-1.9 scenario, which achieves net zero anthropogenic carbon emissions by 2050s, with the SSP3-7.0 scenario based on regional rivalry over carbon emissions policies (Fig. S1; O'Neill et al., 2016; Oin et al., 2021), and quantitatively assess the projected changes in frequency, duration, and intensity of MHWs. The impacts of carbon neutrality are also compared across five ocean regions, i.e., Atlantic, Indian, Pacific, Southern, and Coastal oceans.

2. Data and Methods

2.1. Datasets

Daily sea surface temperature (SST) outputs for historical simulations (1985–2014) and future projections (2015–2100) under two different SSP scenarios from eight CMIP6 models (Eyring et al., 2016; Table 1) are used to calculate the MHW properties. The SSP3-7.0

and SSP1-1.9 scenarios, which are respectively the high and very low greenhouse gas emission scenarios (O'Neill et al., 2016; Oin et al., 2021), are used. The former scenario assumes that the current rate of global warming will continue until 2100 (i.e., regional rivalry scenario). Meanwhile, the latter scenario assumes net-zero carbon emissions by 2050s (i.e., carbon neutrality scenario) (Fig. S1). All models are interpolated to a regular 1°×1° grid using a bilinear remapping, and then the MHW properties are calculated. This procedure allows to minimize the uncertainty arising from different model resolutions (Kim et al., 2020; Li et al., 2021).

To evaluate the model performances for the historical period of 1985–2014, the National Oceanic and Atmospheric Administration (NOAA) 1/4 degree daily Optimum Interpolation (OI) SST V2.0 dataset is used (Reynolds et al., 2017). This dataset is derived from remotely-sensed SST from the Advanced Very High-Resolution Radiometer (AVHRR) and has been widely used to analyze MHWs worldwide (Oliver et al., 2018; 2019; Qiu et al., 2021). To be compared with the coarse-resolution models, this dataset is regridded onto a regular 1°×1° grid before calculating the MHW properties.

2.2. MHW definition

The MHW is generally defined as a discrete, prolonged, anomalous seawater event when daily SST exceeds the 90th percentile for five or more consecutive days. The 90th percentile is determined from a 30-year historical time series from 1985 to 2014 (Fig. S2b, Hobday et al., 2016). This threshold and daily climatology are calculated for each calendar day by using the daily SST within an 11-day window that is smoothed by applying a 31-day moving average. Events with temporal gaps of two days or fewer are considered to be a continuous event. This definition allows MHWs to be detected at any time of the year, as opposed to only detecting events that occur during the warmest months (Hobday et al., 2016; Oliver et al., 2018). The 90th percentile at each grid in the historical period is applied to the period of 1985–2100 to calculate the MHW properties.

The definition of MHWs does not take into account the effect of sea ice. We therefore focus our analysis on five ocean regions: the Atlantic, Indian, Pacific, Southern, and Coastal oceans, between 70°S and 70°N (Fig. S2a, Laruelle et al., 2017; Hauck et al., 2023). To characterize MHWs, frequency (number of events per year), duration (days per event), and mean intensity (average of temperature anomalies per event) are calculated.

2.3. Evaluation matric

This study uses the multi-model ensemble median (MEM), which is more appropriate than the multi-model mean when the ensemble members have unusually large or small values. The model performance for MHW properties is evaluated in terms of the bias, root-mean-square error (RMSE), and correlation for spatial patterns for the historical period of 1985–2014. They are computed as follows.

$$bias = \frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)^2}$$

$$correlation = \frac{\sum_{i=1}^{n}(M_i - \bar{M})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{n}(M_i - \bar{M})}\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})}}$$

where *M* and *O* denote the model and observation. Subscript *i* denotes *i* th grid point and *n* is the number of the total grids at ocean areas. The overbar presents the mean value at the ocean areas. To compare the performance of MEM with that of each model, the scatter plot of RMSE and Taylor skill score (TSS, Taylor, 2001) is used. The TSS is computed as below:

$$TSS = \frac{(1 + correlation)^4}{4(SDR + \frac{1}{SDR})^2}$$

where *SDR* is the ratio of the spatial standard deviation of the model against to that of the observation. This score quantifies the similarity in the spatial distribution and amplitude between the model and the observation. The median value of each evaluation measure is used to calculate the relative RMSE and TSS values for both individual models and MEM.

3. Results

3.1. Historical MHW properties

Figure 1 shows the spatial distribution of SST climatology, MHW frequency, duration, and mean intensity in the historical period of 1985–2014 (left). The model biases are also presented (right). The CMIP6 MEM well reproduces the spatial distribution of SST climatology (Fig. 1a), with a spatial correlation of 0.98 (Fig. 1b). Cold biases ranging from -0.5°C to -4.0°C are prominent over the Northwest Pacific and North Atlantic, while warm biases ranging from 0.5°C to 4.0°C are found over the Northeast Pacific, Southeast Pacific, Southeast Atlantic, and Southern Ocean. On a global average, SST bias is 0.55°C mainly due to warm bias in the Southern Ocean. These biases are the improved results compared to those of the CMIP5 models (Zhang et al., 2023).

The MHW frequency ranges from about one to three annual events, depending on the location (Fig. 1c). The CMIP6 MEM realistically captures its magnitude (bias of -0.59 event) and spatial pattern (correlation of 0.79) (Fig. 1d). The relatively long-lasting MHWs are observed in the eastern Pacific (Fig. 1e) as El Niño-Southern Oscillation (ENSO) events manifest themselves as individual long-lasting MHWs (Oliver et al., 2018). This in turn is associated with less frequent MHWs in this region, as shown in Fig. 1c. In general, the CMIP6 MEM reproduces the spatial distribution of MHW duration reasonably well, with a spatial correlation of 0.64. However, it simulates longer MHW durations, especially in the Southern Ocean and the eastern Pacific, in excess of 20 days (Fig. 1f). The longer duration in the Southern Ocean might result from the warm bias of SST.

The MHW intensity show a large spatial variation (Fig. 1g). Hotspots of strong intensity are observed in the western boundary current extension regions (i.e., Gulf Stream, Brazil and Malvinas currents in the Atlantic, Somali and Agulhas currents in the Indian Ocean, and Kuroshio and East Australian currents in the Pacific) with 2–3°C, the central and eastern equatorial Pacific with 1.5–2.5°C, the eastern boundary current regions (i.e., California Current off North America, Humboldt (or Peru) Current off South America, Canary Current off North Africa, and Benguela Current off South Africa) with 1.5–2.5°C, and Cape Horn current region with 2–4°C (Fig. 1g). The CMIP6 MEM realistically reproduces these features with a spatial correlation of 0.91 with a weak cold bias of -0.16°C on the global average (Fig. 1h). However, relatively large cold biases are regionally found in the Gulf Stream, Brazil and Malvinas current in the Atlantic, and Cape Horn current with -0.7 to -2.1°C (Fig. 1h).

Compared to the individual models, the MEM (Figs. 1b, d, f, and h) shows a better performance in the reproduction of SST climatology and MHW properties (Fig. S3). This result is consistent with previous studies showing that the multi-model ensemble has superior performance in reproducing mean and extreme climates than a single model (e.g., Oh and Suh, 2017; Kim et al., 2020; Li et al., 2021). It justifies the use of MEM for future projection of MHW properties.

3.2. Future projections and the impact of carbon neutrality

Figure 2a shows the time series of globally-averaged SST over 70°S to 70°N for the period of 2015–2100 under the SSP1-1.9 and SSP3-7.0 scenarios compared to the historical period of 1985–2014. If global warming continues without achieving carbon neutrality in the 2050s, SST is projected to increase up to 2.70°C by the end of the century, with a warming trend of 0.29°C per decade (red line in the top panel of Fig. 2a). Achieving carbon neutrality can lead to a significant mitigation in SST warming (blue line in the top panel of Fig. 2a). A warming similar to SSP3-7.0 scenario is projected to occur until the late 2030s, but it slows significantly until the 2050s and then stabilizes at 0.57°C by the end of the century. The reduced SST warming is 2.13°C in 2100. This is a 79% reduction from the SSP3-7.0 scenario (purple line in the lower panel of Fig. 2a). The reduced trend is particularly noticeable after the 2050s. The inter-model spread does not cross the zero line after 2050s, indicating that the difference between the two emission scenarios is distinct in the late 21st century. It evidences the critical role of the carbon neutrality in mitigating the potential climate risks associated with SST warming.

The spatial distribution of SST warming in the late 21st century (2071–2100) is analyzed in Fig. 2b. If global warming continues, strong SST warming of 2 to 3°C are projected to occur at the western boundary current and equatorial current regions (the top panel of Fig. 2b). This suggests that the SST warming is significantly related to regional current changes (e.g., Jeong et al., 2021). Achieving carbon neutrality mitigates SST warming within 0.5 to 1.5°C (the middle panel of Fig. 2b). The benefit of carbon neutrality is particularly evident around the western boundary current and equatorial current regions (the bottom panel of Fig. 2b).

Figure 3 shows the projected changes of MHW properties in the late 21st century (2071–2100) compared to the historical period (1985–2014) and their differences between the two emission scenarios. In a warming climate, the MHW frequency increases by 2–12 events per year with the largest increase in the western boundary current and equatorial current regions (the top and middle panels of Fig. 3a). A larger increase of 2–6 events per year is projected to occur under the carbon neutrality scenario compared to the high emissions scenario (the bottom panel of Fig. 3a). This is not a surprising finding. Under the high emissions scenario, each individual MHW has a much longer duration, even longer than 365 days, and strong intensities greater than 1.0°C depending on the region (the top panel of Fig. 3b and c). A smaller frequency is therefore due to the fact that the MHW duration becomes much longer. We should keep in mind that MHWs of longer duration and higher intensity can have a critical impact on the marine ecosystem.

Under a carbon neutrality scenario, the duration of MHWs is projected to be slightly longer than historical levels, ranging from 30 to 120 days, and their intensity is similar to historical levels (the middle panels of Fig. 3b and c). It is evident that there is a significant reduction in the duration and intensity of MHWs in all oceans except the part of the Southern Ocean and the northern part of the Atlantic Ocean (the bottom panels of Fig. 3b and c). This suggests that achieving net-zero carbon emissions by the 2050s can lead to a significant reduction in potential exposure to more extreme MHWs.

The joint probability distributions of MHW duration and intensity over the five ocean regions (i.e., Pacific, Atlantic, Indian, Southern, and Coastal Oceans; see Fig. S2a) for the historical and future periods are analyzed in Fig. 4. It is clear that MHWs under SSP3-7.0 scenarios would have significantly different features from historical ones, with longer and more intense MHWs over all oceans (red contours in Fig. 4). Specifically, Indian Ocean MHWs under SSP3-7.0 scenario are completely different from the historical ones or SSP1-1.9 scenario in both intensity and duration (Fig. 4d). Durations of the Pacific and Atlantic MHWs are also quite different, while their intensities show slight overlap in some values (Figs. 4b and c). The

Southern and Coastal Ocean MHWs are expected to show a wider range of variability in duration and intensity than other oceans, with more than two-thirds deviating from historical ones (Figs. 4e and f). These results indicate that future MHWs may undergo a complete change beyond the range they had previously experienced. Achieving carbon neutrality can maintain historical MHWs to some extent. However, future MHW duration is still projected to increase about twofold compared to the historical one over all oceans (blue contours in Fig. 4).

Figure 5 presents the spatial proportion of the oceans exposed to permanent MHWs, which are defined as MHW events of duration longer than 365 days. Under the high emissions scenario, about 68% of the global ocean (GO in Fig. 5) is projected to be exposed to permanent MHWs, with a large intermodel spread ranging from 35% in MIROC-ES2L to 86% in UKESM1-O-LL. In the Indian Ocean (IO), 93% of the ocean waters are projected to be exposed to permanent MHWs. This is followed by the Pacific Ocean (PO) with 76%, and the Atlantic Ocean (AO) and the Coastal Ocean (CO) with 68% and 65%, respectively. The Southern Ocean (SO) is projected to have 48% of its waters exposed to permanent MHWs. For all oceans, CanESM5 and UKESM1-0-LL models tend to project relatively extreme scenarios, while MPI-ESM-LR and MIROC-ES2L models project relatively less extreme scenarios.

Not surprisingly, achieving carbon neutrality can lead to a significant reduction in the proportion of the ocean exposed to permanent MHWs. According to CMIP6 MEM, the proportion of the ocean with permanent MHWs is projected to be as low as 0.02% to 0.07% for all oceans. This highlights the importance of carbon neutrality in mitigating long-lasting MHW-related ecological risks.

4. Discussion and conclusions

The present study reports the potential impacts of carbon neutrality on MHWs in the late 21st century using multi-model projections from CMIP6. If the current "regional rivalry" over carbon emissions policy continues to this century, MHWs would become stronger over 1.0°C and longer lasting 365 days than historical ones, especially in the western boundary current and equatorial current regions. In the analysis of the MHW duration-intensity phase, the historical MHW extremes do not correspond to the future extremes, indicating that the future MHW state would enter an entirely new phase. Approximately 68% of the global ocean is projected to be exposed to permanent MHWs, regionally 93% in the Indian Ocean, 76% in the Pacific Ocean, 68% in the Atlantic Ocean, 65% in the Coastal Ocean, and 48% in the Southern Ocean.

It is found that achieving carbon neutrality can significantly reduce such a drastic increase in the future MHWs. It is projected to dramatically reduce the spatial proportion of the ocean exposed to permanent MHWs by as low as 0.02 to 0.07%, depending on the ocean regions. Compared to previous studies using SSP1-2.6 scenario (e.g., Frölicher et al., 2018; Darmaraki et al., 2019; Plecha and Soares, 2020), the duration and intensity of MHW under SSP1-1.9 scenario are further reduced by about 0.5–1.5 times because these properties are well correlated with the SST increase (Oliver et al., 2019; Plecha and Soares, 2020). This result underscores the critical importance of ongoing efforts to achieve net-zero carbon emissions by 2050s to reduce the potential ecological risks due to extreme MHW exposure.

Even if carbon neutrality is successfully achieved, increasing exposure to MHWs is still expected to be unavoidable in future climate (see Figs. 3 and 4). This suggests that marine ecosystems, including coral reefs, fisheries, and biodiversity, would more frequently face significant challenges to their survival. This could potentially result in economic losses for societies dependent on fisheries, tourism, and coastal infrastructure. Continued research is therefore essential to better understand the impacts of MHWs on marine ecosystems, with continued international cooperation to develop resilient marine ecosystems.

Acknowledgements

This research was supported by Korea Institute of Marine Science & Technology Promotion (KIMST) funded by the Ministry of Oceans and Fisheries (20220033). This work was also supported by Korea Environment Industry & Technology Institute (KEITI) through project for developing and observation-based GHG emissions geospatial information map, funded by Korea Ministry of Environment (MOE) (RS-2023-00232066). All authors thank every group involved in Coupled Model Intercomparison Project Phase 6 (CMIP6) model output data provided by World Climate Research Programme (WCRP) CMIP6 Community. We also thank R. W. Reynolds and Co-workers and RECAP2 community for sharing their dataset and providing guidance.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data availability Statement

The data of eight global climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) can be accessed at https://esgf-node.llnl.gov/search/cmip6/, and can also be accessed in Eyring et al. (2016). The NOAA OISST high resolution dataset can be obtained in Reynolds et al. (2007) or via https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html. The five ocean mask dataset can be obtained from https://reccap2-ocean.github.io/regions/.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by S.-G. Oh under supervision of Y.-K. Cho and S.-W. Son. The first draft of the manuscript was written by S.-G. Oh, S.-W. Son, S. Jeong, and Y.-K. Cho and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Table 1. Summary of the CMIP6 models used in this study.

No.	Model	Ensemble information	Institution	Horizontal Resolution (Lon x Lat)
1	CanESM5	r1i1p1f1	Canadian Earth System Model version 5, Canadian Centre for Climate Modelling and Analysis (Canada)	360 x 291
2	CNRM-ESM2-1	r1i1p1f2	National Center for Meteorological Research (France)	362 x 294
3	EC-Earth3	r4i1p1f1	ICHEC, The Irish Centre for High-End Computing, National University of Ireland (Ireland)	362 x 292
4	GFDL-ESM4	r1i1p1f1	NOAA/Geophysical Fluid Dynamics Laboratory, Earth System Model version 4 (USA)	360 x 180
5	MIROC-ES2L	r1i1p1f2	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (Japan)	360 x 256
6	MPI-ESM-LR	r1i1p1f1	Max Planck Institute for Meteorology (Germany)	256 x 220
7	MRI-ESM2-0	r1i1p1f1	Meteorological Research Institute (Japan)	360 x 180
8	UKESM1-0-LL	r1i1p1f2	Met Office Hadley Centre (UK)	360 x 330

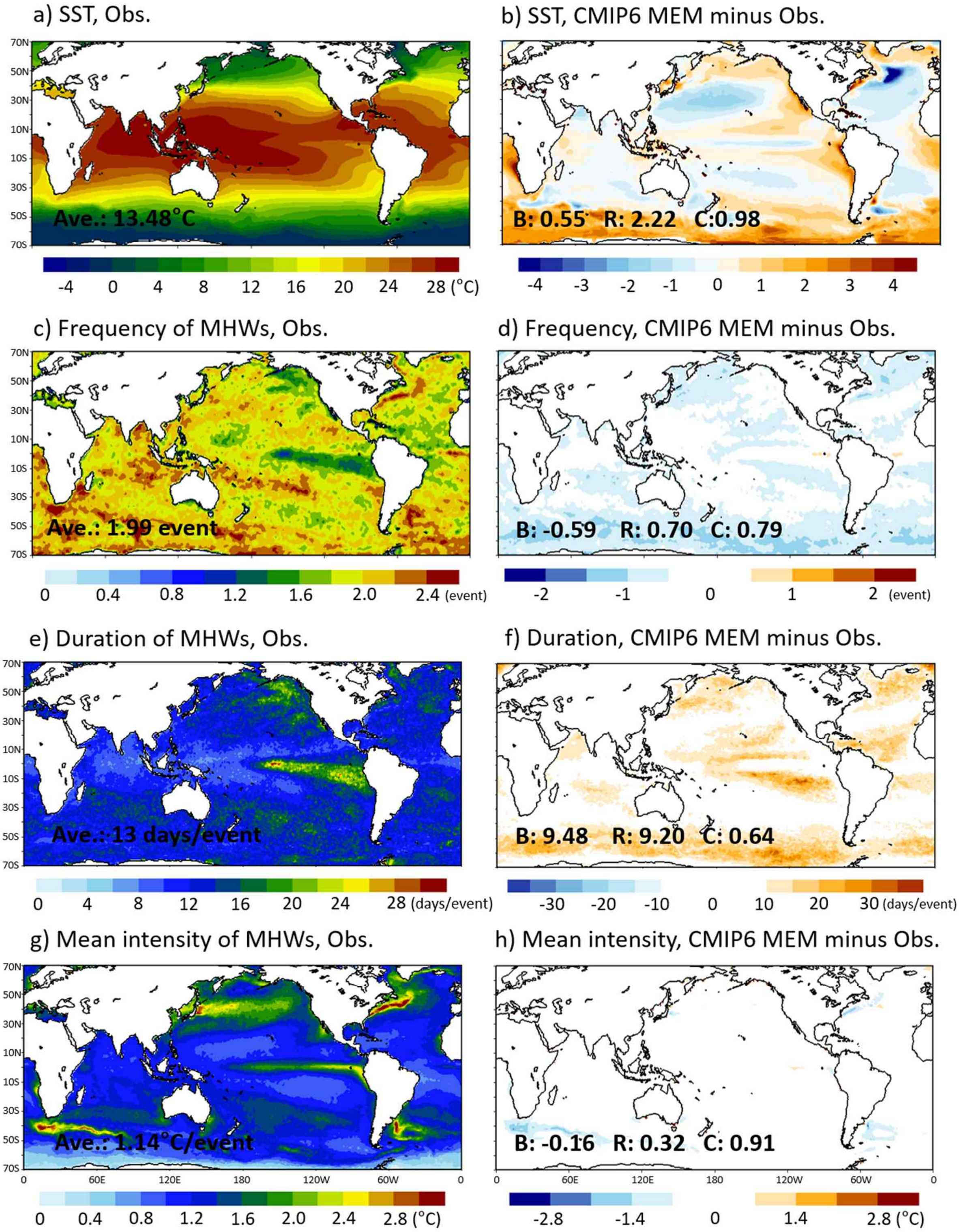
a) SST, Obs.
Ave.: 13.48°C
-4 0 4 8 12 16 20 24 28 (°C)
b) SST, CMIP6 MEM minus Obs.
B: 0.55 R: 2.22 C:0.98
-4 -3 -2 -1 0 1 2 3 4
c) Frequency of MHWs, Obs.
Ave.: 1.99 event
0 0.4 0.8 1.2 1.6 2.0 2.4 (event)
d) Frequency, CMIP6 MEM minus Obs.
B: -0.59 R: 0.70 C: 0.79
-2 -1 0 1 2 (event)
e) Duration of MHWs, Obs.
Ave.: 13 days/event
0 4 8 12 16 20 24 28 (days/event)
f) Duration, CMIP6 MEM minus Obs.
B: 9.48 R: 9.20 C: 0.64
-30 -20 -10 0 10 20 30 (days/event)
g) Mean intensity of MHWs, Obs.
Ave.: 1.14°C/event
0 0.4 0.8 1.2 1.6 2.0 2.4 2.8 (°C)
h) Mean intensity, CMIP6 MEM minus Obs.
B: -0.16 R: 0.32 C: 0.91
-2.8 -1.4 0 1.4 2.8 (°C)
70N 50N 30N 10N 10S 30S 50S 70S
0 60E 120E 180 120W 60W 0

Figure 1. Spatial distribution of annual mean sea surface temperature (SST), marine heatwave (MHW) frequency, duration, and mean intensity for the historical period of 1985–2014. (a, c, e, g) NOAA OISST observation and (b, d, f, h) CMIP6 multi-model ensemble median (MEM) minus observation. The observed area-averaged value (Ave.) and the bias (B), root-mean-square error (R), and correlation (C) of the CMIP6 MEM relative to observation are indicated in the sub-plot. Only ocean areas ranging from 70°S to 70°N are considered.

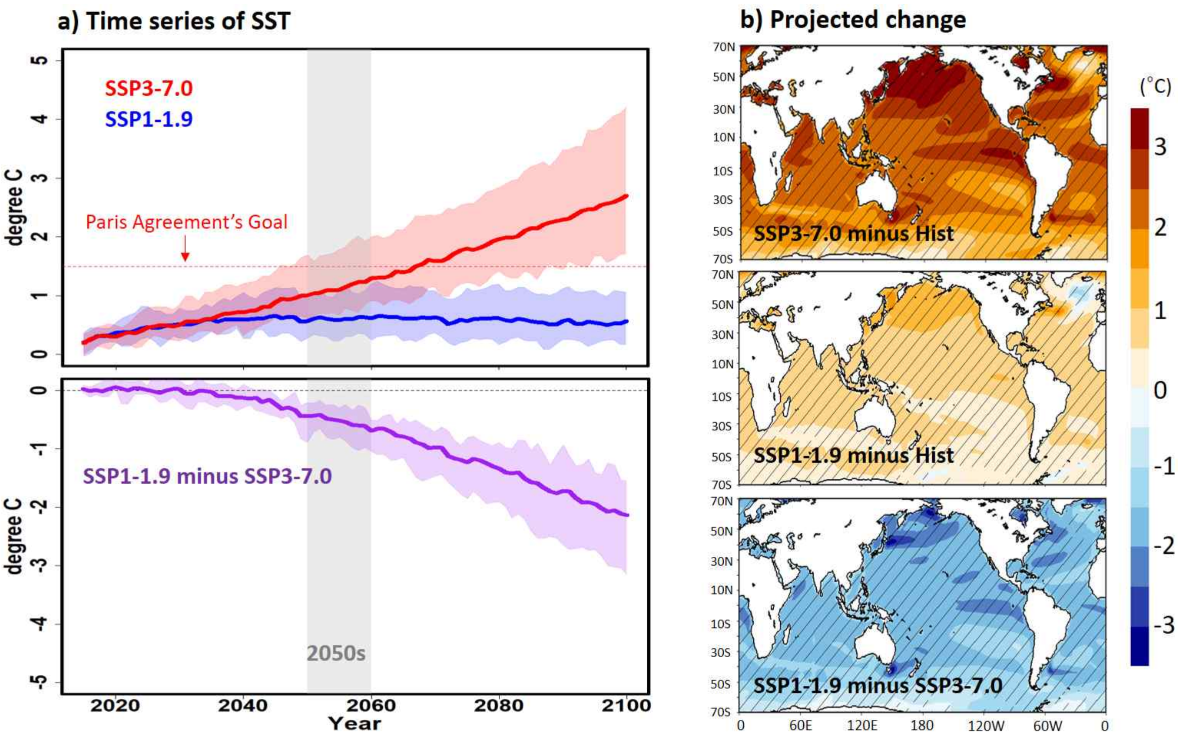

Figure 2. (a) Time series of globally averaged annual mean sea surface temperature (SST) over -70°S to 70°N for the period of 2015–2100. (b) The projected spatial changes in the late 21st century (2071–2100) compared to the historical period (1985–2014) are presented, with their difference. In (a), the red and blue lines indicate the CMIP6 multi-model ensemble median under SSP3-7.0 and SSP1-1.9 scenarios against the historical period. The purple line in the bottom panel in (a) is the difference between SSP1-1.9 and SSP3-7.0 scenarios with time-varying. Shadings indicate the model spread defined by the min-max range for each scenario. The vertical gray shaded area denotes the 2050s, the target goal for achieving net-zero anthropogenic carbon emissions. In (b), the areas with statistically significant differences between future and historical climates (or between two SSP scenarios) at the 5% significance level in the Student's t-test are hatched.

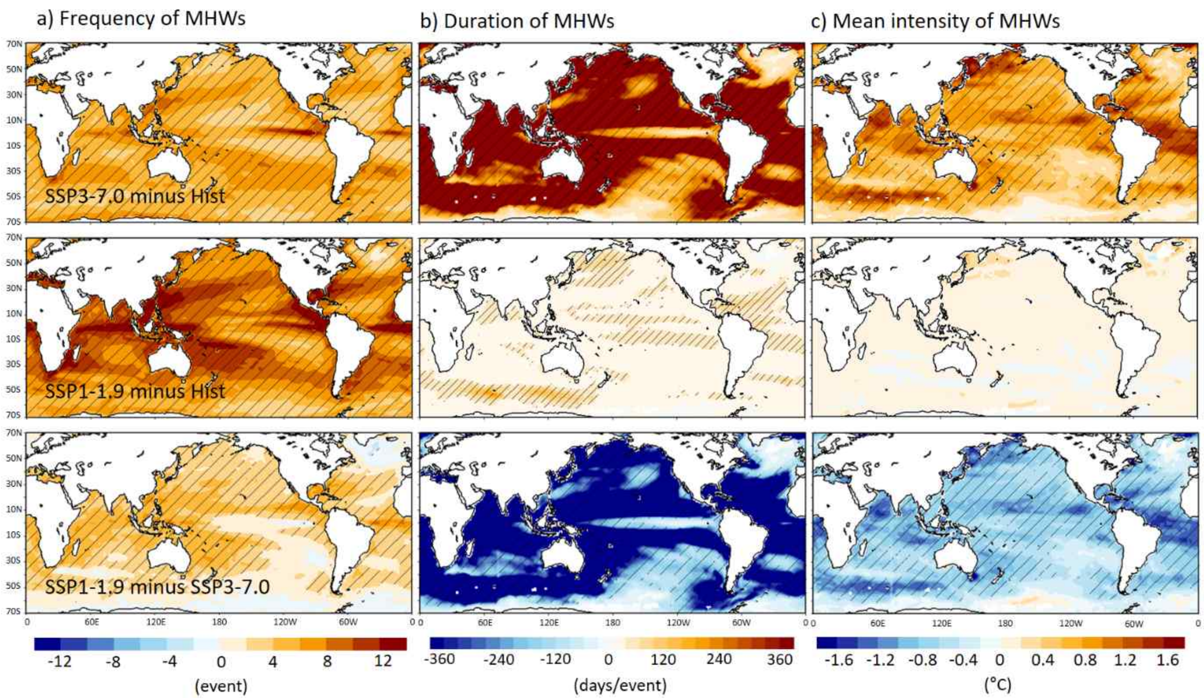

Figure 3. Projected spatial changes of marine heatwaves (MHWs) in the late 21st century (2071–2100) under SSP3-7.0 and SSP1-1.9 scenarios compared to the historical period (1985–2014) and their difference. The CMIP6 multi-model ensemble median is presented. The areas with statistically significant differences between future and historical climates (or between two SSP scenarios) at the 5% significance level in the Student's t-test are hatched.

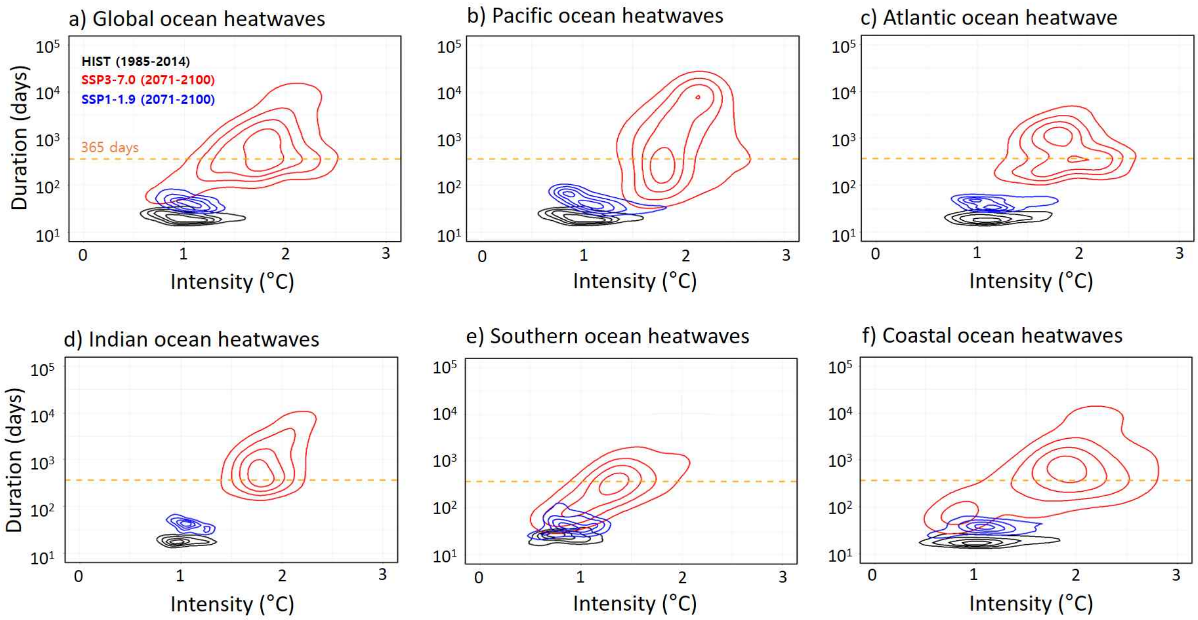

Figure 4. Joint probability distribution of marine heatwave duration (days) and intensity (°C) over the global and the five ocean areas. The black contours denote the historical period of 1985–2014. The red and blue contours denote the late 21st century (2071–2100) under SSP3-7.0 and SSP1-1.9 scenarios, respectively. Note that the y-axis has a logarithmic scale. The horizontal dashed line in yellow indicates the 365-day MHW duration as a reference for permanent MHW.

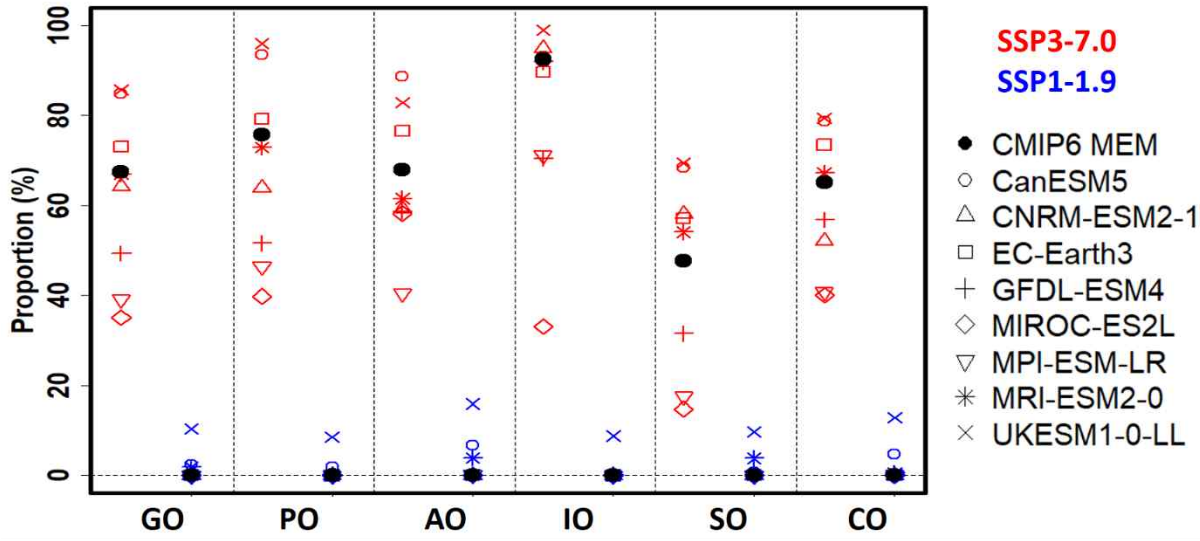

Figure 5. Proportion of ocean exposed to permanent MHWs, which is defined as an MHW duration of more than 365 days, over the globe ocean (GO), Pacific Ocean (PO), Atlantic Ocean (AO), Indian Ocean (IO), Southern Ocean (SO), and Coastal Ocean (CO) in the 21st century (2071–2100) under SSP3-7.0 and SSP1-1.9 scenarios compared to the historical period (1985–2014).

[*Earth's Future*]

Supporting Information for

Significant reduction of potential exposure to extreme marine heatwaves by achieving carbon neutrality

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January 2024

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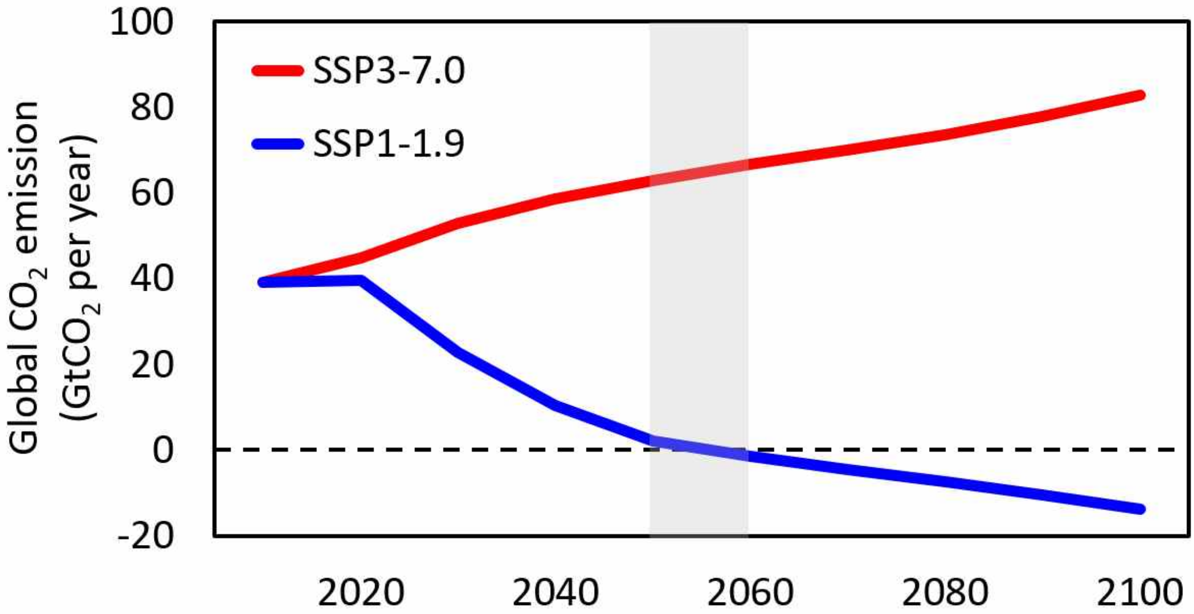

Fig. S1. Time series of global CO_2 emission in SSP1-1.9 and SSP3-7.0 scenarios. The vertical gray shading indicates the 2050s, when net-zero carbon emissions are achieved in the SSP1-1.9 scenario.

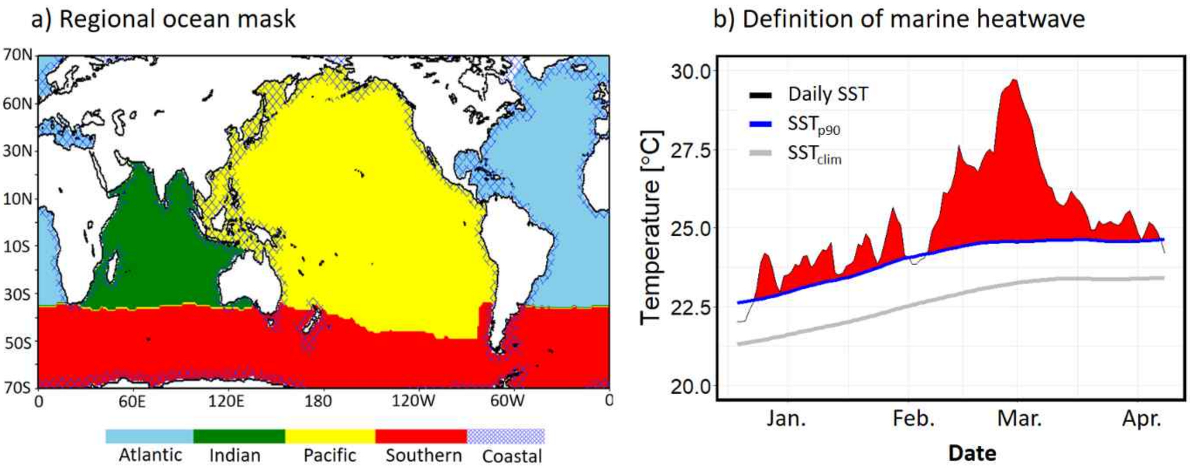

Fig. S2. (a) Sub-regional ocean domain used in this study (https://reccap2-ocean.github.io/regions/) and (b) example for the definition of marine heatwave.

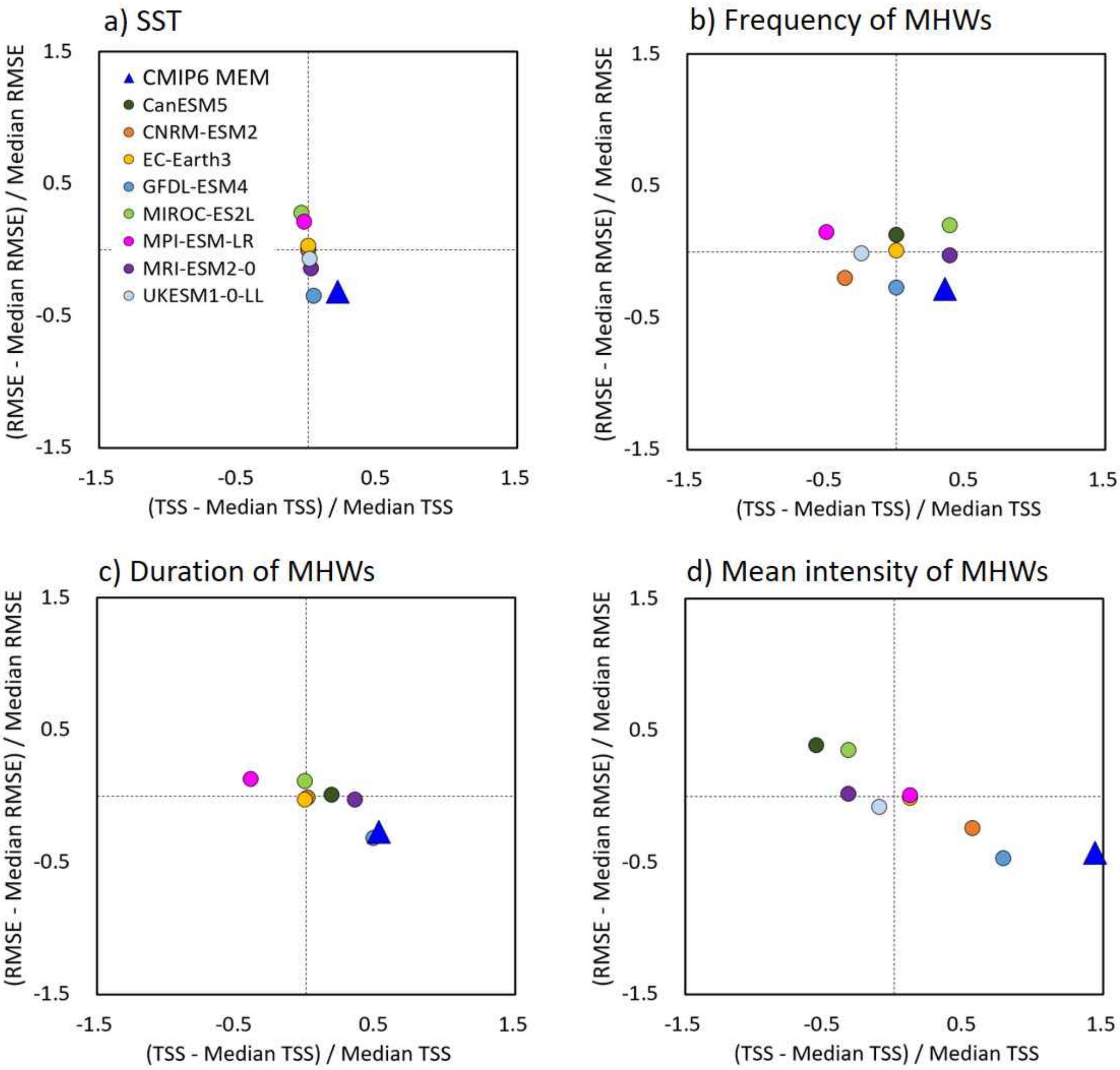

Fig. S3. The relative performance of the eight CMIP6 models and multi-model ensemble median for globally-averaged annual mean sea surface temperature (SST), marine heat wave (MHW) frequency, duration, and mean intensity for the historical period of 1985–2014, based on the root-mean-square error (RMSE) and Taylor skill score (TSS). The closer the symbol is to the bottom right corner, the better the relative performance. The NOAA OISST data is used as a reference in the calculation of evaluation measures. Only ocean areas ranging from 70°S to 70°N are considered.

Significant reduction of potential exposure to extreme marine heatwaves by achieving carbon neutrality

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January 2024

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Highlights (Limit 140 characters)

- Marine heatwaves will be stronger and longer-lasting in a warming climate
- Current warming rate will expose 68% of the oceans to permanent marine heatwaves
- Exposure to permanent marine heatwaves will be greatly reduced by carbon neutrality

Abstract

Marine heatwave (MHW), a prolonged period of anomalously warm seawater, has a catastrophic repercussion on marine ecosystems. With global warming, MHWs have become increasingly frequent, intense, and prolonged. To avoid irreversible damages from such extreme events, net-zero carbon emissions by the 2050s, called carbon neutrality, were proposed. Here, we evaluate the impact of carbon neutrality on MHWs in the late 21st century using multi-model projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) Shared Socioeconomic Pathway (SSP)1-1.9 and SSP3-7.0 scenarios. It is found that if the current regional rivalry over carbon emissions continues (i.e., SSP3-7.0), the MHWs in the late 21st century will become stronger and longer than historical ones, especially in the western boundary current and equatorial current regions. Approximately 68% of the global ocean will be exposed to permanent MHWs, regionally 93% in the Indian Ocean, 76% in the Pacific Ocean, 68% in the Atlantic Ocean, 65% in the Coastal Ocean, and 48% in the Southern Ocean. Such MHWs can be significantly reduced by achieving carbon neutrality (i.e., SSP1-1.9). In particular, the spatial proportion of the ocean exposed to permanent MHWs can be reduced to as low as 0.02 to 0.07%, depending on the regions. This result underscores the critical importance of ongoing efforts to achieve net-zero carbon emissions to reduce the potential ecological risks induced by extreme MHWs.

Plain Language Summary

Marine heatwave, a prolonged period of anomalously warm seawater, has a catastrophic effects on marine ecosystems. To avoid such extreme events, net-zero carbon emissions by the 2050s, known as carbon neutrality, has been proposed. Here, we show that achieving carbon neutrality could result in a significant reduction in the spatial proportion of the ocean exposed to permanent marine heatwaves in the late 21st century compared to current warming projections, with a potential exposure reducing from 48–93% to 0.02–0.07%, depending on the ocean regions. It is clear that achieving carbon neutrality will certainly reduce the intensity of marine heatwaves almost to current levels. This finding underscores the critical importance of ongoing efforts to achieve net-zero carbon emissions to reduce the potential ecological risks posed by extreme marine heatwaves.

1. Introduction

Marine heatwave (MHW), defined as a prolonged period of anomalously warm seawater (Hobday et al., 2016), has devastating impacts on marine ecosystems, resulting in significant ecological, social, and economic losses (Hu et al., 2021; Qiu et al., 2021; Pastor and Khodayar, 2022). Ongoing global warming is expected to lead to more frequent, intense, and longer-lasting MHWs worldwide (Oliver et al., 2019; Qiu et al., 2021; Cheng et al., 2023). This, in turn, has the potential to bring about even more irreversible transformations in marine organisms, induce more profound alterations in marine ecosystems, and trigger more far-reaching societal consequences (Frölicher et al., 2018; Pastor and Khodayar, 2022).

To avoid irreversible damages from such extreme climate events in a warming climate, the 2015 Paris Agreement proposed net-zero anthropogenic carbon emissions by 2050s, also known as carbon neutrality (UNFCCC, 2015). Its potential benefits have often been highlighted by the analysis of climate model simulations, which show that 0.5°C less warming by achieving carbon neutrality compared to 2°C warming can lead to a significant reduction in areas damaged by climate change (Park et al., 2018; King et al., 2021; Nashwan and Shahid, 2022). However, such studies have mainly been carried out in habitable land areas rather than in the ocean. The impacts of carbon neutrality on the marine environment have rarely been studied.

Ocean covers 71% of Earth's surface and contributes to over 17% of edible food production (Nijdam et al., 2012; Edwards et al., 2019). As the source to increase food production on land is limited, the ocean is becoming an increasingly important source of future food for a growing population (Edwards et al., 2019; Costello et al., 2020). In this respect, the

MHWs can have catastrophic repercussions on marine food production by disrupting the food chains and, in extreme cases, causing mass fish kills (Oliver et al., 2019; Qiu et al., 2021; Cheng et al., 2023). Therefore, a quantitative analysis of the potential impacts of carbon neutrality on the anticipated intensification of MHWs, which is likely to be exacerbated by global warming, is critical not only for establishing effective ocean climate change mitigation policies but also for our food security.

Here, we investigate the potential impacts of carbon neutrality on MHWs by examining multi-model projections from the Coupled Model Intercomparison Project 6 (CMIP6, Eyring et al., 2015). Specifically, we compare the Shared Socioeconomic Pathway (SSP)1-1.9 scenario, which achieves net zero anthropogenic carbon emissions by 2050s, with the SSP3-7.0 scenario based on regional rivalry over carbon emissions policies (Fig. S1; O'Neill et al., 2016; Oin et al., 2021), and quantitatively assess the projected changes in frequency, duration, and intensity of MHWs. The impacts of carbon neutrality are also compared across five ocean regions, i.e., Atlantic, Indian, Pacific, Southern, and Coastal oceans.

2. Data and Methods

2.1. Datasets

Daily sea surface temperature (SST) outputs for historical simulations (1985–2014) and future projections (2015–2100) under two different SSP scenarios from eight CMIP6 models (Eyring et al., 2016; Table 1) are used to calculate the MHW properties. The SSP3-7.0

and SSP1-1.9 scenarios, which are respectively the high and very low greenhouse gas emission scenarios (O'Neill et al., 2016; Oin et al., 2021), are used. The former scenario assumes that the current rate of global warming will continue until 2100 (i.e., regional rivalry scenario). Meanwhile, the latter scenario assumes net-zero carbon emissions by 2050s (i.e., carbon neutrality scenario) (Fig. S1). All models are interpolated to a regular 1°×1° grid using a bilinear remapping, and then the MHW properties are calculated. This procedure allows to minimize the uncertainty arising from different model resolutions (Kim et al., 2020; Li et al., 2021).

To evaluate the model performances for the historical period of 1985–2014, the National Oceanic and Atmospheric Administration (NOAA) 1/4 degree daily Optimum Interpolation (OI) SST V2.0 dataset is used (Reynolds et al., 2017). This dataset is derived from remotely-sensed SST from the Advanced Very High-Resolution Radiometer (AVHRR) and has been widely used to analyze MHWs worldwide (Oliver et al., 2018; 2019; Qiu et al., 2021). To be compared with the coarse-resolution models, this dataset is regridded onto a regular 1°×1° grid before calculating the MHW properties.

2.2. MHW definition

The MHW is generally defined as a discrete, prolonged, anomalous seawater event when daily SST exceeds the 90th percentile for five or more consecutive days. The 90th percentile is determined from a 30-year historical time series from 1985 to 2014 (Fig. S2b, Hobday et al., 2016). This threshold and daily climatology are calculated for each calendar day by using the daily SST within an 11-day window that is smoothed by applying a 31-day moving average. Events with temporal gaps of two days or fewer are considered to be a continuous event. This definition allows MHWs to be detected at any time of the year, as opposed to only detecting events that occur during the warmest months (Hobday et al., 2016; Oliver et al., 2018). The 90th percentile at each grid in the historical period is applied to the period of 1985–2100 to calculate the MHW properties.

The definition of MHWs does not take into account the effect of sea ice. We therefore focus our analysis on five ocean regions: the Atlantic, Indian, Pacific, Southern, and Coastal oceans, between 70°S and 70°N (Fig. S2a, Laruelle et al., 2017; Hauck et al., 2023). To characterize MHWs, frequency (number of events per year), duration (days per event), and mean intensity (average of temperature anomalies per event) are calculated.

2.3. Evaluation matric

This study uses the multi-model ensemble median (MEM), which is more appropriate than the multi-model mean when the ensemble members have unusually large or small values. The model performance for MHW properties is evaluated in terms of the bias, root-mean-square error (RMSE), and correlation for spatial patterns for the historical period of 1985–2014. They are computed as follows.

$$bias = \frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)^2}$$

$$correlation = \frac{\sum_{i=1}^{n}(M_i - \bar{M})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{n}(M_i - \bar{M})}\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})}}$$

where M and O denote the model and observation. Subscript i denotes i th grid point and n is the number of the total grids at ocean areas. The overbar presents the mean value at the ocean areas. To compare the performance of MEM with that of each model, the scatter plot of RMSE and Taylor skill score (TSS, Taylor, 2001) is used. The TSS is computed as below:

$$TSS = \frac{(1 + correlation)^4}{4(SDR + \frac{1}{SDR})^2}$$

where SDR is the ratio of the spatial standard deviation of the model against to that of the observation. This score quantifies the similarity in the spatial distribution and amplitude between the model and the observation. The median value of each evaluation measure is used to calculate the relative RMSE and TSS values for both individual models and MEM.

3. Results

3.1. Historical MHW properties

Figure 1 shows the spatial distribution of SST climatology, MHW frequency, duration, and mean intensity in the historical period of 1985–2014 (left). The model biases are also presented (right). The CMIP6 MEM well reproduces the spatial distribution of SST climatology (Fig. 1a), with a spatial correlation of 0.98 (Fig. 1b). Cold biases ranging from -0.5°C to -4.0°C are prominent over the Northwest Pacific and North Atlantic, while warm biases ranging from 0.5°C to 4.0°C are found over the Northeast Pacific, Southeast Pacific, Southeast Atlantic, and Southern Ocean. On a global average, SST bias is 0.55°C mainly due to warm bias in the Southern Ocean. These biases are the improved results compared to those of the CMIP5 models (Zhang et al., 2023).

The MHW frequency ranges from about one to three annual events, depending on the location (Fig. 1c). The CMIP6 MEM realistically captures its magnitude (bias of -0.59 event) and spatial pattern (correlation of 0.79) (Fig. 1d). The relatively long-lasting MHWs are observed in the eastern Pacific (Fig. 1e) as El Niño-Southern Oscillation (ENSO) events manifest themselves as individual long-lasting MHWs (Oliver et al., 2018). This in turn is associated with less frequent MHWs in this region, as shown in Fig. 1c. In general, the CMIP6 MEM reproduces the spatial distribution of MHW duration reasonably well, with a spatial correlation of 0.64. However, it simulates longer MHW durations, especially in the Southern Ocean and the eastern Pacific, in excess of 20 days (Fig. 1f). The longer duration in the Southern Ocean might result from the warm bias of SST.

The MHW intensity show a large spatial variation (Fig. 1g). Hotspots of strong intensity are observed in the western boundary current extension regions (i.e., Gulf Stream, Brazil and Malvinas currents in the Atlantic, Somali and Agulhas currents in the Indian Ocean, and Kuroshio and East Australian currents in the Pacific) with 2–3°C, the central and eastern equatorial Pacific with 1.5–2.5°C, the eastern boundary current regions (i.e., California Current off North America, Humboldt (or Peru) Current off South America, Canary Current off North Africa, and Benguela Current off South Africa) with 1.5–2.5°C, and Cape Horn current region with 2–4°C (Fig. 1g). The CMIP6 MEM realistically reproduces these features with a spatial correlation of 0.91 with a weak cold bias of -0.16°C on the global average (Fig. 1h). However, relatively large cold biases are regionally found in the Gulf Stream, Brazil and Malvinas current in the Atlantic, and Cape Horn current with -0.7 to -2.1°C (Fig. 1h).

Compared to the individual models, the MEM (Figs. 1b, d, f, and h) shows a better performance in the reproduction of SST climatology and MHW properties (Fig. S3). This result is consistent with previous studies showing that the multi-model ensemble has superior performance in reproducing mean and extreme climates than a single model (e.g., Oh and Suh, 2017; Kim et al., 2020; Li et al., 2021). It justifies the use of MEM for future projection of MHW properties.

3.2. Future projections and the impact of carbon neutrality

Figure 2a shows the time series of globally-averaged SST over 70°S to 70°N for the period of 2015–2100 under the SSP1-1.9 and SSP3-7.0 scenarios compared to the historical period of 1985–2014. If global warming continues without achieving carbon neutrality in the 2050s, SST is projected to increase up to 2.70°C by the end of the century, with a warming trend of 0.29°C per decade (red line in the top panel of Fig. 2a). Achieving carbon neutrality can lead to a significant mitigation in SST warming (blue line in the top panel of Fig. 2a). A warming similar to SSP3-7.0 scenario is projected to occur until the late 2030s, but it slows significantly until the 2050s and then stabilizes at 0.57°C by the end of the century. The reduced SST warming is 2.13°C in 2100. This is a 79% reduction from the SSP3-7.0 scenario (purple line in the lower panel of Fig. 2a). The reduced trend is particularly noticeable after the 2050s. The inter-model spread does not cross the zero line after 2050s, indicating that the difference between the two emission scenarios is distinct in the late 21st century. It evidences the critical role of the carbon neutrality in mitigating the potential climate risks associated with SST warming.

The spatial distribution of SST warming in the late 21st century (2071–2100) is analyzed in Fig. 2b. If global warming continues, strong SST warming of 2 to 3°C are projected to occur at the western boundary current and equatorial current regions (the top panel of Fig. 2b). This suggests that the SST warming is significantly related to regional current changes (e.g., Jeong et al., 2021). Achieving carbon neutrality mitigates SST warming within 0.5 to 1.5°C (the middle panel of Fig. 2b). The benefit of carbon neutrality is particularly evident around the western boundary current and equatorial current regions (the bottom panel of Fig. 2b).

Figure 3 shows the projected changes of MHW properties in the late 21st century (2071–2100) compared to the historical period (1985–2014) and their differences between the two emission scenarios. In a warming climate, the MHW frequency increases by 2–12 events per year with the largest increase in the western boundary current and equatorial current regions (the top and middle panels of Fig. 3a). A larger increase of 2–6 events per year is projected to occur under the carbon neutrality scenario compared to the high emissions scenario (the bottom panel of Fig. 3a). This is not a surprising finding. Under the high emissions scenario, each individual MHW has a much longer duration, even longer than 365 days, and strong intensities greater than 1.0°C depending on the region (the top panel of Fig. 3b and c). A smaller frequency is therefore due to the fact that the MHW duration becomes much longer. We should keep in mind that MHWs of longer duration and higher intensity can have a critical impact on the marine ecosystem.

Under a carbon neutrality scenario, the duration of MHWs is projected to be slightly longer than historical levels, ranging from 30 to 120 days, and their intensity is similar to historical levels (the middle panels of Fig. 3b and c). It is evident that there is a significant reduction in the duration and intensity of MHWs in all oceans except the part of the Southern Ocean and the northern part of the Atlantic Ocean (the bottom panels of Fig. 3b and c). This suggests that achieving net-zero carbon emissions by the 2050s can lead to a significant reduction in potential exposure to more extreme MHWs.

The joint probability distributions of MHW duration and intensity over the five ocean regions (i.e., Pacific, Atlantic, Indian, Southern, and Coastal Oceans; see Fig. S2a) for the historical and future periods are analyzed in Fig. 4. It is clear that MHWs under SSP3-7.0 scenarios would have significantly different features from historical ones, with longer and more intense MHWs over all oceans (red contours in Fig. 4). Specifically, Indian Ocean MHWs under SSP3-7.0 scenario are completely different from the historical ones or SSP1-1.9 scenario in both intensity and duration (Fig. 4d). Durations of the Pacific and Atlantic MHWs are also quite different, while their intensities show slight overlap in some values (Figs. 4b and c). The

Southern and Coastal Ocean MHWs are expected to show a wider range of variability in duration and intensity than other oceans, with more than two-thirds deviating from historical ones (Figs. 4e and f). These results indicate that future MHWs may undergo a complete change beyond the range they had previously experienced. Achieving carbon neutrality can maintain historical MHWs to some extent. However, future MHW duration is still projected to increase about twofold compared to the historical one over all oceans (blue contours in Fig. 4).

Figure 5 presents the spatial proportion of the oceans exposed to permanent MHWs, which are defined as MHW events of duration longer than 365 days. Under the high emissions scenario, about 68% of the global ocean (GO in Fig. 5) is projected to be exposed to permanent MHWs, with a large intermodel spread ranging from 35% in MIROC-ES2L to 86% in UKESM1-O-LL. In the Indian Ocean (IO), 93% of the ocean waters are projected to be exposed to permanent MHWs. This is followed by the Pacific Ocean (PO) with 76%, and the Atlantic Ocean (AO) and the Coastal Ocean (CO) with 68% and 65%, respectively. The Southern Ocean (SO) is projected to have 48% of its waters exposed to permanent MHWs. For all oceans, CanESM5 and UKESM1-0-LL models tend to project relatively extreme scenarios, while MPI-ESM-LR and MIROC-ES2L models project relatively less extreme scenarios.

Not surprisingly, achieving carbon neutrality can lead to a significant reduction in the proportion of the ocean exposed to permanent MHWs. According to CMIP6 MEM, the proportion of the ocean with permanent MHWs is projected to be as low as 0.02% to 0.07% for all oceans. This highlights the importance of carbon neutrality in mitigating long-lasting MHW-related ecological risks.

4. Discussion and conclusions

The present study reports the potential impacts of carbon neutrality on MHWs in the late 21st century using multi-model projections from CMIP6. If the current "regional rivalry" over carbon emissions policy continues to this century, MHWs would become stronger over 1.0°C and longer lasting 365 days than historical ones, especially in the western boundary current and equatorial current regions. In the analysis of the MHW duration-intensity phase, the historical MHW extremes do not correspond to the future extremes, indicating that the future MHW state would enter an entirely new phase. Approximately 68% of the global ocean is projected to be exposed to permanent MHWs, regionally 93% in the Indian Ocean, 76% in the Pacific Ocean, 68% in the Atlantic Ocean, 65% in the Coastal Ocean, and 48% in the Southern Ocean.

It is found that achieving carbon neutrality can significantly reduce such a drastic increase in the future MHWs. It is projected to dramatically reduce the spatial proportion of the ocean exposed to permanent MHWs by as low as 0.02 to 0.07%, depending on the ocean regions. Compared to previous studies using SSP1-2.6 scenario (e.g., Frölicher et al., 2018; Darmaraki et al., 2019; Plecha and Soares, 2020), the duration and intensity of MHW under SSP1-1.9 scenario are further reduced by about 0.5–1.5 times because these properties are well correlated with the SST increase (Oliver et al., 2019; Plecha and Soares, 2020). This result underscores the critical importance of ongoing efforts to achieve net-zero carbon emissions by 2050s to reduce the potential ecological risks due to extreme MHW exposure.

Even if carbon neutrality is successfully achieved, increasing exposure to MHWs is still expected to be unavoidable in future climate (see Figs. 3 and 4). This suggests that marine ecosystems, including coral reefs, fisheries, and biodiversity, would more frequently face significant challenges to their survival. This could potentially result in economic losses for societies dependent on fisheries, tourism, and coastal infrastructure. Continued research is therefore essential to better understand the impacts of MHWs on marine ecosystems, with continued international cooperation to develop resilient marine ecosystems.

Acknowledgements

This research was supported by Korea Institute of Marine Science & Technology Promotion (KIMST) funded by the Ministry of Oceans and Fisheries (20220033). This work was also supported by Korea Environment Industry & Technology Institute (KEITI) through project for developing and observation-based GHG emissions geospatial information map, funded by Korea Ministry of Environment (MOE) (RS-2023-00232066). All authors thank every group involved in Coupled Model Intercomparison Project Phase 6 (CMIP6) model output data provided by World Climate Research Programme (WCRP) CMIP6 Community. We also thank R. W. Reynolds and Co-workers and RECAP2 community for sharing their dataset and providing guidance.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data availability Statement

The data of eight global climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) can be accessed at https://esgf-node.llnl.gov/search/cmip6/, and can also be accessed in Eyring et al. (2016). The NOAA OISST high resolution dataset can be obtained in Reynolds et al. (2007) or via https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html. The five ocean mask dataset can be obtained from https://reccap2-ocean.github.io/regions/.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by S.-G. Oh under supervision of Y.-K. Cho and S.-W. Son. The first draft of the manuscript was written by S.-G. Oh, S.-W. Son, S. Jeong, and Y.-K. Cho and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Table 1. Summary of the CMIP6 models used in this study.

No.	Model	Ensemble information	Institution	Horizontal Resolution (Lon x Lat)
1	CanESM5	r1i1p1f1	Canadian Earth System Model version 5, Canadian Centre for Climate Modelling and Analysis (Canada)	360 x 291
2	CNRM-ESM2-1	r1i1p1f2	National Center for Meteorological Research (France)	362 x 294
3	EC-Earth3	r4i1p1f1	ICHEC, The Irish Centre for High-End Computing, National University of Ireland (Ireland)	362 x 292
4	GFDL-ESM4	r1i1p1f1	NOAA/Geophysical Fluid Dynamics Laboratory, Earth System Model version 4 (USA)	360 x 180
5	MIROC-ES2L	r1i1p1f2	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (Japan)	360 x 256
6	MPI-ESM-LR	r1i1p1f1	Max Planck Institute for Meteorology (Germany)	256 x 220
7	MRI-ESM2-0	r1i1p1f1	Meteorological Research Institute (Japan)	360 x 180
8	UKESM1-0-LL	r1i1p1f2	Met Office Hadley Centre (UK)	360 x 330

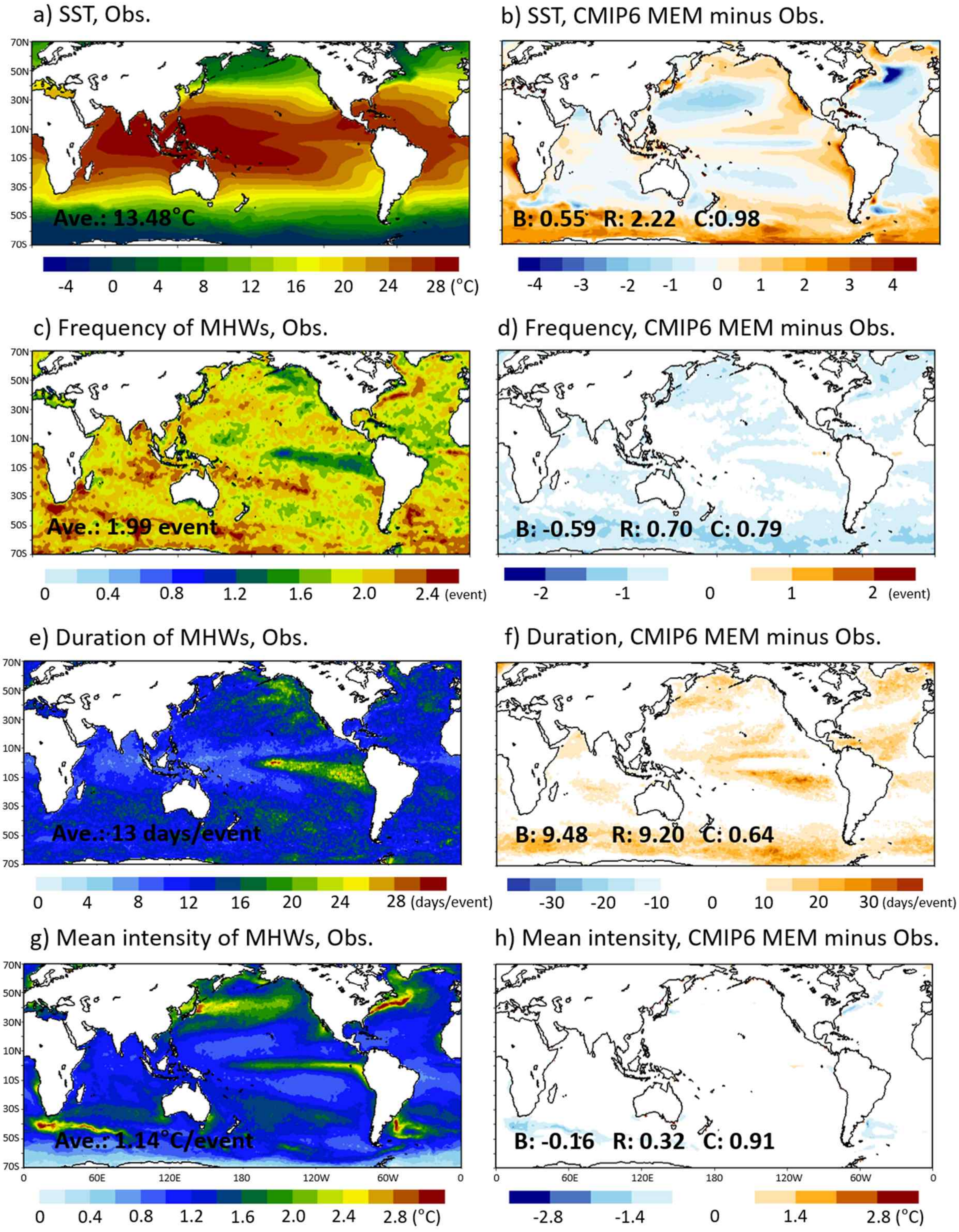
a) SST, Obs.
Ave.: 13.48°C
-4 0 4 8 12 16 20 24 28 (°C)
b) SST, CMIP6 MEM minus Obs.
B: 0.55 R: 2.22 C:0.98
-4 -3 -2 -1 0 1 2 3 4
c) Frequency of MHWs, Obs.
Ave.: 1.99 event
0 0.4 0.8 1.2 1.6 2.0 2.4 (event)
d) Frequency, CMIP6 MEM minus Obs.
B: -0.59 R: 0.70 C: 0.79
-2 -1 0 1 2 (event)
e) Duration of MHWs, Obs.
Ave.: 13 days/event
0 4 8 12 16 20 24 28 (days/event)
f) Duration, CMIP6 MEM minus Obs.
B: 9.48 R: 9.20 C: 0.64
-30 -20 -10 0 10 20 30 (days/event)
g) Mean intensity of MHWs, Obs.
Ave.: 1.14°C/event
0 0.4 0.8 1.2 1.6 2.0 2.4 2.8 (°C)
h) Mean intensity, CMIP6 MEM minus Obs.
B: -0.16 R: 0.32 C: 0.91
-2.8 -1.4 0 1.4 2.8 (°C)
70N 50N 30N 10N 10S 30S 50S 70S
0 60E 120E 180 120W 60W 0

Figure 1. Spatial distribution of annual mean sea surface temperature (SST), marine heatwave (MHW) frequency, duration, and mean intensity for the historical period of 1985–2014. (a, c, e, g) NOAA OISST observation and (b, d, f, h) CMIP6 multi-model ensemble median (MEM) minus observation. The observed area-averaged value (Ave.) and the bias (B), root-mean-square error (R), and correlation (C) of the CMIP6 MEM relative to observation are indicated in the sub-plot. Only ocean areas ranging from 70°S to 70°N are considered.

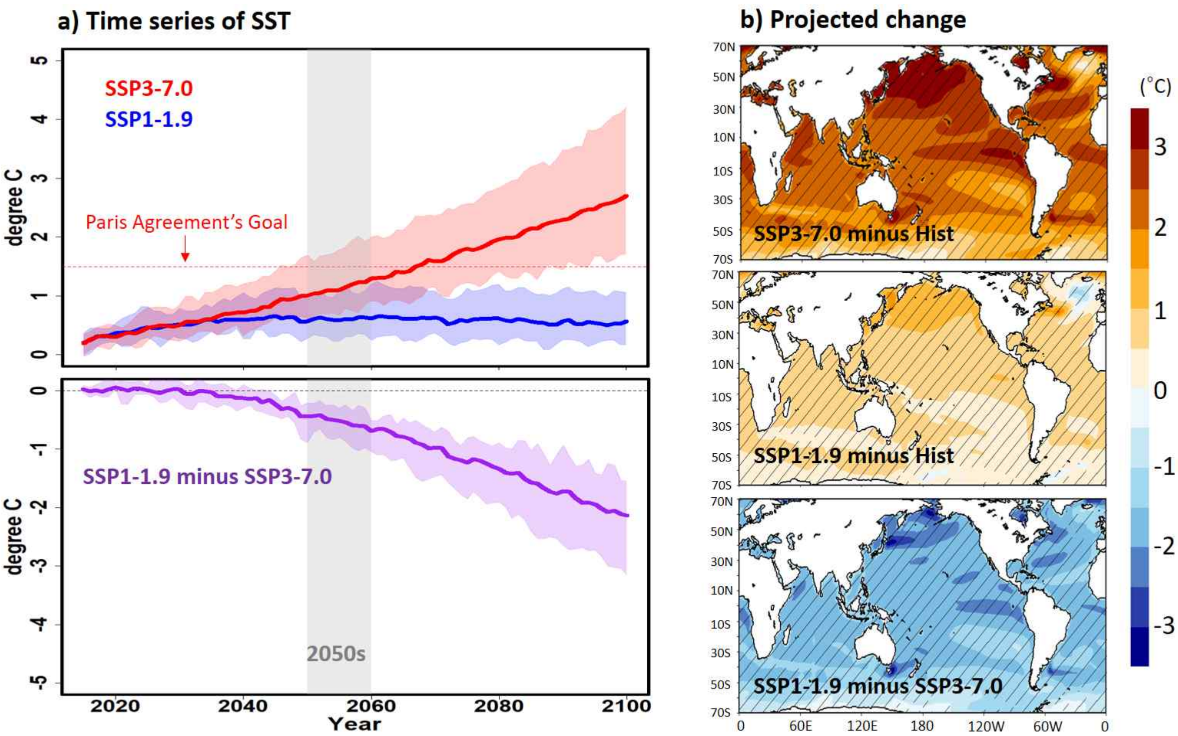

Figure 2. (a) Time series of globally averaged annual mean sea surface temperature (SST) over -70°S to 70°N for the period of 2015–2100. (b) The projected spatial changes in the late 21st century (2071–2100) compared to the historical period (1985–2014) are presented, with their difference. In (a), the red and blue lines indicate the CMIP6 multi-model ensemble median under SSP3-7.0 and SSP1-1.9 scenarios against the historical period. The purple line in the bottom panel in (a) is the difference between SSP1-1.9 and SSP3-7.0 scenarios with time-varying. Shadings indicate the model spread defined by the min-max range for each scenario. The vertical gray shaded area denotes the 2050s, the target goal for achieving net-zero anthropogenic carbon emissions. In (b), the areas with statistically significant differences between future and historical climates (or between two SSP scenarios) at the 5% significance level in the Student's t-test are hatched.

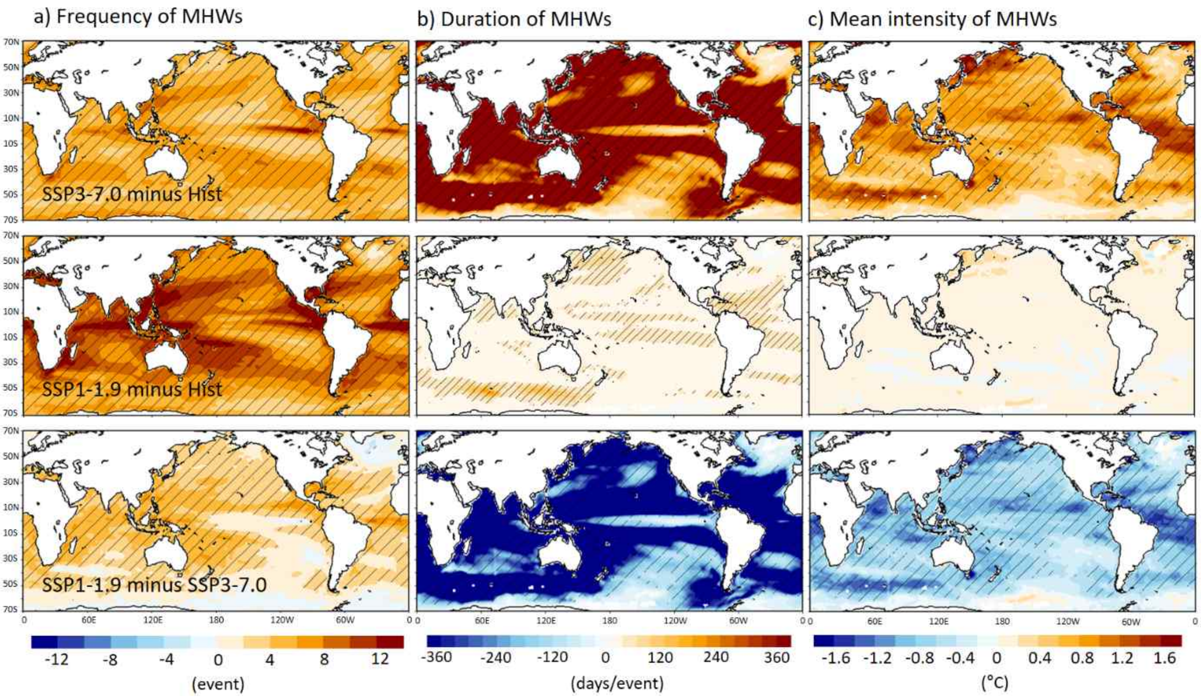

Figure 3. Projected spatial changes of marine heatwaves (MHWs) in the late 21st century (2071–2100) under SSP3-7.0 and SSP1-1.9 scenarios compared to the historical period (1985–2014) and their difference. The CMIP6 multi-model ensemble median is presented. The areas with statistically significant differences between future and historical climates (or between two SSP scenarios) at the 5% significance level in the Student's t-test are hatched.

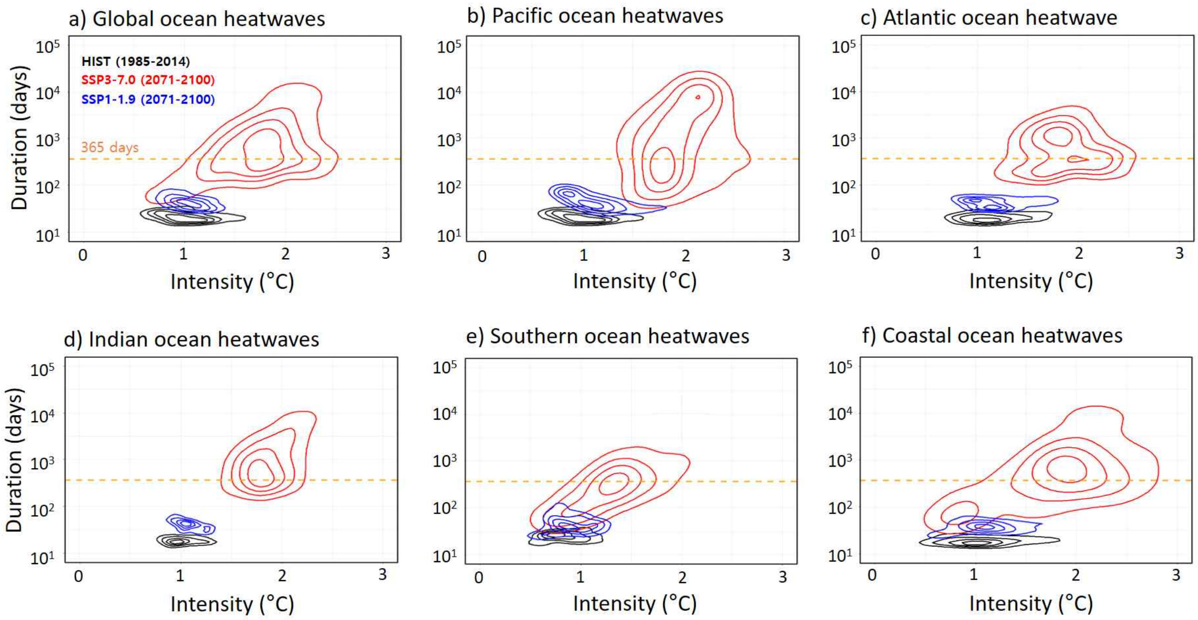

Figure 4. Joint probability distribution of marine heatwave duration (days) and intensity (°C) over the global and the five ocean areas. The black contours denote the historical period of 1985–2014. The red and blue contours denote the late 21st century (2071–2100) under SSP3-7.0 and SSP1-1.9 scenarios, respectively. Note that the y-axis has a logarithmic scale. The horizontal dashed line in yellow indicates the 365-day MHW duration as a reference for permanent MHW.

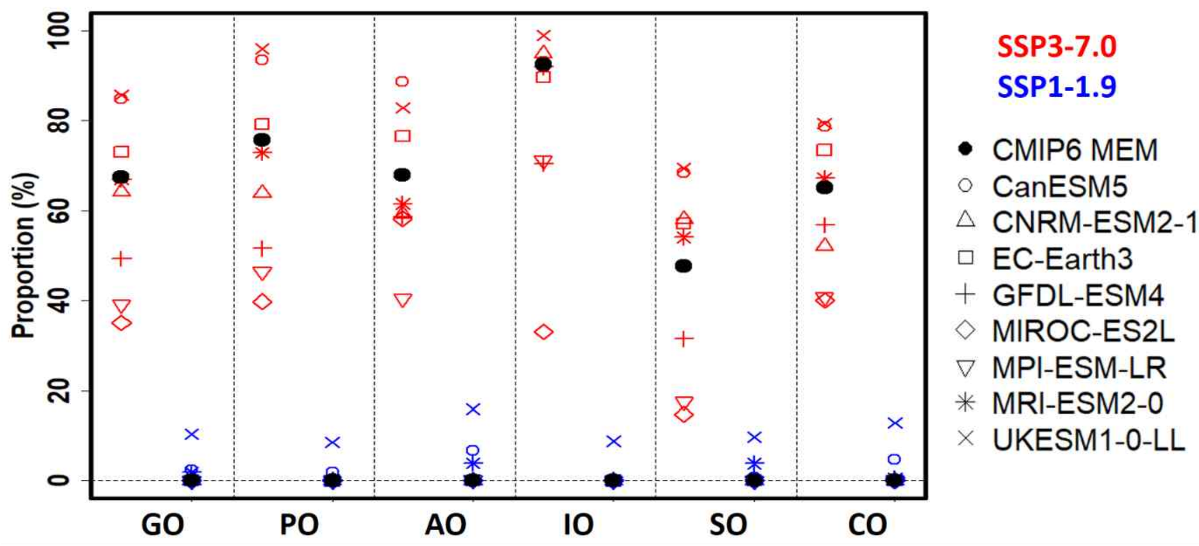

Figure 5. Proportion of ocean exposed to permanent MHWs, which is defined as an MHW duration of more than 365 days, over the globe ocean (GO), Pacific Ocean (PO), Atlantic Ocean (AO), Indian Ocean (IO), Southern Ocean (SO), and Coastal Ocean (CO) in the 21st century (2071–2100) under SSP3-7.0 and SSP1-1.9 scenarios compared to the historical period (1985–2014).

[*Earth's Future*]

Supporting Information for

Significant reduction of potential exposure to extreme marine heatwaves by achieving carbon neutrality

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January 2024

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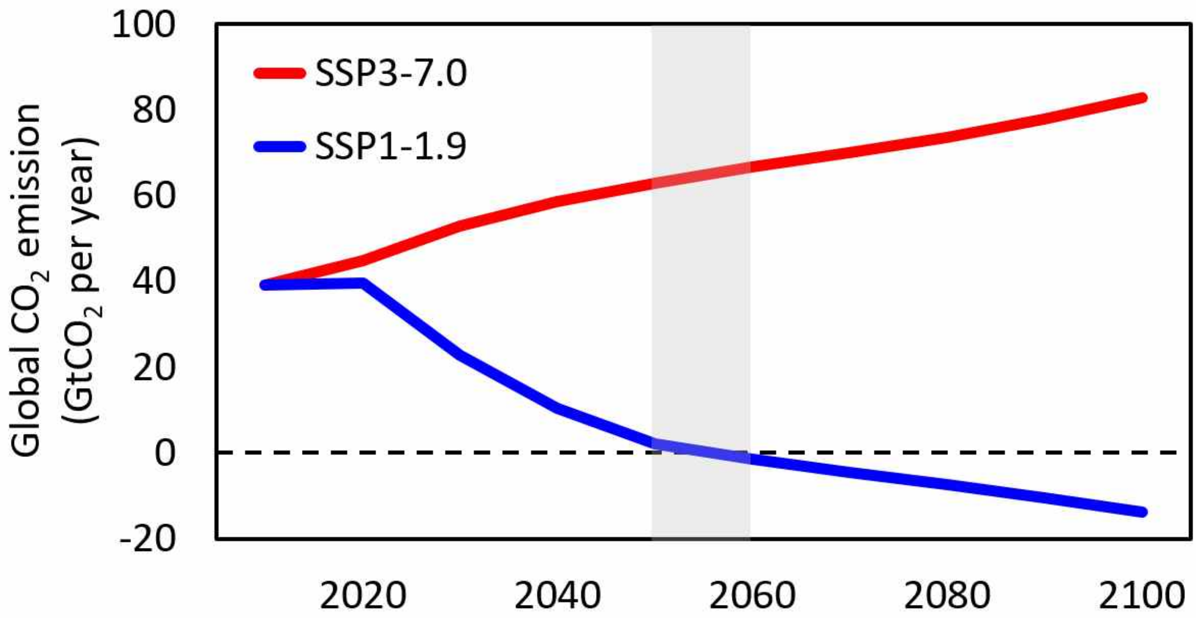

Fig. S1. Time series of global CO_2 emission in SSP1-1.9 and SSP3-7.0 scenarios. The vertical gray shading indicates the 2050s, when net-zero carbon emissions are achieved in the SSP1-1.9 scenario.

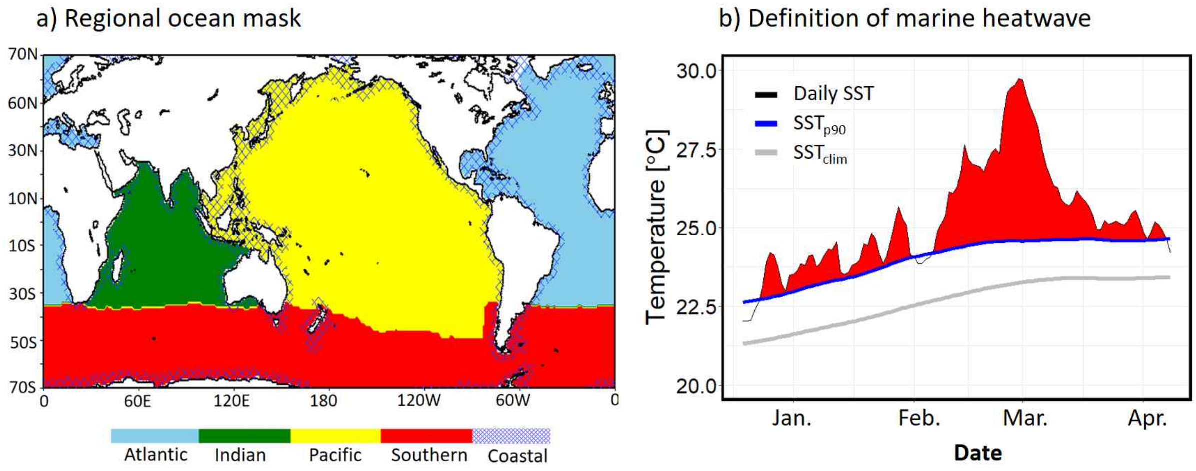

Fig. S2. (a) Sub-regional ocean domain used in this study (https://reccap2-ocean.github.io/regions/) and (b) example for the definition of marine heatwave.

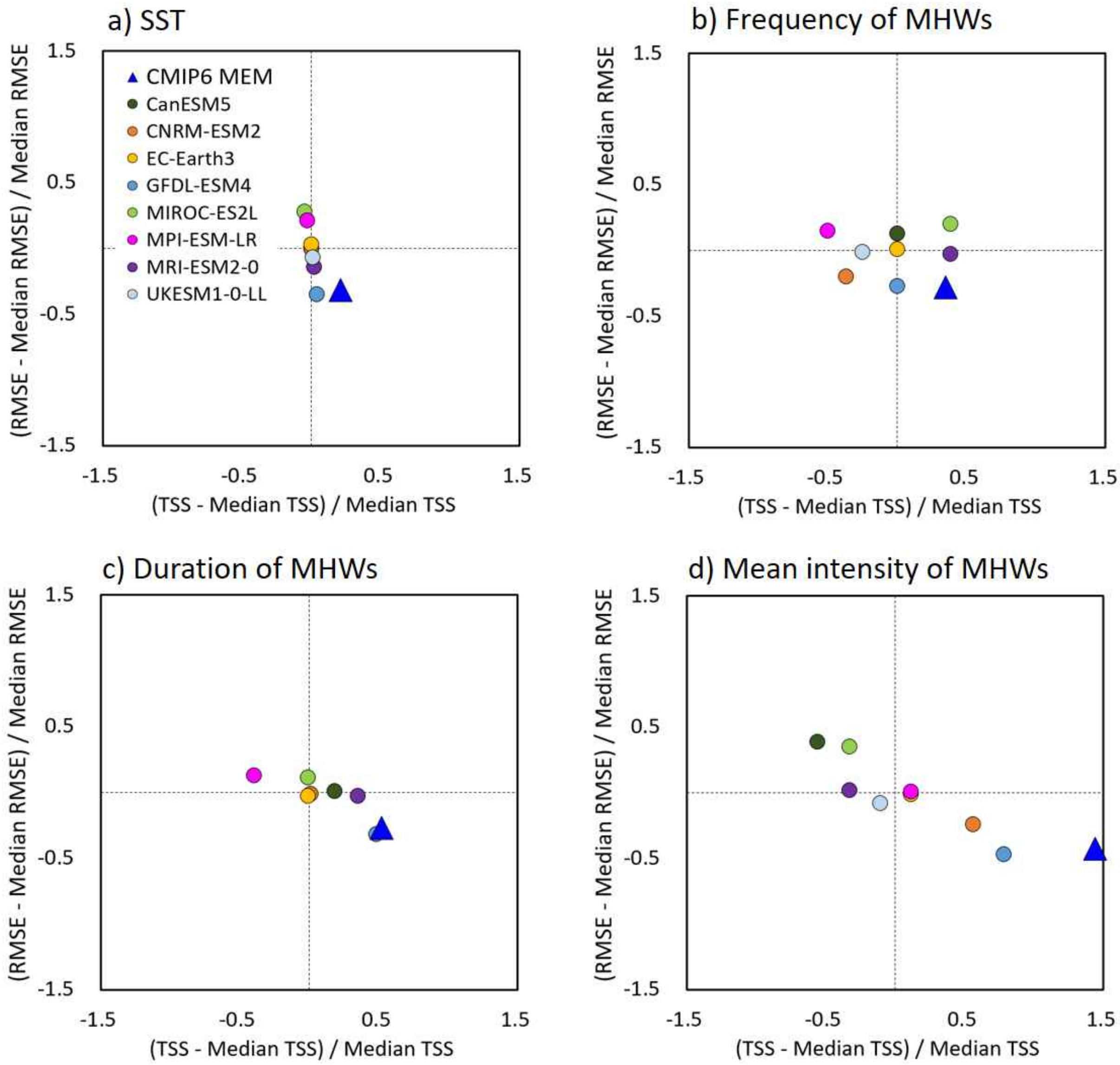

Fig. S3. The relative performance of the eight CMIP6 models and multi-model ensemble median for globally-averaged annual mean sea surface temperature (SST), marine heat wave (MHW) frequency, duration, and mean intensity for the historical period of 1985–2014, based on the root-mean-square error (RMSE) and Taylor skill score (TSS). The closer the symbol is to the bottom right corner, the better the relative performance. The NOAA OISST data is used as a reference in the calculation of evaluation measures. Only ocean areas ranging from 70°S to 70°N are considered.